

Sleep in the Intensive Care Unit: Limiting Elements of Noise in the Critical Care Environment (SILENCE)

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Trinity Term 2019

Thesis submitted for the degree of Doctor of Philosophy in Clinical Neurosciences

“Numbers have no way of speaking for themselves...We imbue them with meaning”[1]

It is traditional to dedicate a thesis to those who have supported and encouraged various endeavours along the way.

Altogether too many people have been a part of this. Some willingly, others more by necessity and proximity. Either way, it would be far too easy to offend by omission. You know who you are, and you know your role in bringing this thesis to submission. You also know that I cannot thank you enough. Without you it would not have been completed at all, let alone roughly on time and more or less within budget. This is for all of you.

[1] Nate Silver, The Signal and the Noise (Penguin, 2012)

Abstract

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Introduction

Sound levels in the intensive care unit (ICU) are persistently higher than World Health Organisation recommendations. This can lead to poor patient experiences including limited sleep, increased risk of delirium during admission, and prolonged recovery. Staff too can be affected. High noise levels are a distractor, can reduce concentration, and impair effective delivery of care.

This thesis explores the working environment of the ICU and proposes practical interventions for reducing sound levels.

Methods

The mixed methods approach incorporates an exploratory sequential design with an embedded convergent parallel design. Findings from secondary analysis of interviews with ICU patients and relatives, staff focus group discussion, ethnography, and sound levels were amalgamated to build a rich sonic picture of the ICU.

These findings generated materials for the accelerated experience-based co-design (AEBCD) trigger film and subsequent discussion with staff and patients.

The AEBCD process facilitated a complex noise reduction intervention focussed on quantitative measures of sound, which were explained by qualitative analyses of ethnography and interviews.

Teaching materials were developed in line with adult education theory. The electronic interface (visual display of sound) was designed using agile methodology with a focus on user-centred experience.

Results

Staff were motivated to reduce sound levels but were unaware how to do this, or how to assess change. This DPhil has identified opportunities for noise reduction strategies. Experiential learning in combination with online modules increased staff knowledge of how high sound levels can affect patients in their care.

High-fidelity sound level monitoring identified elevated levels occurring at handover, and throughout the day are generated mostly close to patients' heads.

Conclusions

It is feasible to reduce sound levels in the ICU. Maintaining long-term support for change in the clinical environment requires an understanding of the social and cultural influences that will facilitate or hinder sustained improvement, and multi-disciplinary involvement at all stages.

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Research Aims and Objectives

This research forms part of a wider programme of research funded by the National Institute of Health Research (NIHR), Research for Patient Benefit (RfPB) stream, ref: PB-PG-0613-31034. A subset of this larger work is incorporated in this thesis.

Aim

The primary aim of this DPhil is to assess the feasibility of lowering sound levels in the adult intensive care unit (AICU).

The rationale for reducing sound levels is to improve the patient experience of their intensive care admission. Lower sound levels may have an impact on the patient experience of intensive care by making the AICU a less hostile environment. A quieter space may better facilitate sleep and/or reduce the incidence of intensive care acquired delirium. Changes may also improve staff wellbeing, reduce communication barriers, and minimise missed alerts due to alarm fatigue.

Objectives

- To assess current sound levels of the intensive care unit
- To describe the sound environment (the 'soundscape') of the intensive care unit and identify sources of modifiable noise
- To design and implement a complex intervention for noise reduction

Within the full DPhil (October 2013 – September 2019), the NIHR RfPB project ran from February 2015 – April 2018. The timeline below illustrates the key events associated with this thesis.

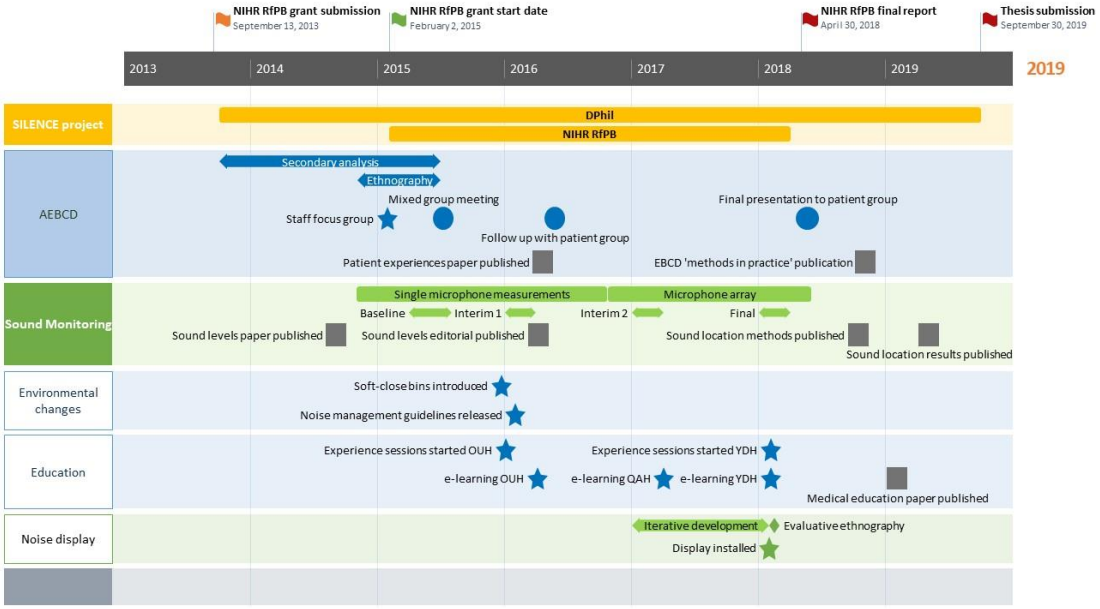
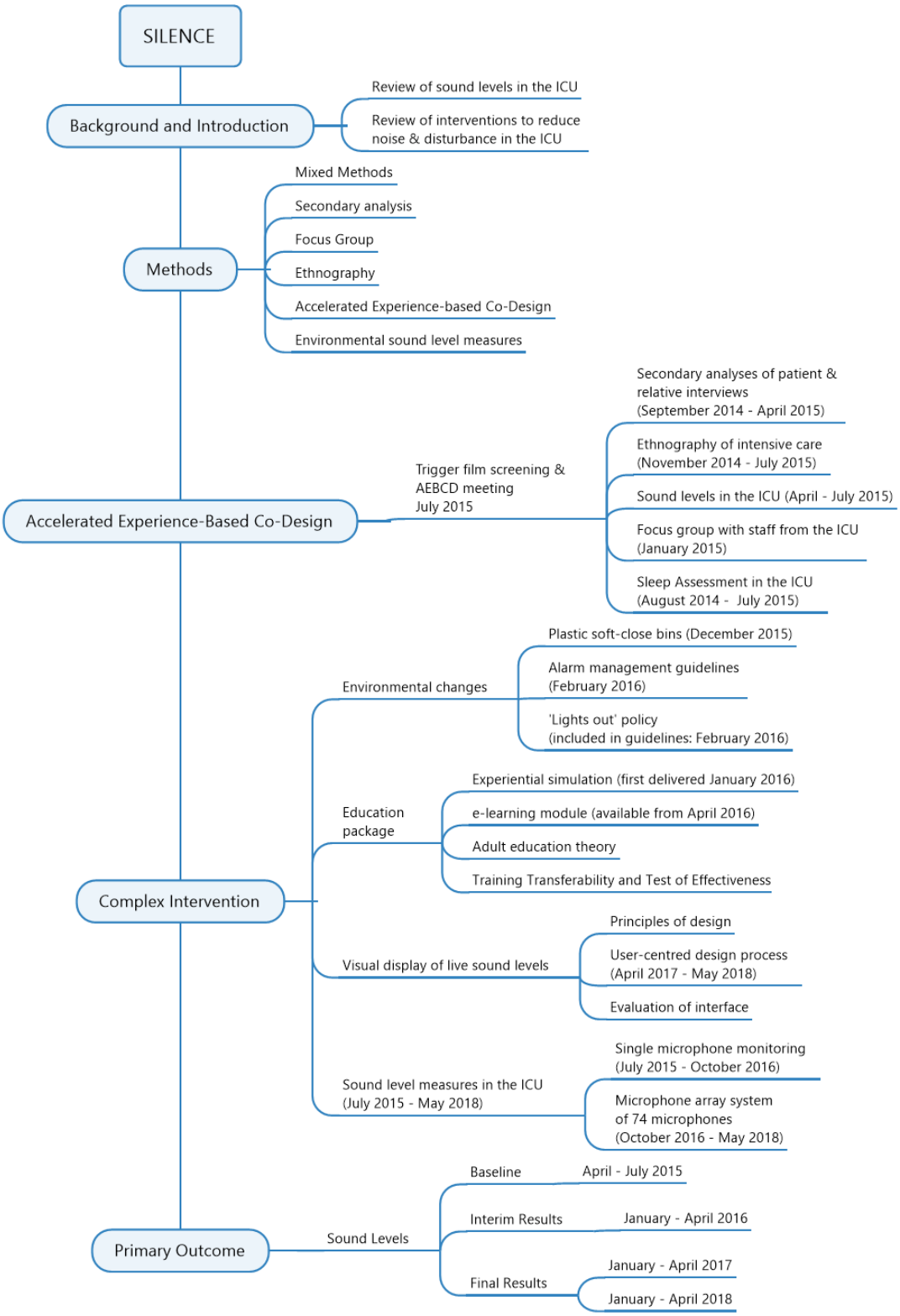


Figure 0-1: Timeline of DPhil showing interaction between interventions, environmental monitoring, and key publications

Additional objectives for NIHR RfPB project not addressed in this thesis

- Assessment of patient sleep in the AICU
    - Assessment of tools used for sleep measurement and monitoring in the AICU
    - Quality and quantity of patient sleep
- Assessment of intensive care acquired delirium
    - Clarification of incidence of delirium in the general AICU
    - Confirmation of screening tools used to identify delirium in the AICU

Organisation and structure of DPhil



The aims and objectives of the DPhil are addressed by:

- A review of sound levels in the AICU (chapter one)
- A review of interventions designed to reduce sound levels in the AICU (chapter one)
- A mixed-methods approach (described in chapter two) through integrated phases of a service improvement project using an accelerated experience-based co-design (AEBCD) which incorporated:
    - Secondary analysis of interviews with patients and relatives discussing their experiences of intensive care (chapter three)
    - A staff focus group to explore their experiences of noise levels in the AICU (chapter three)
    - Observational ethnography to evaluate the sound environment of the AICU (chapter three)
- The co-design phase is described in chapter four. Outcomes from the AEBCD meeting were:
    - Development and implementation of a multi-faceted noise reduction strategy (chapter four)
    - Design, development, and implementation of a teaching package designed to increase knowledge of the effects of high sound levels in the intensive care unit (chapter five)
    - Design and development of a prototype user-centred noise level visualisation (chapter seven)
- Overall primary endpoint results assessed through measured sound levels (chapter six).

Research project output

Journal publications

Darbyshire JL, Young JD, An investigation of sound levels on intensive care units with reference to the WHO guidelines, Critical Care 2013, 17: R187 doi: 10.1186/cc12870

Darbyshire JL, Excessive noise in intensive care units: Bad for staff and very bad for patients, BMJ 2016; 353:i1956 doi: 10.1136/bmj.i1956

Darbyshire JL, Greig PR, Vollam S, Young JD, Hinton L, "I can remember sort of vivid people…but to me they were plasticine." Delusions on the Intensive Care Unit: what do patients think is going on?, PLoS ONE 2016 11(4):e0153775 doi: 10.1371/journal.pone.0153775

Müller-Trapet M, Cheer J, Fazi FM, Darbyshire JL, Young JD, Acoustic source localization with microphone arrays for remote noise monitoring in an Intensive Care Unit, Applied Acoustics 2018 139:93-100 doi: 10.1016/j.apacoust.2018.04.019

Darbyshire JL, Hinton L, Using patient narratives to design an intervention to reduce noise in the Intensive Care Unit, Journal of Health Design 2018; 3(2): 109-112 doi: 10.21853/JHD.2018.51

Darbyshire JL, Hinton L, Young JD, Greig PR, Using the experience-based co-design method to design a teaching package, Medical Education 2018; 52(11): 1178-1179 doi: 10.1111/medu.13720

Greig PR, Darbyshire JL, Medical educational theory in practice, BJA Education 2019; 19(2): 40-46 doi: 10.1016/j.bjae.2018.10.003

Darbyshire JL, Müller-Trapet M, Cheer J, Fazi FM, Young JD, Mapping sources of noise in an intensive care unit, Anaesthesia 2019; 74(8); 1019-1025 doi: 10.1111/anae.14690

Darbyshire JL, Noise in the intensive care unit: where does it come from and what can you do about it?, ICU Management & Practice 2019; 19(2): https://healthmanagement.org/c/icu/issuearticle/noise-in-the-intensive-care-unit-where-does-it-come-from-and-what-can-you-do-about-it

Related journal publications for NIHR RfPB phases

Darbyshire JL, Borthwick M, Edmonds P, Vollam S, Hinton L, Young JD, Measuring sleep in the intensive care unit: Eletroencephalogram, actigraphy, or questionnaire?, Journal of the Intensive Care Society 2018; 21(1): 22-27 doi: 10.1177/1751143718816910

Jeffs EL, Darbyshire JL, Measuring sleep in the Intensive Care Unit: A critical appraisal of the use of subjective methods, Journal of Intensive Care Medicine 2019; 34(9):751-760 doi: 10.1177/0885066617712197

Conference presentations

Darbyshire JL, Young JD, Barrett C, Edmonds P, Hinton L*, Patients and staff join researchers to design environmental changes in the Intensive Care Unit, Kings Fund: Transforming patient experience, London, November 2015

Darbyshire JL*, Jeffs EL, Vollam S, Hinton L, Young JD, Noises in the Intensive Care Unit: What goes bump in the night?, Thames Valley Clinical Research Network Critical Care Research Symposium, Oxford, November 2015

Darbyshire JL*, Edmonds P, Khan N, Hinton L, Experiential learning in the ICU: Using the AEBCD approach in practice, 31st Annual British Association of Critical Care Nurses Conference, Glasgow, September 2016

Hinton L*, Darbyshire JL, Experiential learning in the ICU: Using the AEBCD approach in practice, DIPEx International Meeting, Tenerife, November 2016

Müller-Trapet M*, Cheer J, Fazi FM, Darbyshire JL, Young JD, Machine listening in combination with microphone arrays for noise source localization and identification, 173rd Annual Conference of the Acoustical Society of America, Boston, Massachusetts, June 2017; The Journal of the Acoustical Society of America 2017; 141 3964 doi: 10.1121/1.4989025

Darbyshire JL, Sound! Lights! Action! Noise in the ICU and the SILENCE trial, Intensive Care Society State of the Art, London, December 2017

Darbyshire JL, Reducing noise in the Intensive Care Unit: Why and how?, What's New in ICU, Edinburgh, May 2018

Darbyshire JL*, Greig PR, Edmonds P, Barrett C, Hinton L, Young JD, "You gain strength, courage, and confidence by every experience in which you really stop to look fear in the face": Experiential teaching in the ICU, 33rd Annual British Association of Critical Care Nurses Conference, Bournemouth, September 2018

Darbyshire JL, Noise pollution in the Intensive Care Unit, 27th Update in Critical Care for Physiotherapists, London, November 2018

Darbyshire JL, Building Better ICUs, Intensive Care Society State of the Art, London, December 2019

Related conference presentations for NIHR RfPB phases

Senaratne DNS*[2], Young JD, Darbyshire JL, Sleep in the ICU: Recovering patients continue to experience sleep deprivation, 33rd Congress of the Scandinavian Society of Anaesthesiology and Intensive Care Congress, Reykjavik, June 2015; Acta Anaesthesiologica Scandinavica 59: 41

Darbyshire JL*, Young JD, Sleep deprivation in the Intensive Care Unit, Thames Valley Clinical Research Network Urgent Care Research Symposium, Oxford, November 2016

[2] * denotes presenting author

Poster presentations

Darbyshire JL*, Jeffs EL, Vollam S, Hinton L, Young JD, Noises in the Intensive Care Unit: What goes bump in the night?, Intensive Care Society State of the Art, London, December 2015; Journal of the Intensive Care Society 2015; 16: 104-128 doi: 10.1177/1751143715615287

Müller-Trapet M, Cheer J, Fazi FM, Darbyshire JL*, Young JD, Acoustic Source Localization with Microphone Arrays for Remote Noise Monitoring in an Intensive Care Unit, Thames Valley Clinical Research Network Urgent Care Research Symposium, Oxford, November 2016

Darbyshire JL*, Barrett C, Edmonds P, Young JD, Hinton L, "Deep experience is never peaceful": Raising awareness of noise sources in the ICU, Intensive Care Society State of the Art, London, December 2016; Journal of the Intensive Care Society 2017; 17(4): supplement 1-217 doi: 10.1177/1751143717708966

Darbyshire JL*, Greig PR, Edmonds P, Barrett C, Hinton L, Young JD, "By three methods we may learn wisdom: First, by reflection, which is noblest; second, by imitation, which is easiest; and third by experience, which is the bitterest": Developing a training package to reduce noise levels in the Intensive Care Unit, Royal College of Nursing Education Forum National Conference and Exhibition, Newcastle, March 2018

Darbyshire JL*, Young JD, Bedford J, Redfern OC, Hatch RA, Understanding sound pressure levels in the Intensive Care Unit, 39th International Symposium on Intensive Care and Emergency Medicine, Brussels, March 2019 Critical Care 2019; 23(2): 72 doi: 10.1186/s13054-019-2358-0

Related poster presentations for NIHR RfPB phases

Jeffs EL*, Young JD, Darbyshire JL, Measuring sleep in the intensive care unit: A systematic review of the literature, Thames Valley Clinical Research Network Critical Care Research Symposium, Oxford, November 2015

Hird C*, Wright C, Beck L, Greig PR, Darbyshire JL, An audit to review rehabilitation practices within Intensive Care, Thames Valley Clinical Research Network Urgent Care Conference, Oxford, November 2016

Darbyshire JL*, Young JD, SILENCE – Patient sleep in the intensive care unit remains elusive, 30th Annual Congress European Society of Intensive Care Medicine, Vienna, September 2017

Abbreviations

ADC	Analogue to Digital Converter
(A)EBCD	(Accelerated) Experience-Based Co-Design
AHP	Allied Health Professional
(A)ICU	(Adult) Intensive Care Unit
CCRG	(University of Oxford, NDCN) Critical Care Research Group
CPD	Continuous Professional Development
CUREC	Central University Research Ethics Committee
dB	Decibel
dBA	Decibel (A-weighted scale)
dBC	Decibel (C-weighted scale)
DIPEx	Database of Individual Patient Experiences
ECG	Electrocardiogram
EEG	Electroencephalogram
EM	Environmental Monitoring
GMC	General Medical Council
GUI	Graphical User Interface
HCA	Health Care Assistant
HDU	High Dependency Unit
HERG	(University of Oxford) Health Experiences Research Group
HRO	High Reliability Organisation
HSE	Health and Safety Executive
Hz	Hertz
ICM	Intensive Care Medicine
ICNARC	Intensive Care National Audit & Research Centre
ICS	Intensive Care Society
IEC	International Electrotechnical Commission
IQR	Inter Quartile Range
ISO	International Organisation for Standardisation
ISVR	(University of Southampton) Institute of Sound and Vibration Research
JR	John Radcliffe Hospital
LAeq([time])	Averaged A-weighted sound level [time]; LAeqT used for multiple durations
LAMax	Maximum sound level (A-weighted scale)
LAFMax	Maximum sound level (A-weighted scale [fast measures])
LCPeak	Peak sound level (C-weighted scale)

(L)CRN	(Local) Clinical Research Network
LED	Light Emitting Diode
LNP	Local Noise Patterns
MREC	Medical Research Ethics Committee
MSD-IDREC	Medical Sciences Division Interdivisional Research Ethics Committee
NDCN	(University of Oxford) Nuffield Department of Clinical Neurosciences
NHS	National Health Service
NIHR	National Institute for Health Research
NREM	Non-Rapid Eye Movement stage of sleep
NRES	National Research Ethics Service
OCC	Oxford Computer Consultants
OUH	Oxford University Hospitals NHS Foundation Trust
OSOP	One Sheet Of Paper
PHT	Portsmouth Hospitals Trust
PSG	Polysomnography
PAR	Participatory Action Research
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QAH	Queen Alexandra Hospital (Portsmouth Hospitals NHS Trust)
RCSQ	Richards Campbell Sleep Questionnaire
RCT	Randomised Controlled Trial
REM	Rapid Eye Movement stage of sleep
RfPB	Research for Patient Benefit
SA	Sleep Architecture
SD	Standard Deviation
SILENCE	Sleep in the Intensive Care Unit: Limiting Elements of Noise in the Critical Care Environment
STROBE	Strengthening the Reporting of Observational Studies in Epidemiology
SWS	Slow Wave Sleep stage
UN	United Nations
VARK	Visual Auditory Reading Kinaesthetic
WAD	Work As Done
WAI	Work As Imagined
WHO	World Health Organisation
YDH	Yeovil District Hospital NHS Foundation Trust

Motivation and reasons for embarking on this DPhil

"The intensive care unit, entirely lacking in silence, darkness, privacy, peace, and rest, is as hostile, as toxic an environment for recovery as could be imagined"[3]

As a non-clinician with an academic background in English Literature and Science Communication it may seem unusual to embark on a higher degree with a medical focus. Until taking up a research management role for the University of Oxford Nuffield Department of Clinical Neurosciences my only experience of intensive care (like most non-clinicians) was through television programmes. My 'guided tour' of the critical care area in 2011 was therefore something of a surprise. Although I knew depictions of medical situations on film and TV are notoriously inaccurate, sometimes comedically so, I was wholly unprepared for the bustle of activity. Much less did I expect to see patients sitting up in bed having their breakfast.

During later discussions with senior clinicians I learned that patients attending clinic after their ICU admission also often mentioned how busy and loud they had found their stay, and how this had affected their sleep. This led to preliminary investigations that revealed sleep is well-known to be a problem for patients admitted to intensive care, that sound levels have been under scrutiny for at least forty years, and that both of these problems have been linked to delirium, and mental health and cognitive problems that patients can experience for some time after they have returned home.

Approximately 20% of patients admitted to intensive care units experience delirium during their stay. This figure rises to 75% for patients who are ventilated and sedated. Delirium is not well-known outside of the clinical community. It was clear from these early investigations that patients can be deeply distressed by their experiences. There seemed to be some evidence that the hospital environment might be, at least in part, a trigger for hallucinations and delusionary thoughts and that these can develop into long-term problems for patients, including post-traumatic stress disorder, anxiety, and depression.

I am not alone in thinking a successful outcome for patients admitted to intensive care should more than just being alive. Quality of life is equally important. Thinking about sound levels in particular, I discovered the 1999 World Health Organisation guidelines (limiting sound levels to 35dB in patient care areas) were apparently not achievable, despite best efforts, and that this was possibly leading to despondency and limited engagement with the problem beyond persistently reporting that standards were not being met. I felt there had to be a better way.

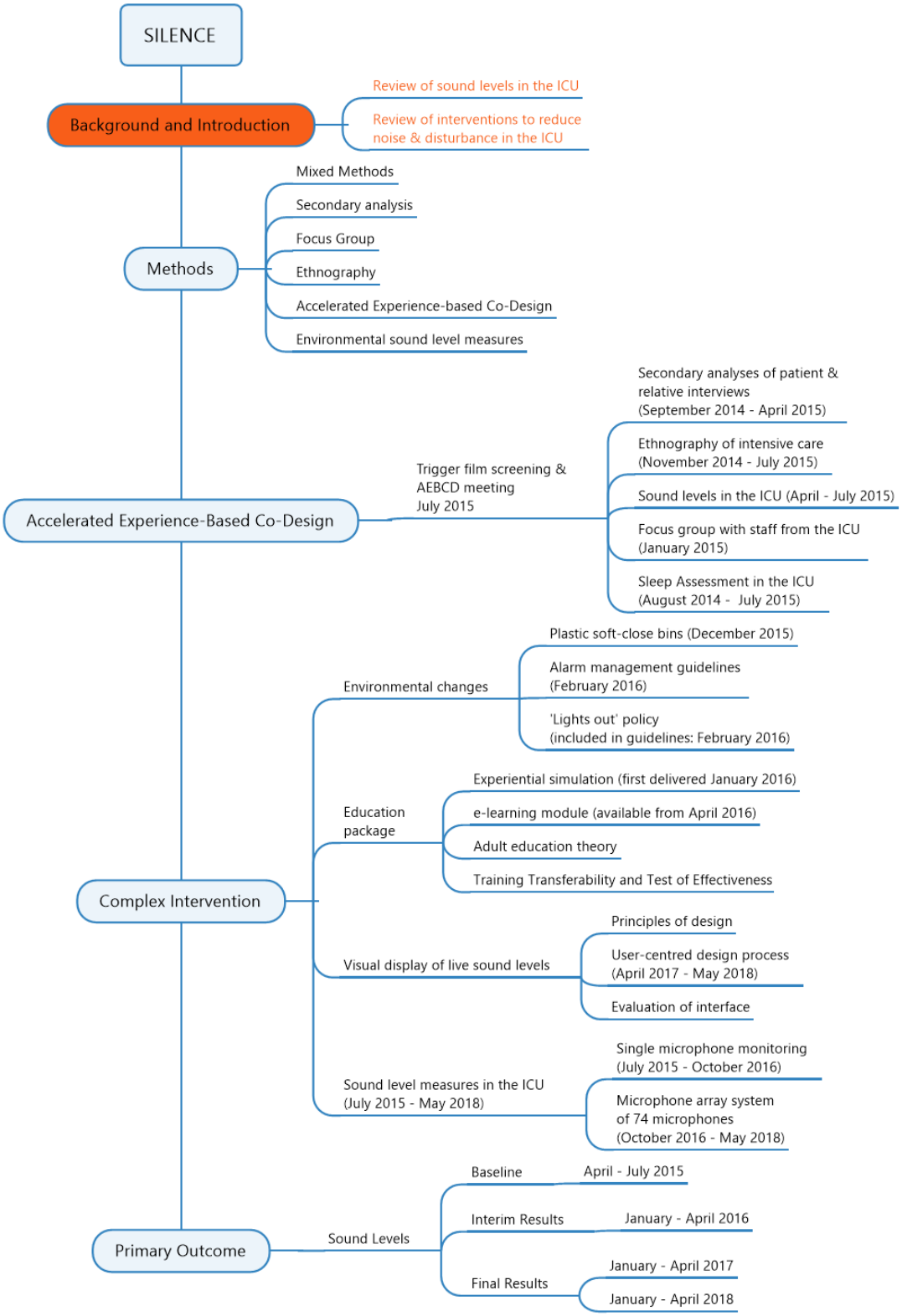
This DPhil is the outcome of those early discussions.

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[3] Ursula Le Guin, Words are My Matter (2016)

1. Chapter One: Introduction and Background

1.1. Chapter summary



This chapter synthesises current literature describing sound levels in adult intensive care units (AICUs), problems associated with noise, and interventions to reduce disturbance.

The principal focus of the first review (section 1.4) is to summarise sound levels of AICUs since 2000. An initial search identified 1264 publications. Of these, 22 papers were reviewed. Over half were published between 2012 and 2017. These publications confirm sound levels in the AICU are consistently much higher than World Health Organisation (WHO) guidelines [1] recommend, however methods of sound level measurement varied considerably. Direct comparison between studies is therefore difficult.

A second review (section 1.5) evaluates sound-reduction interventions tested in AICUs. Only one eligible randomised controlled trial (RCT) was identified from a search result of 159 titles. This study was assessed "not of good quality" using the Revised Cochrane Risk-of-Bias tool for randomised trials (version date 15 March 2019) [2]. This search was broadened to include non-randomised trials (section 1.6) and, from an initial list of 624 interventional studies, twelve were included. The majority of interventions were assessed over a short duration, none demonstrated sustained reduction in sound levels.

1.2. Aim

The aim of this literature review is two-fold. Firstly to confirm current sound levels in the AICU (section 1.4) and secondly to evaluate interventions designed to reduce sound levels (sections 1.5 and 1.6).

1.3. Background

1.3.1. Environmental sound monitoring

Sound level monitoring is outlined in more detail in chapter six. Standard monitoring reports average equivalent levels for a specified duration (LAeq). LAeq24 (the average sound level over 24 hours) is used most frequently. Other durations are reported, with LAeq8 (average equivalent level for an eight-hour working day) being the most frequent alternative.

1.3.2. WHO Guidelines for Community Noise, 1999 (Noise levels in hospitals)

The text in the box below is extracted from the WHO Guidelines for Community Noise, 1999; Noise levels in hospitals

> World Health Organisation (WHO) *Guidelines for Community Noise*, 1999
>
> Section 4.3.3
>
> For most spaces in hospitals, the critical effects of noise are on sleep disturbance, annoyance and communication interference, including interference with warning signals. The LAmax of sound events during the night should not exceed 40dB indoors. For wardrooms in hospitals, the guideline values indoors are 30dB LAeq, together with 40dB LAmax during the night. During the day and evening the guideline value indoors is 30dB LAeq. The maximum level should be measured with the instrument set at "Fast".
>
> Since patients have less ability to cope with stress, the equivalent sound pressure level should not exceed 35dB LAeq in most rooms in which patients are being treated or observed. Particular attention should be given to the sound pressure levels in intensive care units and operating theatres. Sound inside incubators may result in health problems, including sleep disturbance, and may lead to hearing impairment in neonates. Guideline values for sound pressure levels in incubators must await future research.

The WHO guidelines are deliberatively conservative, noting that limits are set at levels at which no adverse effects would be expected. What follows is a review to identify studies designed to measure sound levels in the AICU to determine the extent to which they comply with guidelines.

Patients and their relatives frequently complain about noise levels on an ICU when attending outpatient clinics after admission[4]. Clinical staff make similar comments.

Reducing noise has the potential to improve both the patient experience and staff working environment, but unfortunately there is evidence the ICU environment is getting louder. A 2005 review of hospital noise levels [3] included publications from the last 50 years and suggested an average increase of 4dB every decade. This may be due to increasing workload, a proliferation in technical devices, and more widespread use of monitoring equipment with associated alarms.

An initial review for this project in 2012 considered noise in ICUs and possible solutions to inform work in Oxford. The results indicated the LAeq24 (daily mean sound level) in hospitals globally remains considerably higher than the WHO guideline of 35dBA.

Data from the review, coupled with a small-scale multi-centre observational study [4], informed the grant application to the National Institute of Health Research (NIHR) Research for Patient Benefit (RfPB) funding stream. This grant (ref: PB-PG-0613-31034) funded the SILENCE[5] project from which this thesis is derived.

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[4] Consultant ICU follow up clinics, Oxford University Hospitals NHS Foundation Trust

[5] **S**leep in the **I**ntensive Care Unit: **L**imiting **E**lements of **N**oise in the **C**ritical Care **E**nvironment

The 2012 review highlighted several interventions with potential to reduce sound levels (measured as LAeqT) successfully for a short period of time although none showed evidence of sustained change.

The review was updated in late 2017 to capture overall sound level data (LAeq) and sound reduction interventions reported more recently. This update focusses on publications after 1999, the year the WHO guidelines were issued, and formally separates publications focused on sound level measurement and those primarily concerned with interventions to reduce noise.

1.4. Review 1: Sound levels in the adult intensive care unit

1.4.1. Search strategy

Papers were identified by searching Medical Literature Analysis and Retrieval System Online (MEDLINE), Excerpta Medica database (EMBASE), the American Psychological Association integrated literature database (PsychINFO), and the Cumulative Index to Nursing and Allied Health Literature (CINAHL). Searches were conducted through Ovid.

The search was date-limited to publication after 1999. Although earlier publications exist, they were not considered relevant as the WHO guidelines superseded existing noise policies.

To maintain homogeneity, and recognising that needs of neonatal and paediatric ICUs are different, searches were limited to articles exploring sound levels of AICUs only.

The initial search was formatted for MEDLINE, EMBASE, and PsychINFO. The MEDLINE search strategy is summarised in Table 1-1: Medline search strategy; ti=search in title, ab=search in abstract, “”=search for exact match

Medline search strategy
1. ICU.ti,ab.
2. ITU.ti,ab.
3. "intensive care".ti,ab.
4. "critical care".ti,ab.
5. "intensive therapy".ti,ab.
6. 1 or 2 or 3 or 4 or 5
7. SPL.ti,ab.
8. dB.ti,ab.
9. decibel.ti,ab.
10. noise.ti,ab.
11. sound.ti,ab.
12. "sound monitoring".ti,ab.
13. "sound pressure".ti,ab.
14. LC.ti,ab.
15. LAeq.ti,ab.
16. "noise monitoring".ti,ab.
17. 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16
18. 6 and 17
19. 6 and 17
20. limit 19 to (yr="1999 -Current" and "all adult (19 plus years)")

Table 1-1: Medline search strategy; ti=search in title, ab=search in abstract, “”=search for exact match

The search was modified for PubMed: (((((((intensive care [tiab] OR ICU [tiab] OR intensive care [tiab] OR intensive therapy [tiab] OR critical care [tiab]) AND (SPL [tiab] OR "sound pressure" [tiab] OR db [tiab] OR decibel [tiab] OR noise [tiab] OR sound [tiab] OR lc [tiab] OR laeq [tiab] OR "sound monitoring" [tiab]) OR "noise monitoring" [tiab]) AND ("1999"[Date - Publication] : "3000"[Date - Publication]))) NOT infant*[Title/Abstract]) NOT paed*[Title/Abstract]) NOT child*[Title/Abstract]) NOT baby*[Title/Abstract]) NOT neonat*[Title/Abstract]

The search was also repeated for CINAHL: (TI ICU OR AB ICU OR TI ICU OR AB ICU OR TI "intensive care" OR AB "intensive care" OR TI "critical care" OR AB "critical care" OR TI "intensive therapy" OR AB "intensive therapy") AND (TI SPL OR AB PSL OR TI dB OR AB dB OR TI decibel OR AB decibel OR TI noise OR AB noise OR TI sound OR AB sound OR TI LC OR AB LC OR TI "sound monitoring" OR AB "sound monitoring" OR TI "sound pressure" OR AB "sound pressure" OR TI "noise monitoring" OR AB "noise monitoring")

Titles and abstracts of identified papers were screened against eligibility criteria. There was no blinding to journal titles, study authors, or institutions. Full texts were retrieved for all articles retained after initial screening. Publications were assessed individually and uncertainty over inclusion was resolved through discussion with a second researcher.

1.4.2. Eligibility criteria

Types of study

All observational, non-interventional study reports published in peer-reviewed journals were eligible. Studies were required to report sound levels measured using validated environmental monitoring equipment and must have been conducted in AICUs (providing level 3 care to adult patients).

Population

The population of this review is the AICU environment, rather than individual patients.

Study characteristics

Studies published after 1999 and indexed to the day of search (November 2017) were included. No language restrictions were applied to the initial search, although non-English studies for which no translation was available were excluded later at full-text review.

Phenomenon of interest

Studies were required to report continuously measured A-weighted sound levels[6] in the AICU. Sound level values must have been reported as either LAeq24, LAeq(day), or LAeq(night). Where sound peaks (LCpeak or LAFmax) were reported, data were extracted for analysis. No restriction was placed on ICUs dedicated to narrow cohorts of patients or studies based in specialised ICUs. Neurological, trauma, surgical, and cardiac units were all eligible. Studies reporting appropriate measures where sound was not the primary outcome were included.

[6] 'A' weighted sound levels adjust raw decibel values to partially accommodate for how the human ear hears different frequencies of sound. In general, higher frequencies (such as alarms) are perceived as louder.

Types of studies

Case studies, conference abstracts, grey-literature, editorials, letters, and guidelines were excluded. Review articles were considered separately and assessed for additional publications not identified by searches.

Study characteristics

Studies that did not include continuous measures of sound level[7] were excluded.

Phenomenon of interest

Studies conducted in paediatric or neonate ICUs were excluded. Studies reporting 'spot' measures of sound levels were excluded. Studies which did not report at least one of LAeq24, LAeq(day),, or LAeq(night) were also excluded.

1.4.3. Data extraction

EndNote (vX8; Clarivate Analytics, Philadelphia, USA) was used to manage references and identify duplicate results. Data were extracted by a single researcher.

1.4.4. Quality assessment

Each study included was assessed against STROBE reporting criteria [5], using a validated scoring system devised for evaluation [6]. A maximum of 21 points were available for each study. A highly-rated study was defined as 17 or more points, an acceptable-rated study scored 10-16 points and a poorly-rated study scored 9 points or fewer.

1.4.5. Data synthesis and analysis

A quantitative approach was planned. The intent was that sound level results would be analysed using Review Manager (RevMan) (Version 5.3. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) but, as will be described, this was not appropriate due to study heterogeneity.

[7] Some publications report short periodic or 'spot' measures of sound level. To be comparable with other publications, and to be compliant with environmental monitoring, studies must report LAeq for durations of at least eight hours.

1.4.6. Search results

The review is reported in line with PRISMA guidelines [7].

- After duplicates had been removed, the initial search (1319) resulted in 1264 publications.
    - CINAHL: 392
    - EMBASE: 158
    - MEDLINE: 191
    - PsychINFO: 38
    - PubMed: 540
- Of these, 302 were retained based on title and considered for abstract review
- Full text files were retrieved for 110 publications retained after abstract review
- No additional titles were identified from review articles
- A total of 22 publications were included (summarised in Table 1-2)
- Of the 88 titles excluded:
    - Twenty did not report continuously measured sound levels
    - Nineteen were editorials, reviews, or conference abstracts
    - Fifteen were unobtainable
    - Fourteen evaluated an intervention (outside the scope of this review)
    - Nine were not written in English and no translation was available
    - Six did not report A-weighted sound
    - Five did not report on adult ICU environments

1.4.7. Quality assessment

The majority of studies (n=18) were evaluated as 'acceptable' using the STROBE assessment. Two studies scored highly [8,9] and two were assessed as poor quality [10,11]. The full range of scores was 8.5 – 18, with a mean (±SD) of 13 (±2.5).

1.4.8. Results from identified publications

Papers included in the review

Author [Country]	Year	LAeq(day)	LAeq(night)	LAeq24	Maximum sound level	
					LCpeak* OR LAFmax#	
		dBA (single value, range, mean values +/- SD or 95% CI; per original publication)			Absolute value	Mean (+/- SD)
Gabor [12] [Canada]	2003	44.3 +/-0.5 - 56.2 +/-2.2	43.2 +/-0.7 - 56.2 +/-2.5	Not reported	Not reported	67.1 +/-2.8#
Christensen [13] [UK]	2007	Not reported	55.0 +/-2.3	56.4 +/-5.2	80#	Not reported
Otenio [14] [Brazil]	2007	58 - 65	58 - 61	62.7	Not reported	Not reported
Akansel [15] [Turkey]	2008	Not reported	Not reported	64	89#	Not reported
Ryherd [16] [US]	2008	55-58	53	55	109* 90#	Not reported
Tsara [10] [Greece]	2008	Not reported	Not reported	59 +/-2.2	Not reported	Not reported
Elliott [17] [Australia]	2010	Not reported	Not reported	56.2 +/-1.7	Not reported	107.9 +/-7.2*
Okcu [18] [US]	2011	Not reported	Not reported	57-58	113-120*	Not reported
Salandin [18] [Germany]	2011	2-bed room 59 4-bed unit 53	2-bed room 55 4-bed unit 49	Not reported	2-bed room 95# 4-bed unit 105#	Not reported
Johansson [19] [Sweden]	2012	Not reported	Not reported	53 +/-1.1	101#	Not reported
Darbyshire [4] [UK]	2013	Not reported	Not reported	51.3 – 59.9	127.9#	Not reported
Elliott [20] [Australia]	2013	54.0 +/-2.3	50.2 +/-3.2	Not reported	>90*	Not reported
Kletzenbauer [11] [Austria]	2013	Not reported	50.8 – 61.4	Not reported	Not reported	Not reported
Tegnestedt [21] [Sweden]	2013	Not reported	52.1 +/-2.3 - 53.4 +/-4.0	Not reported	>75*	Not reported
Elliott [22] [Australia]	2014	Not reported	Not reported	56.6 +/-2.16	Not reported	107.33 +/-10.32*
Park M [23] [Netherlands]	2014	Not reported	Not reported	56	106*	Not reported
Kol [24] [Turkey]	2015	67.5	59.1	Not reported	91.9#	Not reported
Park M [25] [Netherlands]	2015	54.2	51.1	53.1	Not reported	Not reported
Galindo [26] [Colombia]	2016	Not reported	59.95	Not reported	Not reported	71.55 +/-2.32# - 77.22 +/-1.94#
Knauert [8] [US]	2016	Not reported	53.5 +/-4.1	Not reported	84.9 +/-5.5*	Not reported
Boyko [9] [Denmark]	2017	Not reported	47.57 CI: 46.6-48.6 46.92 CI: 46.0-47.9	Not reported	84.9 - 86.3	Not reported
Delaney [27] [Australia]	2017	Not reported	52.85 +/-5.89	Not reported	98.3#	Not reported

Table 1-2: Summary of identified papers

Summarised results

The intent was to produce a meta-analysis of LAeq24 but just twelve studies reported this time period. The majority of studies reported maximum sound although this varied between the absolute maximum (LAFmax) and the C-weighted peak sound (LCpeak). The lack of conformity in reported results meant meta-analysis was not appropriate. Instead, the mean for each variable of significance has been calculated to present a simplified overview of sound in the AICU (Table 1-3).

Simple averages of sound measures

	LAeq24 n=12	LAeq(day) n=7	LAeq(night) n=14	LCpeak n=14	LAFmax n=4
Minimum	42.1	43.8	51.2	75.1	80
Maximum	69	65	63.6	120	127.9

Table 1-3: Simple averages of sound levels reported by studies

Of the 22 publications, only 12 reported LAeq24 values [4,10,13-19,22,23,25]. Just six of these also included a measure of variation [10,13,17,19,22,24]. Of the 10 publications that did not report LAeq24, four separately reported day and night values [12,20,24,28]; six reported overnight results only [9,11,21,26,27,29]. Eighteen publications included at least one measure of maximum or peak sound [4,8,9,12,13,15-24,26-28]. Summary values indicate that C-weighted values reported for sudden loud sounds (the LCpeak) were lower than the highest sound value (LAFmax) overall.

1.4.9. Discussion

Sound levels were reported inconsistently which makes it difficult to synthesise data meaningfully.

Standard environmental monitoring in workplace settings reports mean A-weighted[8] values (LAeqT) [30]. The LAeq is most often reported as a 24-hour value but sound levels can be assessed over a shorter timeframe. For conventional industry and community reporting this is the eight-hour working day (generally 0900 - 1700, but this can vary).

For the healthcare environment LAeq(day) and LAeq(night) are also credible as these correspond to common shift patterns, usually 12-hours in duration. Some publications additionally report peak or maximum values. These particularly high values are variously reported as LCpeak[9] or as LAFmax[10].

The decibel scale is logarithmic with intensity increasing ten-fold for every ten decibel increase. The loudest ICU in the review (LAeq24 69dBA) would have sounded over four times as loud as the WHO recommended level of 35dBA. This difference would be like comparing a busy road to a quiet library. Anyone who has spent time in an ICU will recognise it feels nothing like a

[8] 'A' weighted sound levels adjust raw decibel values to partially accommodate for how the human ear hears different frequencies of sound. In general, higher frequencies (such as alarms) are perceived as louder.

[9] 'C' indicates an alternative weighting system appropriate for sudden loud sounds

[10] The maximum A-weighted sound level in any given period of time

library. Despite the variation in reporting, it is clear that no AICU has been able to achieve sound levels within WHO guidelines.

There are a large number of studies that include measures of overnight sound level. This suggests clinical interest in improving the environment to maximise sleep opportunities for patients. The WHO guidelines for night noise management in the community setting [31] conclude there is limited evidence that noise disturbance at night is directly related to biological effects. There is however *plausible association*, particularly with cardiovascular effects, and there is no doubt that overnight disturbance results in self-reported sleep problems leading to increased medication to support sleep [31].

In addition to potential biological effects of prolonged exposure to high sound levels, noise can impair social and cognitive function [32-35]. Hospital patients are particularly vulnerable to noise effects. In community settings, such as homes or workplaces, individuals exert some control over their exposure to noise. Patients are largely passive occupants of an unfamiliar and occasionally hostile environment. The resulting inability to access active coping measures may be a contributor to patients' mental state. Patients admitted to ICU will be particularly vulnerable. The environment is unfamiliar and acute illness is likely to enhance feelings of anxiety [36]. Anxious people are more likely to be sensitive to their surroundings, including noise levels [1,31].

Not all patients develop delirium in the ICU. Incidence is around 20%, higher in those who have been ventilated [37]. The diathesis-stress model [38,39] at least partially explains this difference. The model proposes that individuals have their own predisposition, or diathesis, that makes them differently likely to develop psychopathology. These underlying latent qualities may only surface under specific acute or chronic stress. An unexpected illness leading to ICU admission might easily be such a stressor. Similarly, the unfamiliar environment of the ICU itself might be a trigger.

Effect of high noise levels on patients admitted to the ICU

Studies referenced in the WHO guidelines primarily examine long-term effects of noise exposure. The majority of patients in an ICU have short admissions, generally just a few days [40]. These short-term exposures are still relevant. It is known that transient noise disturbs sleep, particularly during non-rapid eye movement (NREM) stage 2 sleep [41], shortening both rapid eye movement (REM) and deep, or slow wave, sleep (SWS) phases [42], and even modest sleep reduction quickly leads to measurable adverse effects [43].

Healthy adults require on average between seven and eight hours of sleep a night. Limited sleep can quickly affect cognitive and motor abilities [44,45] and sixteen hours of wakefulness degrades performance to the same extent as being over the legal drink-drive limit in England and Wales [46]. Numerous studies demonstrate that patients in AICU are severely sleep deprived [20,47-51]. Their sleep is also highly fragmented, with each individual sleep bout lasting just a few minutes [48,52]. While the healthy adult can expect about 20% of their sleep to be REM, and about 20% SWS, the patient in the AICU has almost none of either with around 70% of sleep being mid-depth NREM 1 & 2. This is important because REM sleep plays an active role in memory consolidation and emotional management, and deep sleep facilitates physical healing [53]. It is also known that returning to sleep takes longer when the wakening has been induced by noise. This affects individuals emotionally, leading to feelings of anger and fear [1]. Whilst there is no direct evidential link, high noise levels, and associated probable sleep disruption, may be linked to delirium in the AICU [54,55] at least in some patients.

Perhaps counterintuitively, a lower baseline sound level may not be the answer. It has been shown that noise related sleep disturbance occurs with sudden peak value increases [56]. Peaks

between 75.1 and 127.9 decibels have been reported in studies in this review. The initial observational study published in 2013 (see figure 0-1) reported peaks above 85dBA up to 16 times per hour overnight [4]. Reducing the volume and number of peak sounds overnight may be an independently effective strategy to reduce patient disturbance. To do this requires an understanding of primary sources of noise, and the effects that different types of sound have on patients[11].

1.4.10. Conclusions

ICU sound levels are persistently above WHO guidelines and this is not a localised problem. This suggests, for the ICU environment at least, the WHO guidelines for the healthcare sector are either unrealistic, or that AICUs around the world are not performing sufficiently good noise hygiene practices.

[11] Humans perceive sounds differently depending on a number of factors. The most obvious factor is volume but sounds of different frequencies at the same volume will be perceived differently. Broadly, sounds of higher frequencies will be perceived as louder, and therefore more annoying or disturbing. Other factors that affect sound perception include duration, tone, quality, and context. This concept of psychoacoustics is explored in more detail later in this thesis.

1.5. Review 2a: Sound level reduction interventions (RCTs)

The previous section described sound levels in the AICU and identified that these are consistently higher than the WHO recommended 24-hour average of 35dBA. What follows is a review of studies, specifically randomised controlled trials, designed to assess interventions to reduce sound levels in the AICU.

1.5.1. Search strategy

The search was conducted through Ovid and used the Cochrane RCT recipe to identify randomised controlled trials [57]. Papers were identified by searching MEDLINE, EMBASE, PsychINFO, and CINAHL. The search was derived from the previous review.

Titles and abstracts were screened against eligibility criteria. There was no blinding to journal titles, study authors, or institutions. Full text was retrieved for all articles not excluded by screening.

1.5.2. Eligibility criteria

Study criteria were as described in section 1.4.2 with the added requirement of testing randomised controlled interventions to reduce sound levels.

1.5.3. Data extraction

EndNote (vX8; Clarivate Analytics, Philadelphia, USA) was used to manage references and identify duplicate results. Data were extracted by a single researcher.

1.5.4. Quality assessment

Risk of bias for included studies was assessed using the revised Cochrane risk-of-bias tool for randomised trials (version date 15 March 2019) [2].

1.5.5. Search results

- After duplicates had been removed, the initial search (161) resulted in 159 publications.
    - CINAHL: 41
    - EMBASE: 22
    - MEDLINE: 41
    - PsychINFO: 13
    - PubMed: 44
- Of these, 55 were retained based on title and considered for abstract review.
- Full texts were retrieved for 6 publications which were retained after abstract review
- One title was retained (Table 1-4)
- Of the five titles excluded:
    - Two were not RCTs
    - Two did not report sound levels
    - One was not written in English

1.5.6. Risk of bias

Using the Revised Cochrane Risk-of-Bias Tool, the overall risk of bias was assessed as 'high'.

1.5.7. Results from identified publication

Author [Country] Year	Intervention	N	Excluded	Control sound level	Control max level	Intervention sound level	Intervention max level	Risk of bias
				dBA (95% CI)	dBA (n > 80dBA)	dBA (95% CI)	dBA (n > 80dBA)	
Boyko **[9]** [Denmark] 2017	quiet routine	17	2	47.57 (46.6 – 48.6)	86.3 (4)	46.92 (46 – 47.9)	84.9 (4)	High

Table 1-4: Summary of results from identified paper

1.5.8. Discussion

With just one publication identified (primarily focussed on sleep outcomes rather than reduction in sound levels), the decision was taken to include non-RCT study designs.

1.6. Review 2b: Sound level reduction interventions (all study designs)

Given the paucity of RCT data on sound level interventions in AICU the search was repeated, now including non-randomised interventional studies.

1.6.1. Search strategy

The search strategy described in 1.5.1 was adapted to remove the requirement of RCTs.

1.6.2. Eligibility criteria

Titles and abstracts of identified papers were screened against eligibility criteria outlined in 1.4.2.

1.6.3. Data extraction

There was no blinding to journal titles, study authors, or institutions. Full texts were retrieved for all included articles. Papers were assessed individually against inclusion and exclusion criteria. Data were extracted by a single researcher.

1.6.4. Quality assessment

Each study was assessed against STROBE reporting criteria [5] using a validated scoring system [6]. A maximum of 21 points were available for each study. A highly-rated study was defined as 17 or more points, an acceptable-rated study scored 10-16 points and a low-rated study scored 9 points or fewer.

1.6.5. Search results

- The initial search identified 656 potential publications for review.
    - CINAHL: 147
    - EMBASE: 195
    - MEDLINE: 46
    - PsychINFO: 53
    - PubMed: 215
- After duplicates had been removed, 624 publications were reviewed by title.
- Of these 446 were excluded, and a further 122 were excluded after abstract review
- Full texts were retrieved for 56 publications which were retained on abstract review
- A total of 12 publications were included (Table 1-5)
- Of the 44 titles which were excluded:
    - Nineteen were observational studies with no intervention
    - Ten were not original research articles (three of these were reviews)
    - Seven were not written in English
    - Six did not report continuous sound results
    - Two were not conducted in AICU

1.6.6. Quality assessment

The majority of studies (n=11) were evaluated as 'acceptable' using the STROBE assessment. One publication scored highly [58]. The full range of scores was 11 – 17.5 with a mean (±SD) of 14.25 (±1.66).

1.6.7. Results from identified publications

Author [Country] Year	Intervention	N	Duration	Baseline / control LAeq24	Baseline / control Max	Intervention sound level	Intervention Max	p value
				dBA (single value, range, mean values +/- SD or 95% CI; per original publication)				
Walder **[59]** [Switzerland] 2000	Light & activity reduction	Period 1: 13 Period 2: 11	Not reported	51.3 +/-2.8	88	48.3 +/-1.4	81	Not reported
Blomkvist **[60]** [Sweden] 2005	Environmental changes	Change 1: 31 Change 2: 44	2*4 weeks	NA	NA	56-57 50-56	Not reported	Not reported
Li **[61]** [Taiwan] 2011	sleep care guidelines; activity reduction	Intervention: 28 Control: 27	2*3 months	57.7 +/-4.5	59.2 +/-4.5	50.1 +/-4.0	(mean peak) 51.3 +/-3.9	<0.001
Winters **[62]** [UK] 2011	Education & environmental changes; sound masking system	N/A	Not reported	55-65	85	Reduction >10dB	Not reported	Not reported
Patel **[63]** [UK] 2014	Non-pharmacological bundle to improve sleep	Intervention: 171 Control: 167	3.5 weeks	68.8 +/-4.3	Not reported	61.8 +/-9.1	Not reported	=0.002
Kol **[24]** [Turkey] 2015	Education & environmental changes; equipment repairs	Not reported	2*3 wks over 6 months	08.00-16.00: 67.6 16.00-24.00: 65.6 24.00-08.00: 59.1	Not reported	08.00-16.00: 56.0 16.00-24.00: 56.1 24.00-08.00: 53.8	Not reported	Not reported
Nannapaneni **[64]** [US] 2015	Staff education; environmental changes; pharmacological sleep intervention	Not reported	Baseline: 48 hours Post-intervention: 48 hours	54.2	LAFmax: 83.0 LCpeak: 109.9	53.8	LAFmax: 89.6 LCpeak: 120.3	Not reported
Riemer **[65]** [US] 2015	Activity reduction	22 (nurses)	5 weeks	62.93 +/-5.7	Not reported	[interim 60.88 +/-7.5] 61.69 +/-5.0	Not reported	=0.08
Luetz **[66]** [Germany] 2016	Environmental changes	Intervention: 8 Control: 8	96 hours (4 x 24 hours)	53.17 +/-4.1 – 56.18 +/-4.43	65.43 +/-7.59 – 69.29 +/-6.72	50.91 +/-2.54 – 54.89 +/-3.89	62.92 +/-8.65 – 64.99 +/-8.71	<0.001
Boyko **[9]** [Denmark] 2017	Activity reduction	19 (17 included in analysis)	48 hours	47.6 (CI: 46.6-48.6)	86.3 >80 x4	46.9 (CI: 46.0-47.9)	84.9 >80 x4	=0.3
Gallacher **[67]** [UK] 2017	Noise-cancelling ear protection	3 (polystyrene heads)	10 x 24 hours	[control]: 57.2	Not reported	[headphones]: 54.5 [headphones with active noise cancellation]: 50.4	Not reported	Not reported
Johansson **[58]** [Sweden] 2017	Environmental changes	Intervention: 6 Control: 25	Variable (individual patient lengths of stay)	[control]: 52.0 +/- 4.7 48.4 +/- 6.3	Not reported	49.9 +/- 3.7 46.6 +/-4 5.8	Not reported	Not analysed

Table 1-5: Summary of identified papers

As with the sound levels synthesis, the variability in interventions and reported outcomes makes direct comparison between studies difficult. However, there are some broad similarities in terms of fields of clinical interest, patient experience, and practicalities of delivering a complex intervention in the AICU.

There is a strong emphasis on introducing change through environmental factors. These can be physical changes to the architecture or, more usually, changes to activities that might lead to improvements in the patient experience of their admission to AICU.

Sleep and overnight interventions

Five of the 12 publications selected for review were primarily focussed on delivering change to improve sleep quality and quantity, and/or reduce disturbance and sound levels overnight [9,59,61,63,64].

Walder et al (2000) focussed on reducing sound and light between 23.00 – 05.00. The intervention was simple and included door closure, minimisation of alarm volume, fewer nursing interventions, no television or radio, and no artificial light. The intervention was not successful in lowering background sound levels and there was also no change in overall mean light levels (although variability of light intensity was higher post-intervention). However, peak sounds were lower in the post-intervention period and there were fewer alarms identified. Patient sleep was estimated by nurses in the morning.

Li et al (2011) also aimed to reduce overnight (23.00 – 05.00) disturbances. Their intervention was similar. Doors were closed, lights dimmed, volume of alarms and telephones lowered, interventions rearranged, and staff conversation limited. Average sound levels and patient perceptions of noise were both reduced significantly during the intervention period. Sleep was shown to be improved, as measured by self-assessed Richards Campbell Sleep Questionnaire (RCSQ).

Patel et al (2014) conducted the largest study, recruiting 338 patients. Patient care activities were limited to a greater extent than Walder or Li, and patients were offered eye masks where this was appropriate. Environmental changes were similar to those reported by Walder and Li. All variables, including patient sleep (which was linked to a lower risk of developing delirium), were improved as a result of the intervention. Sleep was measured by self-assessed RCSQ.

Nannapaneini et al (2015) followed a similar protocol to reduce noise and disturbances overnight (22.00 – 06.00). This study also included staff education and visual alerts to high sound levels. Average sound levels did not drop significantly, and absolute peak levels increased. However, the *number* of peaks >60dB decreased, and there was an increase in the proportion of staff who perceived patient slept >5 hours overnight. Patient sleep was assessed by staff questionnaire.

Boyko (2017) tested a 'quiet night' (22.00 – 06.00) protocol including the same key features as other studies. The primary outcome was sleep quality measured using polysomnography. Sound levels were collected as a secondary outcome measure. The study showed no difference in sleep between protocols. Sound levels were lower during intervention nights, but not significantly.

Environmental / architectural feature changes

Three of the studies [58,60,66] physically altered the AICU architecture. A further two [24,62] made more generalised environmental changes.

Sound absorbing tiles were installed in the Blomkvist study [60], but these did not reduce average sound levels in the central area. They did however halve reverberation time. Two patient rooms recorded lower sound levels after sound absorbing ceiling tiles had been installed. Subjective reporting of speech intelligibility went from "good" to "excellent" with the new tiles.

Architectural alterations made by Luetz et al [66] involved remodelling a two-patient room by installing sound shielding measures and removing some monitoring equipment. This transferred alarm functions outside the room and significantly lower sound levels were achieved when compared against a similar, non-modified room.

Johansson et al [58] also made infrastructure changes to the patient space but experienced technical problems that resulted in intervention failure, recording faults in key data sources, and data loss. Indicative values for their experimental rooms suggest a slight reduction in average sound levels.

Winters [62] installed sound alert devices and a sound masking system alongside some simple sound reduction modifications. Sound levels dropped by more than 10dBA.

Kol et al [24] ensured that patient monitoring equipment was in good order and rearranged the AICU space to allow staff to talk and prepare treatment without disturbing patients. A simple sign informing staff and visitors that sound levels were being monitored was placed at the entrance. All measured values of sound were statistically lower after changes were implemented.

Daytime interventions

The Riemer study [65] considered the impact of noise interventions on staff, investigating changes in nurse stress levels as a result of implementing 'quiet time'. This was largely achieved by dimming lights for two hours. Sound levels were reduced, but not significantly. Nurse reported stress levels reduced significantly during quiet time, and this was sustained for up to two hours after quiet time ended.

Duration of intervention

Interventions were evaluated over short periods of time, typically only a few days. Only two studies [61,65] recorded intervention data for more than one month.

1.6.8. Discussion

Sleep

Studies repeatedly demonstrate that patient sleep in the ICU is poor, and this has been highlighted by patients as one of the main problems during their admission to the intensive care unit [68-70]. The link between sleep deprivation and poor outcome is well-known. It is one of the UN definitions of torture [71] and poor health after ICU admission has been well-reported in recent years [49,72-74] High noise levels in the AICU increase the use of sleep medication [75] and sedatives [76], as well as the incidence of delirium [75]. There is some evidence to suggest that ear plugs to protect patients from the noisy environment can reduce the risk of developing delirium [77]. Noise levels appear to affect mental state, but there is limited evidence that noise levels are directly responsible for poor sleep. Studies suggest that noise peaks are responsible for 11-20% arousals and awakenings in the ICU [12,56] and, as described earlier in section 1.4.9, these awakenings will have a disproportionate effect on patients. Despite limited evidence, the focus on interventions to improve patient sleep is consistent with the interest in overnight sound level measures highlighted in the first review (section 1.4).

There is limited consensus on how best to monitor sleep in the ICU [78]. The five studies included in this second review do not record sleep consistently. One uses polysomnography, widely regarded as the 'gold standard' measure but, given the complexity of equipment required, recognised as being difficult to achieve in the ICU [48]. Two use patient-completed versions of the Richards Campbell Sleep Questionnaire (RCSQ), one asked the patients' nurse to estimate how much they thought their patient had slept overnight, and one surveyed staff to ask their perception of patient sleep more generally.

The RCSQ has been validated against polysomnography for patients in the ICU [47]. As such this is the most appropriate method to measure sleep in the ICU as it achieves a pragmatic balance between accuracy and practicality. Not all patients will be able complete the questionnaire without help, but if assisted it is a feasible option.

Some studies (including the sleep assessment phase of the SILENCE NIHR project) have assessed the RCSQ completed by nurses on behalf of their patients [52,79-81]. These demonstrate that nurses overestimate both quality and quantity of sleep which is consistent with other third-party assessments of subjective measures, for example pain [82,83]. The implication is that any external evaluation of sleep is likely to be flawed, with inaccuracies increasing with each degree of separation from the patient.

Whilst limited correlation between nurse and patient completed RCSQs means they are not directly interchangeable, it is likely that nurse completed RCSQs remain the best option for monitoring sleep in those patients who are unable to complete questionnaires themselves, but care is required when interpreting results.

It is apparent that comprehensive practices that modify night-time environment can influence noise and sleep overnight, but the magnitude of these changes is difficult to ascertain.

Staff wellbeing

One study in this review considered the effect of changes in working practice on staff. There has been recent interest in recognising and preventing burnout in the ICU workforce. Health and wellbeing may affect motivation, and diligence when performing patient care activities [84]. It may also contribute to burnout resilience and staff retention [65]. Staff sickness absence in the NHS is almost a third higher than other public sector organisations and almost 50% higher than other workforce sectors [85]. Absence rates vary between professional groups with nurses reporting almost four times more sickness than doctors [86]. This is a high cost burden on the health service [87]. The incidence of burnout in critical care staff is significant [88].

Noise is a social stressor and a known distractor [89-92]. Where levels are routinely higher than ~50dB vocal communication becomes difficult [93]. This can disrupt communication, and contributes to a vicious circle whereby staff must raise voices, causing further escalation and higher volume [94]. Although it is not possible to conclude if this translated into a safety improvement because the study was not designed to assess communication, the Blomkvist study finding that sound absorbing materials improved speech intelligibility should not be ignored.

Staff working in the ICU are likely to become habituated to elevated noise levels. This can lead to complacency [95], and a culture of 'normalised deviance' [96] can develop where disturbances are so ingrained they become routine. Whilst staff may not feel irritated by high noise levels, social effects of constant noise (masking of speech and distraction) still occur. The brain has limited processing capacity [97]. Sensory overload caused by high levels of activity and constant noise can lead to a loss of situational awareness [23,98]. This includes psychological phenomena such as 'inattentional deafness' [99,100] where individuals fail to notice sounds that would otherwise be considered obvious because their sensory systems are overloaded. Vulnerability to perceptual failures is dependent on cognitive workload, and distractors such as excessive background noise are key contributors. Desensitisation can also lead to alarm fatigue [101], a significant problem for healthcare environments [102,103]. Up to 75% of alarms are false alerts [104], and staff quickly become conditioned to alarm tones being irrelevant. This can slow responses to genuine alerts, and alarm fatigue has been cited as one of the leading patient safety hazards [105].

Introducing technological change into the healthcare environment

It is well-recognised that 'more training' is not a robust solution to healthcare challenges, particularly when implemented in isolation [106]. Passive engineering solutions (those that do not require staff to modify their behaviour or practices) are likely to be more successful over a longer period of time. The architectural changes evaluated confirm that acoustic engineering interventions can make appropriate and meaningful changes to the AICU environment. Unfortunately, introducing substantial changes to organisational infrastructure (such as those described in Johannson et al, 2017 [58]) also attracts significant cost [107-111].

Retrofitting an existing space may not be practical, or even possible, particularly in older buildings where building materials (for example, asbestos) limit scope of renovation. Architectural measures may only be feasible when planning new-build areas, but it is not clear that potential solutions to noise control are highly prioritised by either clinicians or commissioners [112,113].

It is well-documented that many new technologies fail when introduced into the working environment [114]. Johansson et al explained the difficulties they encountered in some detail. It

is important to recognise that whilst it may be relatively straightforward to monitor environmental interventions closely for short periods required for a research project, it is much harder to maintain long-term change.

Most of the studies were short. Sustainability should be better with passive intervention strategies that do not require human intervention to maintain effectiveness. Longer evaluations to allow natural variation of practice to occur and evaluation including economics and other analysis methods to incorporate interconnected complexities would be beneficial [115]. Long-term change was not measured in the studies and other outcome measures that incorporate the social, cultural, and organisational complexities [116-118] need to be included in the evaluation and assessment of future studies.

1.7. Strengths and Limitations

Strengths

- Comprehensive and structured synthesis of sound levels, and interventions designed to improve the ICU environment, since publication of WHO guidelines in 1999
- Reviews used robust methodology including the following tools: PRISMA (review 1: quantitative studies), Cochrane risk of bias (review 2a: interventions), and STROBE (review 2b: observational studies)

Limitations

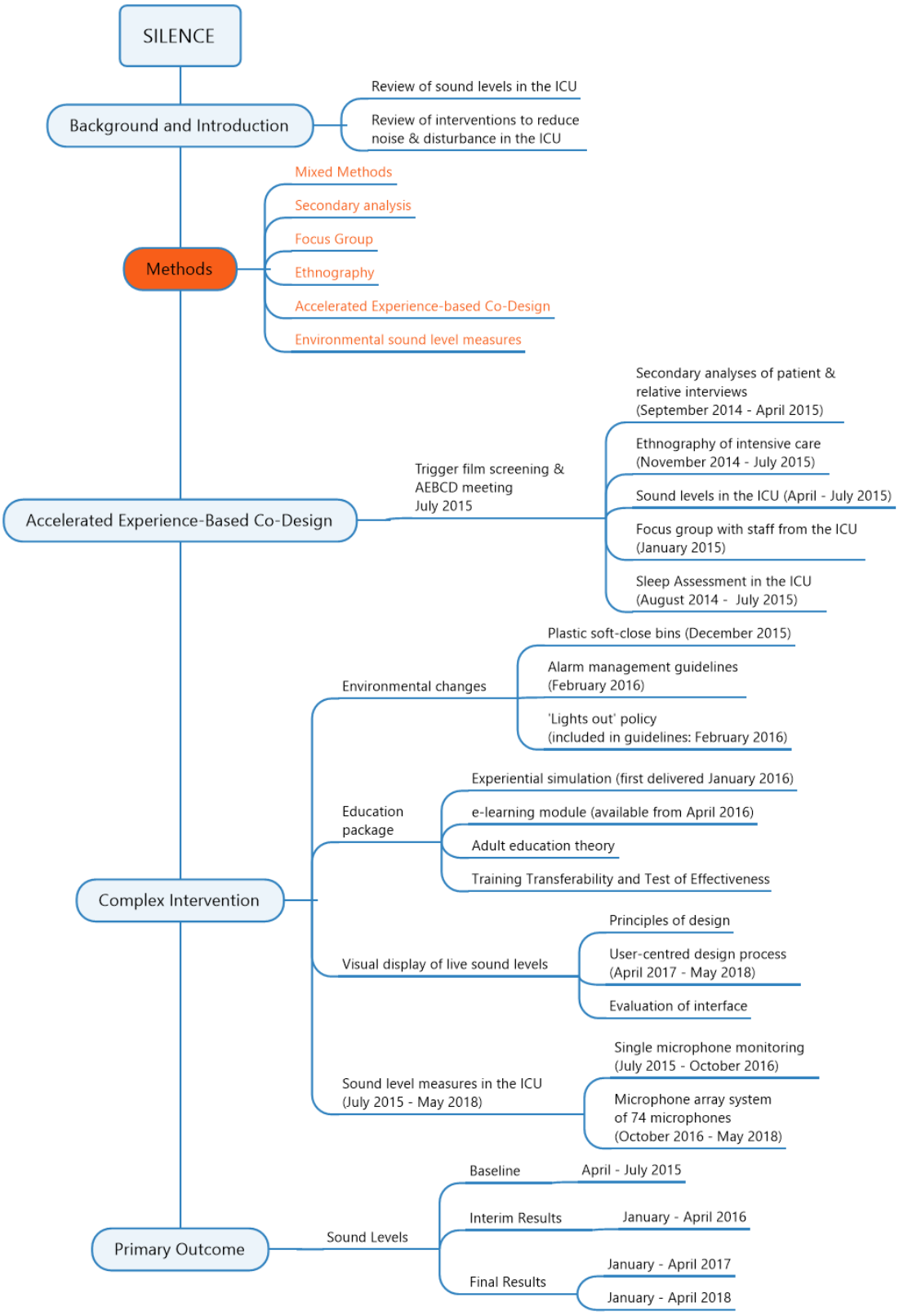
- Search strategy and data extraction were not verified by a second researcher
- A number of publications identified were not written in English and were not translated for inclusion
- Few studies were categorized as 'good' when assessed using STROBE or risk of bias tools
- Heterogeneity in sound level reporting meant that data synthesis by meta-analysis was not possible to conduct
- No study included long-term outcomes so sustainability of intervention success could not be explored

1.8. Conclusions

Although there were flaws in both delivery and reporting of outcomes, studies in these reviews indicate that change is feasible. Benefits for both patients and staff working in the environment seem likely with even modestly lowered sound levels. Infrastructure change and interventions that re-model the environment appear to offer the best opportunities for lower sound levels.

2. Chapter Two: Mixed methods in healthcare research

2.1. Chapter summary



This chapter summarises research methods used during this DPhil. More detailed explanations of specific methods appear in chapters three (secondary analysis of interview transcripts, focus group, ethnography), four (accelerated experience-based co-design), five (teaching theory), six (sound level data analysis), and seven (user-centred design). Separating these then situates specific methods applicable to each phase of the project adjacent to their results, discussion, and associated interpretation.

2.2. Aim

The aim of this chapter is to summarise the rationale for choices of research methods. The implications of employing multiple, or mixed, methods within a single project are also considered, with particular reference to data interaction and interpretation. Whilst several philosophical approaches are summarised, it is not the intent to cover the full repertoire of research theory. The following section highlights the approaches which are in line with my theoretical stance and which are relevant to this project.

2.3. Overview of research methods

James Lind (1716 – 1794) is best known as the Scottish physician who confirmed scurvy could be prevented and treated with citrus fruit. He has popularly been credited with completing the first controlled clinical trial in 1747 whilst serving as surgeon on board HMS Salisbury. Through adding various supplements to a basic diet Lind demonstrated that sailors given citrus fruits recovered from scurvy better than those who tried other 'remedies'.

> *'I shall propose nothing dictated merely from theory; but shall confirm all by experience and facts, the surest and most unerring guides.' [119]*

Given these words, he should perhaps also be credited as being the first to acknowledge that quantitative measures alone are not sufficient to answer a research problem. Experience too, is vital.

2.3.1. Quantitative research methods

In healthcare research a well-executed randomised controlled trial (RCT) is widely considered the best research design method to determine the effect of a given treatment. The design ensures confounders are evenly distributed between treatment and control groups, allowing the RCT to highlight differences in outcome caused by the treatment. RCT analysis results in binary interpretation (significant/non-significant). This simplicity means comparison between studies is relatively straightforward and there are well-known, well-practiced and well-established methods for assessing different study designs.

However RCTs do have significant limitations [120-122]. A trial may not be a feasible design for some interventions. It may be difficult to replicate results because of differences in patient characteristics and more complex interactions between patients, healthcare providers and the healthcare environment that can influence outcomes and which cannot be easily predicted [123,124].

A standard RCT does not include scope to explore *why* the results are as they are, or *how* results might impact on the lived experiences of patients. Qualitative methods can complement the RCT and some trials include sub-studies of participants (more usually sub-groups) to attempt to bridge this gap. Examples of qualitative research used to extract additional knowledge from data recorded in an RCT can be found in the medical literature. Primarily these qualitative reports evaluate the intervention tested but can also include qualitative evaluation of trial administration and management, assessment measures, and patient experience of the target condition [125]. Largely the motivation for using qualitative methods in the studies identified by O'Cathain et al

was to evaluate the underlying quantitative work. Work has also been completed to assess (and improve) recruitment practices for RCTs [126,127]. O'Cathain et al conclude their evaluation by recommending that better use could be made of qualitative methods, results, and understanding if they were better embedded within planned trial designs [128].

2.3.2. Qualitative research methods

Qualitative research methods are now widely used in clinical and healthcare environments to capture social meanings; the 'what', 'how', or 'why' that lie behind the 'how many' or 'how much' of quantitative research [129]. The primary aim is to explore a problem, usually from the point of view of patients, sometimes professionals. Rather than measuring changes in quantifiable variables, qualitative studies seek to understand the effects of treatments or illness as experienced by patients (or healthcare workers, or systems) and identify appropriate outcome measures that are relevant to the individual. Accordingly they rarely report objective, numerical outcomes. This can make qualitative research more complex to interpret than RCTs, and makes synthesis of results from multiple studies difficult. Clinicians, who are often trained exclusively in quantitative methods, can find it difficult to understand the relevance and importance of qualitative methods, but this view may be changing [130].

2.3.3. Mixed Methods

Although most research projects in healthcare are predominantly either quantitative or qualitative, there are limitations to using solely one method of approach to data. To focus entirely on one aspect of a problem is to ignore the multi-faceted and complex nature that is the reality of modern healthcare.

Using rigorous research techniques from both quantitative and qualitative fields, mixed methods approaches aim to integrate findings from multiple sources to enable wider interpretation of data and better understanding of the research problem.

One of the earliest definitions of mixed methods described the approach as "multiple ways of seeing and hearing, multiple ways of making sense of the social world, and multiple standpoints on what is important and to be valued and cherished" [131]. By addressing different aspects of the same problem, and converging or "triangulating" [132] data available it is possible to derive an enhanced understanding of the issue. Put rather more simply, in mixed methods study designs "Researchers situate numbers in the contexts and words of participants, and they frame the words of participants with numbers, trends, and statistical results" [133].

This is a heterogeneous field. At least nineteen different versions of the mixed methods approach have been proposed [134], differing in the varying degrees of importance placed on background philosophies, data collected, and research methods used. At their core however, all mixed methods studies combine quantitative, numerical, and statistical values with qualitative, thematic, and experientially-based data in ways that make the whole greater than the sum of its parts.

Despite the apparent complexity, all mixed methods designs can be succinctly described as either convergent, explanatory, or exploratory (see section 2.3.5). Whilst there are specific qualitative and quantitative methods that are better suited to some study designs, broadly the overarching mixed methods design chosen will reflect the paradigm or worldview adopted by the researcher, and their own philosophical beliefs and assumptions.

2.3.4. Philosophical assumptions and theoretical ontological perspectives

Epistemological ontology is the study of how we understand our experiences of reality, and how we believe that reality is constructed. These are situated within the context of interpretive frameworks which "frame the theoretical lens" [135]. Some major ontological standpoints are discussed below briefly, followed by a summary table of common frameworks and how they inter-relate with philosophical assumptions and research methods (Table 2-1).

Positivism (alternative terms: objectivism or empiricism)

Very simply, positivism seeks to explain the world.

Scientific philosophical assumptions have traditionally been rooted in positivism; the idea that the world exists in its own right, outside of our experiences of it, and that there is a single 'truth' that can be known, observed, and measured. Through this view of the world the more knowledge gained, the better the understanding, and the closer we find ourselves to the truth.

Knowledge in this worldview is authoritative, free from bias, and considered objective and therefore true regardless of context. Under principles of positivism research is conducted within an observable context, using logical statements that can be tested, resulting in knowledge gained though empirical determination and situated in observable and measurable, verifiable, scientific facts [136].

Constructivism (alternative terms: subjectivism, relativism, or interpretism)

Conversely, constructivism seeks to understand the human experience of the world.

The key assumption behind the constructivist worldview is that truth is mutable and that humans seek individualised meanings and make sense of their personal worlds based on their own experiences. There are therefore multiple meanings and multiple 'truths' within a socially negotiated reality which is dependent upon interaction and shared cultural heritage.

The constructivist researcher also recognises their own place in the research project and acknowledges any meanings inferred are based on their interpretation of the participants' description of their experiences.

Within the broader term 'constructivism' there are a number of approaches. Recognising the dangers of a populist post-truth belief system pushing "alternative facts" [137], and where public opinion is influenced by emotion, feelings and beliefs, it is vital to understand how academic and scientific interpretation can be constructed within accepted valid models.

With a strong personal belief in the role played by the diverse influences of individualism in decision making and behavioural change, a brief summary of some of the major schools of thought within the constructivist tradition seems relevant.

Critical Realism

Critical realism is part of the post-positivist movement and conceptualises reality as existing beyond the observable features. Recognising that social constructs, cultural norms, power struggles, and individual predispositions and tendencies all contribute to the generation of an understanding of 'reality', critical realism incorporates these dynamic fluctuations in its description of the physical world. In contrast to 'closed systems' (such as randomised controlled trials) where interaction between variables is controlled tightly [123], critical realism favours open or linked systems which more naturally mirror social context [138]. A critical realist believes there is a 'real' truth which exists but that this is not possible to describe as a single

entity since all understanding is interpreted in some way. The truth is always therefore filtered through a lens, and observations of the truth will always differ.

In the critical realist world, research interventions exist within the wider social context. Success or failure can be variably influenced by fluctuating causal relationships [139], which are themselves influenced by variable external circumstances. Results are therefore collated from multiple measures and compared and contrasted to mitigate errors and determine the *best estimate* of the truth that can be assembled.

Pragmatism

Pragmatists "recognise that there are many different ways of interpreting the world and undertaking research, that no single point of view can ever give the entire picture and that there may be multiple realities" [140]. As such, the pragmatic approach is not limited to any single framework, and is likely to incorporate a variety of research methods which are dependent on the needs of the research problem.

'Truth' for the pragmatist is constructed but because it is also rooted in practice it is non-arbitrary [141].

Individualism

With a primary focus on how the individual understands and explains the world they experience, individualism questions the legitimacy of objective knowledge [142,143]. This approach presents the positivist concept as a power-invoked social construct without any independent reality [142,144]. Through an understanding of the 'parts', the 'whole' can be more fully explored and the complex inter-relationships can be considered.

Phenomenology

Phenomenology, or interpretative phenomenological analysis, is concerned with describing what the experience of being a human is like.

Husserl is one of the most important proponents of phenomenology. Husserl describes a mental switch from a *natural attitude* to the *phenomenological attitude*. By this he meant that through reflection on our perception of experiences we become aware of how and why something achieves importance: "In everyday life each of us is something of a phenomenologist insofar as we genuinely listen to the stories that people tell us and insofar as we pay attention to and reflect on our own perceptions" [145]. In other words, we come to understand what someone is telling us because of the way that we think about how we might react/behave in the same circumstance. The phenomenological approach can also teach us how we understand our own place in the world as we reflect upon the experience of being human in the process of contrasting social interconnections and the collectively negotiated balance of shared experiences [146].

Table 2-1 is an extract from a larger table in Cresswell's book 'Qualitative Inquiry and Research Design: Choosing Among Five Approaches' [135]. It is included here to reflect approaches taken for this project and summarises common frameworks used by researchers to consider their approach and choose appropriate study designs.

Approach		Practice
Post-positivism	Scientific, Reductionism oriented, Cause/effect, A priori theories	Inquiry in logically related steps; Multiple perspectives from participants not single reality; Rigorous data collection and analysis; Use of computer programs
Social Constructivism	The understanding of the world in which we live and work, The development of multiple meanings, The researchers look for complexity of viewpoints	Researchers ask broad general open-ended questions; Focus on the 'processes' of interaction; Focus on historical and cultural settings of participants; Acknowledge their background shapes interpretation, 'Interpret' the meanings others have about the world.
Postmodernism Perspectives	Knowledge claims in multiple perspectives such as race, gender, class and group affiliations; Negative conditions revealed in presence of hierarchies, power, control, by individuals in the hierarchy and multiple meanings of language; different discourses; marginalized people that are important; Meta-narratives or universals hold true of the social conditions; Need to 'deconstruct' text to learn about hierarchies, oppositions and contradictions.	Interpretive biography; Narrative; Grounded Theory; Ethnography
Pragmatism	Focuses on outcomes; 'What works' to address research problem; Researchers freedom of choice of methods; Many approaches to collecting & analysing data	Researchers use multiple methods to answer questions; Research is conducted that best addresses the research problem

Table 2-1: Cresswell's research approaches

2.3.5. Mixed Methods study designs

The design of mixed methods studies broadly follows one of three formats; convergent, explanatory, or exploratory [133]. The specific design is determined by the order of data collection and degree of data interaction. Different design models are outlined below.

Convergent Parallel Design

For studies using Convergent Parallel Design both qualitative and quantitative data are collected independently but concurrently. Data are merged and results are interpreted jointly. The underlying assumption is that by providing different kinds of information about the same topic, subject, or problem, the two distinct datasets can be used to confirm (or not) parallel findings.

Explanatory Sequential Design

Explanatory Sequential design seeks to explain results from quantitative data through a follow up phase consisting of qualitative data collection and analysis.

Exploratory Sequential Design

Exploratory Sequential design seeks to explore a problem through an initial qualitative stage which is followed by one, or sometimes two, quantitative phases which seek to test (and sometimes validate) a measure identified during the qualitative analysis.

Prioritisation of data

A hierarchy of evidence determines the weight given to different sources of knowledge (the data). Qualitative and quantitative data may be weighted differently in any study. Either may take precedence, or both may be considered of equal importance. The choice for emphasis depends largely on the research question and the problem to be investigated. Standard notation for indicating this is to CAPITALISE the higher priority dataset with lower priority data being referred to in lower case [133].

2.3.6. Summary of research approaches relevant to this project

Participatory action research

Participatory action research (PAR) is an approach that enables research to be designed and conducted *by* the research participants rather than *to* them [147]. PAR therefore provides opportunities for interaction and engagement for all levels of stakeholder [148]. Through reflection and iteration, utilisation of constructivist theories, and principles of shared power dynamics, PAR partnership processes encourage people to have control over changes that affect them.

The core ideology behind PAR is a desire to identify and challenge the relationship between knowledge and power. Understanding power as articulated by Michel Foucault, it can be recognised that power is not a single entity, but a dispersed social construct [149]. In contrast to the positivist view that requires control of variables to discover a single truth, the collaborative nature of PAR is grounded in experience and social perspective, and actively seeks to acknowledge and incorporate the wider cultural context that is inherent in all social environments.

The fluid nature of PAR means it is often difficult to define specifics at the outset. Whilst a primary outcome can be identified, the direction of the project to achieve that outcome, and therefore specific outcome measures required for assessment, will be determined by emergent themes and ideas that develop over time.

Experience-Based Co-Design (EBCD)

Experience-based co-design (EBCD) is a Participatory Action Research (PAR) approach that uses narrative theory to engage stakeholders [150]. It is a process that has proven effective when considering specific quality improvements to services within the healthcare industries both in the UK [151] and abroad [152]. In the healthcare sector the practice is based on narrative interviews with patients and staff, combined with observation. Excerpts from interviews and examples from observations are selected to highlight emotionally significant moments, known as 'touch points'. These clips are collated and presented separately to staff and patients in the form of a 'trigger film' to stimulate discussion within each group, enabling each group to identify priority areas for change. A joint event is then held to consolidate priorities with the intent to narrow these down to a manageable number of key target areas for service improvement. Participants in these discussions work together to develop specific areas in the months following and assist with the delivery and implementation. A typical timeline for a full EBCD project is around 12 months.

Accelerated experience-based co-design (AEBCD)

Research using archived interview data demonstrated that a rapid, or 'accelerated' format can be as effective in supporting local quality improvement [153]. Removing the need to complete local interviews reduces the typical EBCD timeline to around six months.

2.4. Rationale for using mixed methods for the SILENCE project

The advantages of a mixed methods approach for this project were clear from the beginning. It is simple to assess noise levels using standard commercially available environmental monitoring equipment. To truly understand the multifaceted human interactions between noise generation and noise response however, a more in-depth analysis is required.

Incorporating the patient experience from the beginning of the project offered insight from a distinctive perspective and provided a solid grounding for the research aims and objectives. Keeping the patient experience at the heart of the project was key to success both in engaging clinical staff, and ensuring results were in line with patient needs. Including staff in the planning phase meant that proposed and implemented interventions could be accommodated in normal clinical practice. Staff were also given the opportunity to explore their own (working) experiences of the intensive care unit environment and to reflect on their impact on the patient experience. Including both patients and staff in the development processes of intervention design and implementation ensured mutual goals were understood and remained relevant to outcomes.

The rich data sets generated by qualitative methods such as interviews and ethnographic observations provide a broader overview of the problem of high noise levels in the ICU as a whole, and allow exploration of relevant themes and potential outcome measures which would be lost if measures were reduced to simple numerical values.

The simplicity of an objective primary outcome, the sound level, ensures this project is easily comparable with other studies in the field.

2.4.1. Data interaction

The SILENCE research programme is a series of interlinked studies. The data are integrated at all levels and although the primary outcome is quantitative, datasets are treated equally (QUAL + QUAN to use the accepted notation)[133]. This thesis presents an integrated understanding of sound levels in the AICU though use of robust quantitative and qualitative research methods which both inform and enrich each other.

The programme as a whole can be illustrated as two linked mixed methods designs (Figure 2-1). Using terminology from Cresswell and Plano Clark [133], the initial phase is an Exploratory Sequential Design with an embedded Convergent Parallel Design where findings were combined to build a full and rich picture of the patient experience of intensive care. Results from this phase produced materials for the AEBCD trigger film [154] and subsequent discussion. The AEBCD process led to a noise reduction intervention which focussed on quantitative changes in sound level, which were explained by qualitative analysis of observations and interviews.

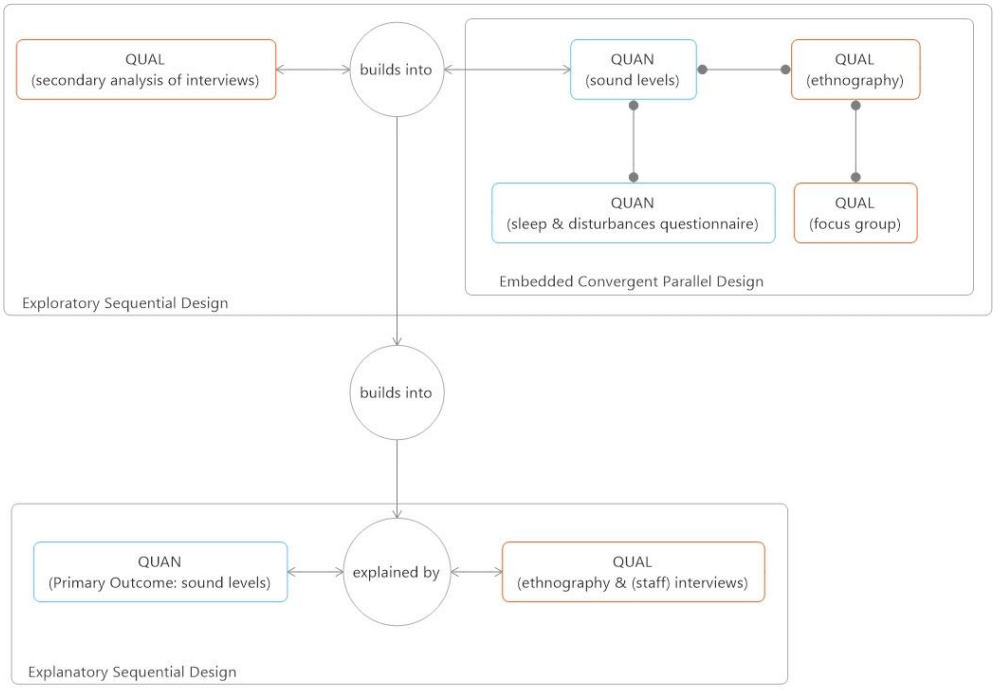


Figure 2-1: SILENCE Mixed Methods design

2.4.2. Temporal relationships between datasets

Secondary analysis of patient and relative interview transcripts (chapter three) initiated the SILENCE programme. Transcripts were made available with permission for secondary analysis. These data informed the study design as a whole, and were integral to understanding the patient experience of the AICU. These interviews were conducted by the University of Oxford Health Experiences Research Group (HERG) in 2005/6. Discussion with practising intensivist clinicians confirmed issues highlighted in these interviews resonated with accounts of the ICU experience given by patients in follow-up clinic appointments.

In-situ ethnographic observations (chapter three) were conducted (November 2014 – July 2015) and, as part of the full NIHR study, patients and staff completed sleep and disturbances questionnaires[12]. Results from these confirmed the main sources of noise and disturbances were very similar to those described by patients in their interviews, and staff during their focus group. It was therefore determined that the ICU had not changed significantly in the ten-year interlude and that the interviews dataset remained valid as a basis for quality improvement.

[12] Questionnaire data used for this phase of the project were completed August 2014 – July 2015.

Results (themes) from secondary analysis and ethnographic observations guided the content of the accelerated experience-based co-design (AEBCD) [153] trigger film (screened July 2015) and development of the topic guide for the staff focus group (January 2015). This focus group (chapter three) enhanced the patient interview data by providing a professional viewpoint to the problem of noise levels in the AICU which included practicalities associated with noise control.

Sound levels were measured alongside observations and questionnaire data allowing real time objective assessment of baseline sound levels (April – July 2015). These early sound level data are included in chapters three and four. The sound level data, including measures up to May 2018, are presented in chapter six.

Teaching materials (chapter five) were designed and assessed (August – December 2015) in line with adult educational theory and training was delivered from February 2016.

The design and development of the display screen to visualise noise levels in the intensive care unit is described in chapter seven. The iterative design process (April 2017 – April 2018) incorporated principles of behavioural change and user-centred theories of design.

The primary outcome (chapter six) was the exploration of sound levels in the AICU. Specifically how sound levels differ by day and by time of day, and how overall levels change over time (from baseline (April 2015) to final data collection (May 2018)). The ultimate focus of the project was therefore quantitative. Qualitative and other forms of quantitative data were used to explain the primary results (Table 2-2).

The first post-baseline data collection (April 2016) consisted of quantitative sound level measures alongside ethnography sessions to identify behavioural changes in clinical practice following the initial phase of interventions which might explain any detected change in sound levels.

Final data collection (May 2018) consisted of quantitative sound level measures alongside ethnography sessions and interactive discussion with staff to assess satisfaction with the display and to identify any ongoing or new behavioural changes in clinical practice which might explain any detected change in sound levels.

2.4.3. Strengths of the mixed methods approach

The experience of and perceived nuisance from sound depends on the qualities of the sound (repetition, frequency content, modulation) as well as the emotional response to the sound source, individual sensitivity to noise, beliefs about noise prevention, the importance of the noise source, and annoyance at the cause. Using a mixed methods approach brings together the objectively measured sound levels (decibel values) and the human relationship with noise, specifically the effects that different sounds have on the individual and how this might relate to the intrinsic nature and characteristics of any given sound in context. The importance of psychoacoustics in relation to this project is explored in chapter six.

The multiphase mixed methods design allows a higher degree of flexibility than would be possible through either purely quantitative study of sound levels, or the patient experience alone. It is only through integration of findings from both types of data that the full and rich picture of the experience of noise levels in the AICU can be understood.

2.4.4. Research approach for the SILENCE project

It was obvious to me that the SILENCE project would be essentially constructivist in its nature. The central pivot point of the project was always the experience of intensive care and it was important to acknowledge that this could be defined from a number of different viewpoints. Patients and relatives find themselves in an unfamiliar environment in which they are often passive participants. Clinical staff working in the AICU are busy, often stressed, and self-acknowledge that their day revolves around patient-care tasks. The motivation for the SILENCE project was to bring these two groups of people together in an environment where they were no longer focused on their 'within the moment' experience and allow them time in a safe space [155] to reflect on what it is really like *to be* in the AICU. Through this shared exploration of lived experiences it was possible to identify individual motivations behind attitudes, understanding, and practices.

The project therefore draws upon aspects of interpretive phenomenology as I seek to define *what it is like* to be a patient/relative/member of staff in the AICU and reflect on what this might mean in terms of identity and understanding of the self within the social context of the AICU. The concept of participatory action research is also embedded within the project through use of the AEBCD method [153].

2.4.5. Introducing change

Introducing change is frequently problematic [156]. Lack of cohesion and teamwork can manifest in poor implementation practices, limited engagement with change, and ultimately failure for reasons that are external to the specifics of the intervention [114]. The complexities of clinical teams, mixed hierarchies, and often conflicting priorities mean that power struggles in the clinical workspace are common [157].

To maximise engagement with the project and address potential problems associated with power struggles, it was important to offer control over changes which would affect staff and patients. The interventions were determined by stakeholders. Through honest and reflective discussion, the mixed group recognized the need to raise awareness of noise pollution in the ICU before implementing a novel intervention. In keeping with the fluidity of PAR decision making, the final interventions were not necessarily in line with those initially proposed. Elements of pragmatism were intrinsically a part of the decision-making process and delivery. Whilst academic rigour was maintained, the need for the project to succeed overrode unquestioning adherence to method.

The possibility of being able to translate this programme of research into the wider UK National Health Service was important, both for personal satisfaction and to meet the wider endpoints of the feasibility study funded by the NIHR. The generalisability of sound levels as a primary outcome was therefore attractive.

2.4.6. Summary of research methods employed

	AEBCD preparatory work	Baseline analysis	Exploration of results	Post AEBCD intervention development	Interim analysis	Soundscape Development	Primary data analysis	Secondary data analysis	Exploration of results	Overall assessment of results
Quantitative		●[b]			●[e]		●[g]	●[h]		
Qualitative						●[f]			●[i]	
Mixed	●[a]		●[c]	●[d]						●[j]

Table 2-2: Summary of research methods employed

[a] Qualitative secondary analysis of patient interview transcripts, qualitative thematic analysis of prospectively collected staff focus group transcript, quantitative analysis of disturbances questionnaire completed by patients and nurses, qualitative ethnography, quantitative sound levels

[b] Sound levels, presented as 24-hour average as per industry standard reporting

[c] Assessment of all data collected as described in (a)

[d] Implementation of alarm management guidelines (including recommendations for monitoring volume levels, individualizing alert parameters, and a 'lights out' policy to increase differentiation between night and day), installation of soft-close plastic lidded bins, introduction of multi-phase teaching programme including online materials and experience session delivered in-situ in the ICU. Teaching programme developed using recognized theories of adult learning.

[e] Sound levels, presented as 24-hour average as per industry standard reporting. Also presented by shorter time periods, and included peak values as requested by AEBCD group

[f] The visual soundscape was developed in collaboration with staff from the AICU and incorporated theories of design, motivation and behavioural change, and theories of user-centred development. This is presented in chapter seven

[g] Sound levels, presented as 24-hour average as per industry standard reporting. Also presented by shorter time periods, and included peak values as requested by AEBCD group. The structure of the data enabled higher fidelity spatial reporting. This is presented in chapter six.

[h] Knowledge transfer was tested quantitatively through before and after assessment (self-directed quiz). These results are presented in chapter five.

[i] Follow-up ethnography sessions and discussions with staff recognized behavioral change and explored projected use of soundscape in clinical practice (chapter seven).

[j] The interaction between results throughout this project and the contrast and comparison of findings across all phases situate this project firmly within the methodological structure of mixed methods design. See Figure 2-1.

2.5. Strengths and Limitations

Strengths

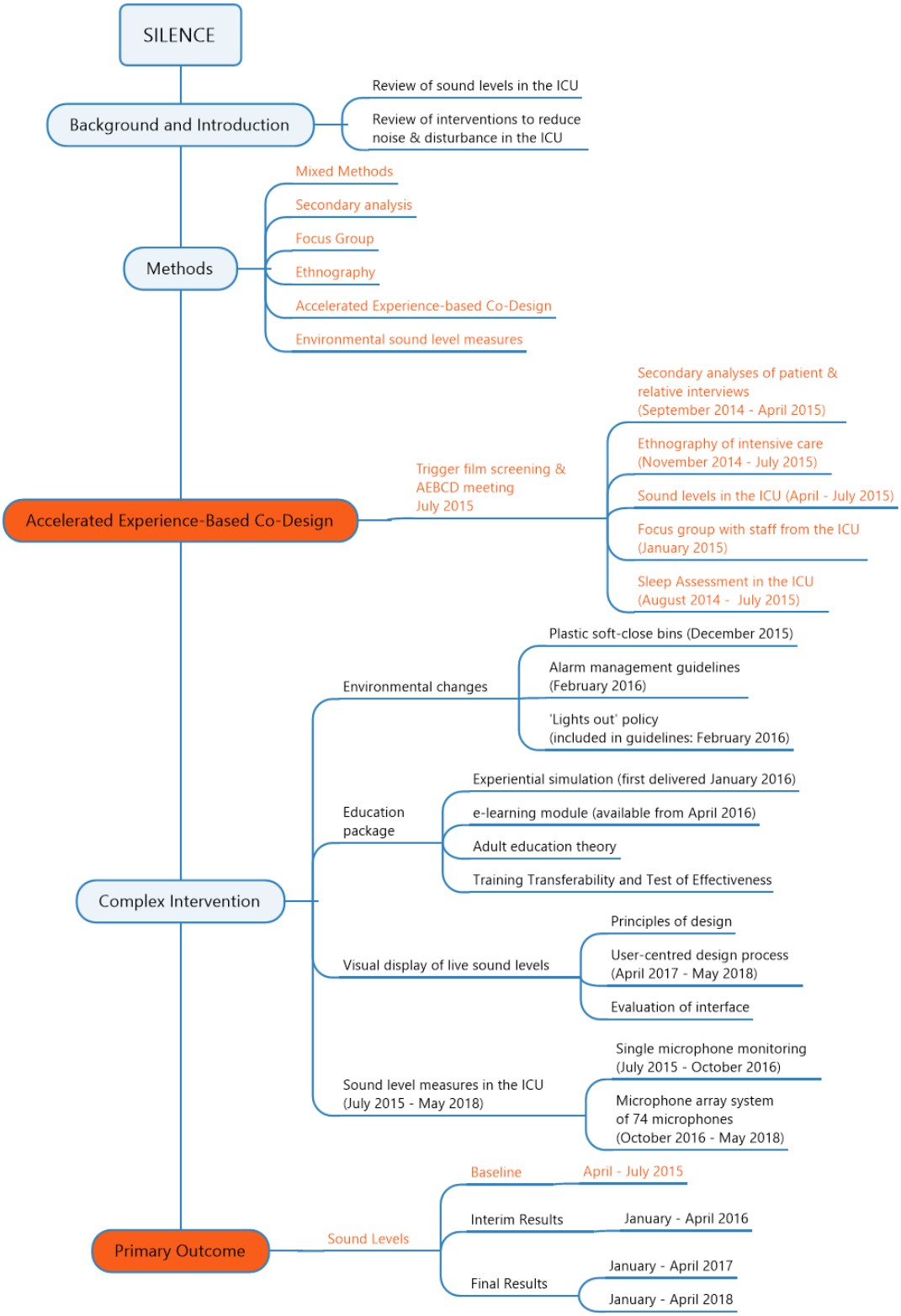
- Mixed methods combines assessment of data from multiple paradigms and viewpoints, allowing more detailed evaluation of a posed problem
- Combination of inductive and deductive processes enables identification and exploration of a problem within the same study
- Project planned as a mixed methods study from the beginning therefore data interaction and scope was accommodated by design

Limitations

- Mixed methods study design is more complex than simple qualitative or quantitative studies which has implications for resourcing and time
- Choice of qualitative methods used in this project was to some extent limited by pragmatism
- Individual researcher perspectives may interact with data collection or analysis
- Data integration can be difficult due to the inherent differences between quantitative and qualitative results
- Reporting and disseminating mixed methods results can be challenging to present to audiences with more familiarity with one approach over the other

3. Chapter Three: Characterisation of noise in the ICU

3.1. Chapter summary



This chapter covers preparatory work completed ahead of the accelerated experience-based co-design (AEBCD) [153] event (July 2015) and includes a variety of research methods. Results were **amalgamated** to form a cohesive exploration of sound and noise in the intensive care unit (ICU). Data from secondary analyses, ethnography, focus group, questionnaires, and sound level monitoring were presented to a mixed group of stakeholders: clinical staff from the adult ICU (AICU), patients, relatives, and researchers. The group identified a number of key areas to improve noise levels in the AICU, and proposed a plan for a complex intervention designed to reduce noise levels in the AICU.

Later chapters will address individual intervention phases. The following chapter describes the development, implementation, and interim results. Chapter five describes the teaching package that was designed as a result of the AEBCD process, and a detailed exploration of the design and development process to create a visual interface of sound in the AICU can be found in chapter seven.

3.2. Aim

The over-arching aim of the AEBCD process was to increase staff understanding of environmental sound levels and reduce noise and disturbance in the intensive care unit. Specifically, the AEBCD approach facilitated exploration of the experience of sound levels in the AICU from both patient and staff points of view. This led to a co-designed complex intervention.

Data collected during this phase of the National Institute of Health Research (NIHR) funded SILENCE project (ref: PB-PG-0613-31034) were used alongside secondary analyses of interview transcripts collected by the University of Oxford Health Experiences Research Group. Primarily this was to inform an AEBCD quality improvement exercise to reduce the impact of noise on patients admitted to intensive care. This included exploration of potential interventions and how they could be delivered in the AICU.

3.3. Background

The principles of AEBCD are that solutions are designed by a collaborative team which ensures that changes implemented are relevant to, and are supported by, all stakeholders; in this example patients and their relatives/visitors, AICU staff, and hospital management. For this project this involved bringing together a mixed group (staff, patients, relatives, and researchers) to consider issues relating to noise in the AICU, particularly those affecting patient sleep and potential onset of delirium.

As a precursor to developing a practical complex intervention it was important to understand the main sources of noise in the intensive care unit, specifically those which might be modifiable. The aim of this preparatory phase was to collate information on staff and patient perceptions of disturbances in the AICU as well as objective measures of sound levels.

Information from sound level monitoring, in-situ observations (ethnography), ad-hoc discussions, and disturbances questionnaires was then used alongside summary results from patient interview transcripts [158,159] and a staff focus group to inform discussions and identify "touch points" that would provide the structure for the trigger film and underpin the proposed interventions.

3.4. Methods

3.4.1. The Mixed Methods approach

Data were collected simultaneously in this convergent parallel design project [160] This allowed concurrent comparison of the rich mixed datasets and enabled detailed identification and review of specific themes and interpretation of the various data types. Ethnography field notes and the staff focus group transcript both validated and expanded thematic data collected previously from patient interview transcripts. The rich qualitative data also enabled exploration of, and helped to explain, the quantitative data (sleep and disturbances questionnaires completed by patients and nurses and sound level monitoring). Each phase of this part of the project is outlined in more detail in sections 3.4.2 (patient experience interviews), 3.4.3 (sound level monitoring), 3.4.4 (sleep and disturbances questionnaire), 3.4.5 (ethnography), and 3.4.6 (focus group).

Prospective data collection (ethnography) continued until thematic saturation was reached. To enhance quality of coding using a breadth of experience [161], two researchers (JD and EJ) analysed field notes using the method of constant comparison [162], seeking to define and interpret the concepts within the data [163]. This process of coding identified key themes from which a coding frame [164] could be developed. This coding frame allowed cross-mapping of themes between interview and focus group transcripts, observations and ad-hoc discussions, and disturbances questionnaires, enabling analysis of the full dataset.

3.4.2. Patient experiences

The University of Oxford Health Experiences Research Group (HERG) are the custodians of an archive of interviews conducted for a series of qualitative interview studies on a range of different health conditions, disseminated on the Healthtalk.org online resource. Where patients consent to future use of their interviews for education and research, Healthtalk project interviews are copyrighted and archived at the University of Oxford. Data of relevance to this study included interviews from a study originally conducted in 2005-2006 and funded by the Intensive Care National Audit & Research Centre (ICNARC). This archive includes 77 transcripts (40 patients and 37 relatives) describing experiences of treatment during and recovery after ICU admission.

The original study (the 'personal experiences of health and illness' project) was granted ethical approval from the Eastern MREC (ref: 03/5/016). All patients took part with informed consent. Participants were invited to take part through health professionals, charities, and support groups. The purpose of the original study was to understand patients' and relatives' experiences of treatment on an ICU and their recovery. A maximum variation sample was recruited and included both men and women who had been admitted to the ICU as emergency and elective cases between 1994 and 2005. Patients' admissions were of different durations (see Table 1 in [36]) and they were interviewed at different time points after discharge. No demographic details of the relatives have been published.

In-depth narrative-style interviews were completed and recorded in 2005–6. Patients and relatives were recruited from across the whole of the UK. Results were published both in the scientific press [158,159] and on the Healthtalk website in 2006 [165].

For this project access to the anonymised interview transcripts was granted by HERG. This enabled a secondary analysis exploring themes relating to noise and disturbance specifically.

Secondary analysis is becoming increasingly common across all fields of research. A primarily cited advantage of secondary analysis is that it enables further questions to be asked of data that were not prioritised in the original analysis. This maximises output from the originally funded

project promoting cost effective data re-use. This is particularly relevant for projects financed from public funds [166,167] as long as original datasets are appropriately de-identified and consent confirmed for archiving [168].

For qualitative research specifically, secondary analysis allows exploration of a new conceptual focus using existing data [169]. However, in contrast to quantitative data which can be said to be objective, impartial, and contextually neutral, there are unique challenges with re-use of qualitative data. Through familiarity with the participants (having also conducted the interviews), the original analyst has access to additional social meta-data that will be unavailable to secondary analysts who have transcripts only. Both real time data collection and interpretation are influenced by the world view of the time. Prevailing culture and events can shape how people interpreted circumstances at the time, interpretations that may not be stable over time [170]. Retrospective review and analysis will similarly be influenced by current social, cultural, and political contexts. Conversely, this opportunity for reinterpretation could also be beneficial as it may be possible to recognise the evolution of general societal perspectives and preoccupations between original and subsequent analyses.

When reporting secondary analysis of any type, it is best practice to outline the original study and primary research questions [171]. Differences can then be clarified, along with a transparency in the process of any data manipulation or changes in philosophical assumptions and theoretical ontological perspectives (see chapter two) between primary and secondary analysis.

For this secondary analysis, the broad purpose (to explore details of patient experiences of the intensive care unit) matched that of the original study. The secondary analysis had a more detailed focus on experiences of the physical environment, specifically the extent to which patients were disturbed during their admission.

The transcripts were analysed by two researchers (JD & EH) independently using a coding frame as outlined by Ziebland and McPherson [164] to focus on sleep and delirium. As new themes were identified the initial frame was adapted. The 'one sheet of paper' or OSOP method [164] was used to cluster data by key themes. Initial analysis followed principles of constant comparison [163] before interpretation [172,173].

As these transcripts described historical experiences (from 2005-6) it was important to ascertain their relevance to current clinical practice. To do this the research team conducted ethnographic observation sessions in the local intensive care unit (section 3.4.5).

3.4.3. Sound level monitoring

Sound level measurement in the ICU was performed as a local NHS Trust service evaluation within the Oxford University Hospitals (OUH) NHS Foundation Trust (Ref 3247). Sound levels were collected continuously using CEL-630 portable sound level monitors with integral recording fitted with a CEL-495 preamplifier and a CEL-251 microphone (Casella Measurement, Kempston, UK). During each evaluation period, monitors were sited at patient bed spaces approximately central in each AICU. The devices were calibrated before and after use using an acoustic calibrator (CEL-120/1; Casella Measurement) and set to record continuously, saving a discreet dataset every 24 hours. Every minute, devices recorded peak noise levels (LApeak) and averaged sound level (LAeq) from the preceding 60 seconds (see chapter six for a full description of sound level recording methods). Additional intermittent sound level measures were taken using iOS App Decibel Ultra (dev-apps.de; Patrick Schaefer) using an iPhone 5.

3.4.4. Sleep and disturbances questionnaire

Adult intensive care patients with capacity to provide informed consent[13] and their usual care nurses were invited to complete sleep and disturbances questionnaires as part of the wider SILENCE sleep assessment study funded by the NIHR and approved by NRES committee South Central – Hampshire A in June 2014 (NRES ref: 14/SC/0164; OUH R&D ref: 10664; CRN portfolio ID: 17647).

These sleep and disturbances questionnaires (appendix B) measured subjective quality and quantity of sleep and perceptions of environmental disturbance. Subjective measures of sleep were assessed using the Richards Campbell Sleep Questionnaire (RCSQ) [174] and environmental disturbances were assessed using visual analogue scales of significant disruptions based on an existing questionnaire used to measure sleep and disturbances in the ICU (Freedman 1999).

Results were ranked within each group (patient and nurse) and comparisons made between groups. As part of the sleep assessment study, correlation analysis was performed specifically for the RCSQ to determine whether a nurse completed questionnaire would be a valid alternative to a questionnaire completed by a patient. This has particular value for patients who are unable to complete questionnaires, for example patients with disrupted cognition as a result of their illness.

3.4.5. Ethnography (in-situ observations)

The in-situ observation (ethnography) sessions for this phase were approved under OUH service evaluation (ref 3247) and by the University of Oxford Central University Research Ethics Committee (CUREC) (ref: MSD-IDREC-C2-2014-037). Information sheets, leaflets and posters were circulated and displayed during observation periods. This study was designed to have no significant impact on the treatment received by patients, or the working patterns/processes of staff, and it was made clear that neither patients nor staff members were the direct focus of the research, rather that it was the general environment that was being observed. Two qualitative researchers (JD & EJ) independently conducted in-situ observations in four of the Intensive Care Units in the Oxford University Hospital NHS Trust. These included 'fly-on-the-wall' non-participatory observations (researchers aimed to be inconspicuous) and ad-hoc discussion with staff, patients and visitors to capture a full and in-depth reflection of noises generated within the environment. Ethnography sessions were conducted in the general adult intensive care unit (John Radcliffe Hospital), the predominantly surgical intensive care unit (Churchill Hospital), and the neurosciences intensive care unit. Observations also took place in the neonatal intensive care unit (John Radcliffe Hospital). Although patient care needs differ between AICU and the neonatal intensive care unit, it was hypothesised there would be opportunities to share noise reduction strategies between disciplines. Although direct involvement with patients', visitors' or staff activities was not sought, ad-hoc discussions occurred. If it was clear that observation was inappropriate or unwelcome, researchers moved location or left completely[14].

The ethnography sessions served three broad purposes. Firstly, they provided a practical method of assessing information collated from interview transcripts. These transcripts describe

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[13] https://www.bma.org.uk/advice/employment/ethics/consent/consent-tool-kit/5-assessment-of-competence

[14] This only occurred once during observations in the neonatal unit where the researcher felt it to be inappropriate to be in the area when the hospital chaplain was present.

experiences of treatment in intensive care units during 2005-6. It would be realistic to expect some changes to routine clinical practice over the intervening decade. Observation of current practices however revealed similarities with many of the points raised in the interview transcripts. This suggests the ICU environment has not changed significantly since 2006, at least with regard to noise.

Secondly, the sessions enabled me to spend valuable time in the ICU. This personal experience of the environment led to a deeper understanding of cultural norms and practical limitations that might affect any future intervention to reduce sound levels in the unit. The staff also became habituated to my presence which helped normalise behaviours. This meant observed behaviours were more likely to be routine and unaffected by the presence of a stranger[15].

Finally, the sessions generated primary research data for the project. These data enabled rich descriptions of the sound environment of the intensive care unit.

There is a known disconnect between work as imagined (WAI) and work as done (WAD) [175]. At best this can lead to mild misunderstandings. At worst, it can lead to a catastrophic series of failings that together prevent adequate learning and opportunities for improvement [176]. This is particularly emphasised in 'high-reliability organisations' (HROs). The defining characteristic of an HRO is that despite (often extremely) hazardous conditions they sustain almost error-free performance. The positive safety culture that is embedded is rooted in the reality that errors in these industries could be catastrophic [177]. Traditionally HROs are considered to be aviation, the military, railways, and the nuclear industry but increasingly the healthcare sector is being included in this definition [178,179].

It is therefore vital to understand the potential gap between WAI and WAD. A key purpose of observing in the AICU was to corroborate or refute information gleaned from other methods of data collection [180]. Areas of specific interest included response to alarms, compliance with best practice recommendations for personalised alert thresholds, and differentiation of workload/patient care needs between level 2[16] and level 3[17] patients.

Using the method of constant comparison [162], data collection continued until thematic saturation [181]. This process of coding identified key themes from which a coding frame [164] could be developed. This allowed cross-mapping of themes between interviews, questionnaires, and observations, enabling concurrent analysis of the full dataset.

It is not realistic to expect complete data capture. Even with multiple researchers and/or video capture it is not possible to record everything. Measures were taken to maximise opportunities to capture a good range of behavioral practices and people observed [182]. Observation sessions were completed during the day and overnight, both during the week and at weekends, and in a variety of ICU settings. Using a structured form (appendix B) observers noted types of sound (alarm, device, environmental, or staff, patient, or visitor generated), duration of sound, and

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[15] Thus mitigating the 'Hawthorne effect' whereby natural behaviours may change if test subjects perceive that they are being observed.

[16] Patients requiring single organ support (excluding mechanical ventilation for respiratory support) that cannot be delivered on a usual care ward. These patients are often admitted to a High Dependency Unit (HDU).

[17] Patients requiring either mechanical ventilation for respiratory support or multiple organ support. These patients are admitted to an Intensive Care Unit (ICU). In Oxford there is no separate HDU and both level 2 and level 3 patients are admitted to intensive care for their treatment.

how much (if at all) patients/staff seemed affected. Patient information collected from adult units included basic demographics (age, gender, reason for admission, and length of stay). Brief notes were made during active observational periods to enable full, descriptive reports to be written afterwards.

3.4.6. Focus Group

There are four main formats of group interview (Table 3-1). All involve collection of data from more than one participant at a time and have two main advantages over one-to-one interviews. Firstly, they provide an opportunity for the researcher to observe a (usually) culturally cohesive group interact and impart information. Secondly, where resources are limited, they are an efficient approach to accrue data and establish priorities [129]. For this project we were specifically exploring service user views and wanted a broad range of ideas. A focus group was agreed to be the most appropriate.

Interview type	Features	Typical uses
Consensus panel	Often composed of key informants or experts. Seeks group consensus or normative reactions. More narrow, closed-ended stimulus material.	Agreeing clinical protocols, resources prioritisation.
Focus group	Participants selected to meet sampling criteria. Seeks broad range of ideas of open-ended topic. Formal, controlled pre-arranged time and place. Usually audio-recorded and transcribed for analysis.	Testing health promotion materials, exploring service users' views.
Natural group	Group exists independent of the research study. Format formal or informal. Interview guide loosely followed. Usually recoded by written notes.	Ethnographic data collection (informal), social research (formal).
Community interview	Open to all or large segments of a community. Usually recorded by written notes.	Project planning, programme evaluation.

Table 3-1: Coreil's typology of group interviews, adapted from Coreil (1995)[129]

The staff focus group was part of the local NHS Trust service evaluation (Datix ref 3247). The focus group was widely publicised within the AICU. Emails were circulated through group mailing lists and posters were displayed prominently in staff areas. Staff from all professional backgrounds were encouraged to attend.

The topic guide (appendix B) was based on themes generated from the secondary analysis of the patient interviews, in-situ observations, and sound level monitoring completed to date.

The specific purpose of the staff focus group was to bring together members of staff from the AICU and encourage them to share their thoughts, understanding, and feelings about sound and noise levels in the ICU. In addition to adding rich data on staff perspectives this would generate audio clips to include in the AEBCD (accelerated experience-based co-design) trigger film to present both staff and patient viewpoints for wider group discussion. See point 12 of the EBCD Toolkit [183].

The session was recorded (audio and video). A verbatim transcript was produced from the audio recording after the focus group. This was analysed by two researchers using qualitative data analysis software (NVivo; QSR International Pty Ltd. Version 10, 2014). The coding framework developed for the secondary analysis of the patient experiences interview transcripts and ethnography was adapted to incorporate new themes that emerged from the focus group.

3.5. Results

3.5.1. Sound levels

Continuous sound level monitoring confirmed average daily sound levels remain significantly higher than the World Health Organisation recommended limit of 35dBA. A total of 49 days were recorded at the Oxford University Hospitals NHS Foundation Trust between March and July 2015. No single day average (LAeq24) was less than 54dBA. The median LAeq24 values measured at the Intensive Care Units at the John Radcliffe Hospital (n=32 days), the Churchill Hospital (n=10 days) and West Wing (n=7 days) were 57.2dBA (IQR 5.9), 58.9 (IQR 5.7), and 61.4dBA (IQR 0.6) respectively. All LCpeak values were >100dBA, the highest recorded being 124.8dBA.

Table 3-2 is an example of qualitative and quantitative data collected concurrently during observation sessions.

Observation session John Radcliffe Adult ICU 15th/16th November 2015			
Time	Elapsed time*	LAeq (dBA)	Subjective comments
20.00	30mins	60.8	Filter (disconnected) making loud alarm sounds. Nurse clearly frustrated with device.
20.30	60mins	60.6	Noticeable drop in noise when radio switched off at ~20.15
21.00	90mins	60.7	Lights dimmed/switched off across bay between 20.30-21.00
22.30	3hrs	62.0	Conversations seem to take place outside of immediate patient space although limited distance due to infrastructure obstructions. Lower speech volume when curtains are open ?patient more visible therefore staff more aware
23.00	3hrs 30mins	57.9	Filter alarms chirrups are quite loud (indicated ~60decibels at ~2400Hz. Background frequency tends to hover 300-700Hz
03.00	10mins	51.4	Alarms silenced (no patient interaction). Main door into unit has squeaky hinge. Left open = higher light levels. Seems to increase noise level.
04.00	1hr 10mins	50.7	Does seem very quiet
06.30	20mins	50.2	Alarms suspended on patient – activity behind curtain – HR 104-113 (was high 60s earlier) Quite loud, fairly rhythmic white noise from sluice room
07.00	40mins	52.3	Drug cupboard door very noticeable
07.30	1hr 20mins	53.4	Day shift arriving from 07.15; cleaning staff arrive 07.20; activity & noise levels have increased
*from start of observation session (three sessions overnight, 19.30-23.00; 02.50-04.00; 06.10-07.30)			

Table 3-2: Observation session summary notes

Subjective reflection on environmental noise levels during in-situ observations at times contradicted objective sound level measures. Staff consistently report (in general ad-hoc conversation) that the newer unit at the Churchill Hospital seems quieter and this was repeated in both the focus group and during ethnography sessions. The researcher observational field notes also support this however sound level records indicate the LAeq is lower in the older unit at the John Radcliffe.

3.5.2. Patient experiences, staff perspectives, and in-situ observations

Themes from secondary analysis of interview data included noise on the ICU, particularly from equipment, other patients and their visitors, personal (dis)comfort, and disturbance from treatments. This formed the base coding frame for qualitative analyses that followed.

All AICU staff were invited to the focus group but just five nurses attended. All five had current experience of the Oxford AICU participated in the focus group. All were female with mid-level seniority (Bands 6/7). All attending signed an agreement confirming their understanding that their (anonymised) comments might be used for the forthcoming staff-patient event, and future research purposes.

New themes identified from the focus group included staff perception of noise, the effect that noise could have on staff (for example as a distraction or source for increased stress), and the futility that some staff felt about their lack of control over noise levels.

A total of approximately 35 hours of observations were completed in the two general adult ICUs with shorter comparison sessions in the neo-natal unit (six hours) and adult neuro-ICU (three hours). The environment of each unit is unique, and the patient population differs. The neo-natal unit cares for newborns with critical care needs. The majority are premature births. There are 16 cot spaces in one large open unit. Both general units and the neuro-unit admit patients over the age of 16 years. The general AICU at the John Radcliffe Hospital (JR) has three separate clinical areas, known locally as 'A', 'B', and 'C', each with four bed spaces and a nursing station. Areas 'A' and 'C' each have two additional side rooms where patients can be isolated from the rest of the unit. The general AICU at the Churchill hospital has a nursing station and six beds in one large space and two side rooms. The neuro-ICU can treat up to 13 patients, ten in an open space area surrounding a central nursing station and three side rooms. The two general units treat both surgical and medical patients from the base hospitals. Due to the nature of the local ward specialties the Churchill AICU admits more patients who have undergone oncology or transplant surgery than the JR. The JR AICU admits the majority of patients who present to hospital via the Emergency Department and require immediate transfer for critical care, with the exception of those with neurological injuries for example trauma, sub-arachnoid haemorrhage, and stroke. These patients are admitted to the neuro-ICU. An overview of observations sessions completed is summarised in Table 3-3.

Date	ID	Time/s	Total Duration (hh:mm)	LAeq (adult ICUs only)	Unit	No. of patients	Age in years	Gender	ICU stay (days)	Status at discharge
							Adult ICU observations only			
							mean ± SD	N male	Median (IQR)	N alive
15/11/2014	DS & VO	14.20 – 15.20	1:00	-	JR A	5		-		
15/11/2014	JD	19.15 – 23.00 03.00 – 04.00 06.00 - 07.30	6:15	62.1	JR B	4	50 ±16.8	3	12 (15.5)	3
26/01/2015	JD	19.45 – 11.45 02.50 – 03.30 06.10 – 07.30	6:00	50.4	JR A	5 (2 side rooms)	69 ±12.9	2	9 (130)	4
19/03/2015	EJ	09.05 – 10.30	1:25	-	Neo			-		
25/03/2015	EJ	09.05 – 11.00	1:55	-	Neo			-		
27/03/2015	JD	20.50 – 23.10 23.20 – 00.25	3:25	56.8	JR A	3 (2 side rooms)	59 ±12.1	3	18 (89)	3
28/03/2015	JD	22.00 – 02.30 07.00 – 07.45	4:15	66.8	JR C	5 (1 side room)	56 ±14.8	4	13 (11)	4
10/04/2015	EJ	13.40 – 14.40	1:00	-	Neo			-		
14/04/2015	EJ	14.25 – 3.15	00:55	-	JR A	6 (2 side rooms)		-		
17/04/2015	EJ	09.45 – 11.30	1:45	-	JR A	6 (2 side rooms)		-		
19/04/2015	JD	07.30 – 11.00	3:30	60.5	JR A	4 (2 side rooms)	66 ±14.3	4	30.5 (48.3)	3
20/04/2015	EJ	14.00 – 15.00	1:00	-	Neo			-		
16/05/2015	JD	07.15 – 12.00 15.45 – 19.15	8:15	63.5	CH	5 (1 side room)	55 ±13.9	5	4.5 (10)	5
17/05/2015	JD	07.20 – 09.00	1:40	63.3	CH	7 (1 side room)	52 ±14.1	5	4 (8)	6
28/05/2015	EJ	11.00 – 12.30 14.25 – 16.00	3:05	61.0	NITU	11		-		
8-9/07/2015	JD	21.10 – 01.00	3:50	59.0	CH	7 (1 side room)	60 ±8.3	4	22 (29.5)	7
OVERALL			44:15				57.5±14.9	30	15 (28)	35

Table 3-3: Observations sessions demographics summary

The qualitative data were ultimately synthesised into two overarching themes; the sources of noise in the ICU, and noise reduction strategies employed by staff. Sources of noise were identified as originating from either people (patients, relatives, or staff), or infrastructure (for example bin lids, trolleys, cupboards and drawers). It was also recognised that supportive infrastructure could reduce noise. The main barrier to noise reduction was perceived conflict between patient safety and noise reduction. Almost all staff members were aware that noise levels were high but were unaware of reliable strategies to reduce them. As a result, a culture of ad-hoc and sporadic attempts to lower noise levels has developed.

Throughout the focus group discussion there was a strong sense that nurses were aware of high noise levels in the ICU but that they felt there was little that could be done to change them. It was largely accepted that the ICU is a busy environment with a lot of equipment and machinery, all making noise. Staff also defended noise made during patient care activities:

"sometimes it kind of passes you by but to be honest you're so busy you don't realise how much you're clattering around [...] sometimes making noise is the last thing you're thinking about." (FG)[18]

Staff activities (physical and verbal), particularly at handover periods and when preparing patients for transfer, and alarms were identified as primary sources of noise and disturbance. Several occurrences of 'alarm blindness' were witnessed. Supportive infrastructure in the neo-natal ICU was introduced as a response to potentially damaging effects of noise. Illuminated signs are in use and privacy screens encourage foot traffic away from patient cots. Neo-natal staff demonstrated increased awareness of maintaining a calming environment, such as speaking quietly and holding clinical discussions away from bed spaces.

Most visitors were quiet but some could be loud and disruptive. Staff chatter was predominantly focused on patient care but not exclusively. Colleagues who were also friends with each other were observed to silence alarms for patients other than their own.

Sleep assessment study disturbances questionnaires completed up to July 2015 were included in this analysis dataset, the demographics of which are summarised in Table 3-4.

Demographic Data	
Patients recruited to 30 June 2015 (n)	20
Median age in years: (range, IQR)	63.5 (20-80, 16)
Gender (n)	Male: 11 / Female: 9
Admission source (n)	Surgical: 12 / Non-surgical: 8
Status at discharge (n)	Alive: 19 / Dead: 1
Median length of ICU stay in days prior to recruitment (range, IQR)	2.5 (0-28, 7.75)
Number of patients who completed disturbances questionnaire	12
Number of nurses who completed disturbances questionnaire	8

Table 3-4: Summary of sleep assessment demographics

[18] FG denotes quotation from focus group

Both patients and nurses ranked alarms and interventions as the most frequently disturbing to patients in the intensive care unit (Table 3-5).

Disturbance	Patient ranking	Nurse ranking
	(n=12)	(n=8)
Alarms	1	1
Interventions	2	2
Bleeps	3	5
Handover	4	6
Chatter	5	3
Footsteps	6	4
Phones	7	7
Entertainment	8	10
Visitors	9	8
Cleaners	10	9

Table 3-5: Comparison ranking of sleep disturbances

The final sleep assessment results from the Richards Campbell Sleep Questionnaire were published in December 2018 [52] and the publication is included for reference in appendix E. Briefly, correlation between nurse and patient completed RCSQs was extremely limited ($\rho = 0.537$ ($n = 444$)) indicating that the nurse completed version of the RCSQ is not a viable alternative to use in routine clinical practice. The results from the SILENCE sleep assessment study conclude that no current method of sleep monitoring appears appropriate for patients admitted to the intensive care unit. However, to enable between-study comparison and evaluation, the patient-completed RCSQ seems the most appropriate measure at the current time.

Alarms

Many of the most invasive and intrusive noises heard on observations were from alarms.

One patient seemed reassured that staff understand the different alarms, offering this thought for potential patients and visitors:

> *"…don't worry about things going off because they're all looking after you. They're all there for a purpose and they're gonna do, they're all doing a job and it's wonderful, you know. If something does go beep and it shouldn't go beep they'll straightaway come over […] They're listening for those beeps […] It might just sound nothing to you, that beep means something. Very often they can be going for a little while and somebody will say, "What's that?" "No it's nothing, don't worry". Then*

all of a sudden another beep would go off, zoom they're there, you know, sort of on it straight away, so it all means things to them 'cause they're training that way." (IC07)[19]

But many found alarms confusing and worrying. Patients described alarms as the most highly ranked disturbance and the interview transcripts also indicate how bewildering patients and their relatives can find them.

"you hear an alarm…you don't know what's going on" (R01)

"lights flashing, beeps going, buzzers going….overpowering" (R31)

"I found myself looking at the monitor all the time, every time an alarm went off I'd try to fathom if anything, I think you get to the stage then where you're waiting for something else to go wrong" (IC01)

Some patients did not understand why they were being monitored:

"every time I went to sleep I moved and of course I moved in such a way that it set it off and woke me up And I found that very annoying and I thought to myself well there's no real reason, they don't need to monitor my heart like that, you know I'm perfectly healthy [laughs] Obviously I wasn't but I thought I was." (IC02)

Some patients felt nursing staff placed too much trust in the monitoring:

"even though I was asking, nobody actually would explain to me why I was being ignored in favour of the computer […] They would disappear for long periods of time, […] And they would get, they would say "Oh, we've got other equipment over there that we're monitoring. And we can monitor you while we're over there" but I actually didn't believe them. And I felt very frightened because I was frightened when I was on my own and nobody else was there, And that happened a lot. It was, became very depersonalised". (IC30)

Staff in the focus group commented that junior staff were less likely to adjust their monitor alert limits and make clinical judgments about patient care.

you can set your parameters wisely and then you haven't got them going off […] I don't think they [junior nurses] consider it do they, they just set their alarms and like a car alarm it goes off like anything even if the patient moves […] I know obviously people are fairly routinely monitored and often its hourly that they're getting blood pressures do you think nurses are allowed to be clinically thinking about how necessary it is to be doing those hourly blood pressures? (FG)

During the observation sessions, high level alarms from vital signs monitoring were attended to quickly in most cases, although occasionally parameters seemed restrictive and alarms sounded frequently in a short period of time without prompting clinical action. On a few occasions, a high-level vital sign monitoring alarm was caused by clinical or personal care. These were rarely silenced until the task was completed.

Alarm caused by nursing activity so left to run for quite a while. Nurse acknowledged "it's me, sorry, all OK" from behind curtain. (FN)[20]

The run-on of low-level alarms when vital signs monitoring cables were unattached was frequently observed. This was mostly from detached oxygen saturation monitors or heart rate monitoring. At one point there was a fault in the monitoring system which meant an almost

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[19] 'IC' denotes patient ID; 'R' denotes a relative (quotations from interview transcripts)

[20] FN denotes quotation from ethnography field notes

constant 'sats off' alert. This was witnessed over two consecutive days during the observation period.

Infusion pumps often alarmed and in most cases did not seem to signify that the patient needed clinical attention. Rarely was immediate action prompted by these alerts.

> *Low level alarm left to run while nurses completing handover. At 4th 'set-off' both nurses went to patient. Day nurse looked at monitor & silenced alarm. Night nurse programmed pump. Low level alarm again. Both nurses looked at monitor but not silenced for a couple of minutes (FN)*

Both observers and staff frequently noted key press confirmation for infusion pumps was incongruously loud.

Such was proliferation of alarms that both I and the other researcher found that, after observing for a few hours, we no longer noticed them. At times there were so many different alerts coming from many directions that it was difficult to isolate their source.

> *Have noticed I've stopped recording every alarm, beep and ping. Too many. Also general activity levels in each space are quite high so it is hard to document everything. Some degree of 'blanking' after only a couple of hours. Not surprised that nurses seem to ignore some alerts. (FN)*

Several occurrences of 'alarm blindness' were noted during observation sessions. One case was during a night of high activity level with higher than average noise levels. In two other cases it was noted that the nurse was temporarily fixated on another task (ongoing IT issues with bedside computer and cleaning equipment respectively).

Nurses also ranked chatter and footsteps as highly disturbing for patients however patients did not find either of these particularly concerning, reporting bleeps and handover more intrusive. One of the nurses in the focus group commented on the culture of chatter on the unit:

> *one of my biggest bugbears ever since I've qualified is people just incessantly talking (FG)*

Talk of a non-clinical nature was frequently heard, however when staff appeared to have a friendly working relationship, other noise reduction benefits were observed. This included attending to each other's patients, equipment, and alarms.

Visitors, cleaners, or patient entertainment (TV/radio) were not rated highly by either nurses or patients as significant sources of disturbance.

Staff generated noise and disturbance

Human generated noise was most commonly observed from staff members rather than from patients. Much of this was related to the clinical care of patients, and intensified during significant patient events such as handover at shift changes, transfer of patients (to theatre or for off-unit investigations), admissions, and discharges.

> *07.40: shift change. Sudden influx of nurses and noticeable increase in noise [...] bedside handovers individually quiet but "hubbub" has increased [...] is there a natural inclination to speak louder when the environment is noisier? (FN)*

Staff were observed to appear frustrated at times of increased environmental noise.

> *"Nurse on phone states "it's really loud in here, can people be quiet! I can't hear the phone!" Highlights how noise can affect professional practice as well as patients. Beneficial for remaining focussed when work environment quiet. (FN)*

Staff demonstrated an awareness that high noise levels are an issue for patients, particularly relating to poor sleep.

[housekeeping staff] states she has purchased the earplugs and eye masks for the patients. They have gone through about 30 in a couple of months. She said "if you're semi awake here, or semi with-it, there's no way you can sleep." (FN)

Efforts to improve sleep hygiene for patients included dimming lights at night, and providing eye masks and ear plugs although it was acknowledged that there are problems making sure that patients are aware these are available

they're not offered all the time the earplugs and there's some [patients] that say they don't want them anyway I think some people just don't want them anyway, they're so stressed anyway and earplugs just make them more stressed [...] we've got a large amount of agency nurses so they don't realise that there are eye masks and ear plugs available (FG)

During the focus group there were several comments about discussions with patients about the effect that limited sleep had on their experience of the ICU:

"I would say the majority and well over 50% will say, probably 80/90% will say I didn't sleep and is it because you didn't sleep because of dreams or was it noisy and the majority of them will says its noisy" (FG)

"sleep deprivation is a massive issue isn't it? I spoke to somebody yesterday and she was on ITU for three days and didn't sleep a wink and I said 'why was that?' and she said it was just so noisy, it was constant all the time and again I think she was next to, she was a level two patient, a level three patient with every piece of equipment possible so the patient was just busy constantly [...] a paper curtain's not going to keep any noise out is it really?" (FG)

The clear cots in the neo-natal ICU were routinely covered by blankets to limit light stimulation.

The clinical ward round was observed on a few occasions, and individual cultural practices around how this was done affected noise levels. On some occasions discussions were held over a patient's bed, with voices at normal conversational volume. Others were conducted slightly away from the patient, usually with staff clustered round a mobile computer. In the neo-natal ICU, the rounds were observed to be held away from the patient bed space more often than in the AICU, and staff more routinely made an effort to speak quietly. In the AICU the ward rounds were noted to be louder and more intrusive when the unit was busier.

Noise from patients themselves was not observed on many occasions. When it did occur it was mostly from confused patients responding to alarms and noises in the environment, patients talking to nursing staff, and sneezing/agitation from their endotracheal tube. Noise from other patients was also not something that the patients mentioned in their interviews.

Some of the nurses described experiencing lower noise levels when patients were ventilated and sedated. Observations did not support this, demonstrating there is perceived noise associated with the awake patient.

Noise from visitors

Increased noise was associated with an increase in the number of visitors. On the ICUs where observations were conducted, there is a visitor limit of two visitors per patient, however this was frequently breached. Most visitors were observed to sit quietly at patient bedsides, but others were observed to intrude into other bed spaces, and demonstrate a lack of understanding of confidentiality. This was witnessed in particular in the neo-natal ICU.

Are visitors told how important it is be quiet in NICU? Some people naturally assume this, while others not...Open bays facilitate movement of families between cots to have a 'look'.... Grandmothers told off for looking at other babies. (FN)

Some families demonstrated their lack of familiarity with the clinical environment when visiting their loved one. This was most noticeable with larger family groups who had a tendency to talk loudly amongst themselves. Patient interviews also highlighted this as a problem

> *"You're mixed with all sorts of people, and some people just don't care about anybody else. They're very selfish. You know they clatter about. They talk loud on the phone. They at night – they've got their TVs on late at night […] you could hear them laughing at something, and then their visitors stayed until late at night […] five and six people round the bed, and there are supposed to be two […] Nobody puts their foot down and says, you must go home." (IC10)*

Noise from infrastructure

Basic infrastructure was observed to make frequent, jarring noises that felt disruptive. Drawers and cupboards (behind patients and out of their sight in the AICU) were often not soft close, and were accessed many times in preparation for one procedure. Main entrance doors often had faulty soft-close mechanisms resulting in repetitive knocking as double-hinged doors swung shut. Metal bins 'clanged' against the underside of sinks when opened, and also frequently clanged shut where soft-close mechanisms had failed. Use of bins included multiple open/close occurrences to dispose of single-use aprons after patient care activities. Many patients described hearing bin lids during their stay on the ICU and how they were confused by the sound.

> *when people put their foot on the pedal of the bin and the bin crashes down and you're just dropping off to sleep and, you know, you already think you're in a strange environment, that you've been abducted like by aliens and then this thing comes crashing down (IC01)*

> *when I woke up I thought, because I was so frightened, I thought they were like champagne corks popping and that wasn't because I thought people were having champagne, I thought I hope the doctors and nurses aren't drinking, I've nearly died (IC04)*

Staff also identified bins as a source of unnecessary noise, and took steps to reduce their sound.

> *Chat with nursing staff member about bins. He was saying that there is a particular 'problem bin' …. It is often lined with foam or a towel by nurses on night shift because it is so noisy and disrupts the patients. (FN)*

Other sources of noise from infrastructure included apron rollers which were wall mounted, metal, and had a loose roll of aprons that banged around when pulled. Patient disturbance from bins and apron rollers were also mentioned in the focus group:

> *It tends to be similar kinds of things, bin lids and stuff like that. Everybody says bin lids […] one patient I know in particular was moved into a side room because of the apron rollers […] another patient … said as soon as I heard the roller I knew they were going to do something to me […] They're anticipating that pain and that intervention and you get the same for suction (FG)*

Chairs were observed to have broken wheels, or (for non-slip designs) no sound insulator when dragged across the floor. The non-slip models seemed designed to be lifted but appeared too awkward or heavy for most staff to manoeuvre, leading to dragging across the floor. The act of opening the controlled drugs cabinet was always loud, particularly overnight, due to a large bunch of metal keys against a metal cabinet. The door itself had no cushioning.

The layout of the AICU seemed to influence some of the noises caused by people and equipment. For instance, the neo-natal ICU had screened off a thoroughfare to direct walking through the unit, so traffic diverted from patient spaces. In a similar fashion the large nursing station in the centre of the adult units provided a focal gathering point at some distance from the patients. In contrast, where there were building obstructions, such as mid-unit columns, foot traffic was forced closer to some patient beds.

The telecommunications process was noisy and multi-phased, and included telephones, bleeps, and several different doorbells. Sometimes attempted communications involved a circular process of bleeping and telephoning as staff were unavailable, missed bleeps, or failed to answer the phone before it stopped ringing.

Lighting

Subjectively the ICUs felt quieter when lights were dimmed. This was both overnight and during daytime 'quiet time'. Light pollution from neighbouring areas was a commonly observed issue as light was not well blocked by curtains. Lights were generally dimmed overnight however there were occasions where lights were on over individual bed spaces causing illumination across the bay. Disturbance from lights was something patients mentioned in their interviews, both as a reason for lack of sleep and also as a source of circadian confusion.

> *The Thursday I didn't get any sleep when I came, when they took me into that room because the fluorescent light was on ahead, on top of me, adjacent to me where the sluice room was, a fluorescent light was on. On the left hand side of me there was a door with a light shining right through (IC14)*

> *you don't have any conception of time. It could be day, it could be night, it could be the middle of the afternoon, as a patient you don't know, because the lights are on all night, the lights are on all day, there's activity all night and there's activity all day. So I didn't, half the time I didn't know what time it was (IC01)*

There was acknowledgement during the focus group that the ICU is a 24-hour space and that this is not ideal, particularly for the less sick patients who, in other hospitals, might be cared for on a High Dependency Unit rather than in the ICU.

> *"you've got people that have just been admitted so there is a general noise because you're getting things together and ready and like you say [ ] you're so busy trying to get everything together I think if there was a way of working out a system and… let's talk about the high dependency or ICU, but a system where patients that were together that didn't need that much intervention compared to say a patient like an emergency area where the patients are first bought in and they're all sorted out so you've got that clattering and battering in one area and I know its been mentioned before by [ ] and I know they've talked about it previously but I think it would help because patients will be admitted twenty four hours a day" (FG)*

Patients were also aware of the 'round the clock' nature of intensive care but felt that disturbances and interruptions for care were not always appropriate:

> *"I couldn't focus on her cos she was very close to me. And she said, "Oh, I'm the midwife that's looking after you, she said, "its three o'clock in the morning and I may be popping in and out." And I said, "Look, I haven't had any sleep at all, and I just managed to get off and you've just woken me up so I don't need anything, if you could just let me sleep and then maybe in the morning you could talk to me." (IC14)*

Noise reduction strategies and barriers to success

There were many instances of ad-hoc noise reduction strategies being employed. For instance, some ward rounds on all units were witnessed to be conducted in low voices with staff clustered away from patient bed spaces minimising patient disturbance, alarm parameters were seen to be adjusted and individualised, high level alarms were often attended to quickly, and alarm volume was sometimes lowered overnight.

The conflicting goals of maintaining a quiet environment, but also attending to patient care in a timely manner, were observed on all units. Both the general AICU at the John Radcliffe and the neuro ICU had 'quiet time' during the day. Reasons for this are unclear, with both patient and

visitor rest and professional benefits cited. During the focus group it was also suggested that quiet time for patients might have associated benefits for staff:

> *"if you're kind of full on all the time it's not great on your stress levels either so if you could just have a couple of hours where you could just go ….. and catch up you could just concentrate and do only what is absolutely necessary then that may make your day better too." (FG)*

For the neuro unit this involved dimming the lights and restricting visitors to facilitate patient rest. However, nursing interventions including waking the patient for neurological observations, or attending to washes and patient hygiene were observed during this time. When a staff member was asked about this, they stated that there is so much clinical need for the highly acute patient, that it can be very difficult to isolate intervention-free time.

> *Neuro ICU: "1455 Patient hygiene being attended to in bed 7. The staff may have selected quiet time to do this because the patient was soiled. Or they may have chosen this time because the patient was free from other interventions." (FN)*

During one ad-hoc conversation with a doctor overnight it was suggested that higher noise levels and activity might be what keeps staff from making mistakes. This conversation suggested that some staff considered noise to be an essential and unavoidable feature of AICU.

Other examples of the balance between patient safety and loud noise included a fire alarm (no patients moved), safety obligations of x-ray personnel in making everyone aware of radiation exposure, the co-ordination of staff for rolling highly dependent patients, and more generally the alarms. As one of the nurses said during the focus group:

> *obviously there's nothing we can do about some of the noise as much as we might want to because it is always going to be there because people are going to get really, really sick and we are going to be being noisy and have the lights on at two o'clock in the morning. There is some of the noise that we can definitely do nothing about (FG)*

Control over individual patient environments was much more obvious in the neo-natal unit, for instance blocking light and maintaining body temperature as well as limiting disturbance from noise. It was hypothesised by the researchers reflecting on the observational data that increased awareness of the patient environment (both social and physical) in neonatal ICU may lead to increased reverence around noise management.

The neo-natal ICU had an 'electronic ear' on the wall which flashed when sound breached a certain level. When researchers spoke to staff on the unit about sound, many of them referenced this 'ear'. Although it seemed to increase awareness of the impact of noise, it was flashing routinely during observations and did not seem to change action that was taking place. Some staff were sceptical as to its influence on noise, because they felt it was too sensitive. No-one we asked knew at what specific level it activated.

Cleaning staff were observed to be both very noisy and to take steps to reduce noise for instance replacing furniture carefully or altering movement to limit wheel rattle when pushing trolleys. A housekeeping staff member demonstrated awareness of noise reduction strategies, highlighting the integral role of non-clinical staff in maintaining a quiet environment. Suggestions for workflow re-organisation to improve the management of sound levels in the clinical environment were also made during the focus group

> *it was a patient who suggested this to me and he said I don't know why you have somebody in a centralised area and then an alarm will go off it will go to a centralised area. When an alarm goes off on the ward it wakes the whole bay up because the alarm is pulling for the nurse and it wakes the whole bay and he said why isn't there a centralised area where an alarm goes off with some monitoring service. (FG)*

3.6. Discussion

Staff and patients agreed the ICU is louder than they would like it to be. Sound level monitoring confirmed that it was significantly louder than World Health Organisation guideline levels [1].

It was not surprising that patients in Oxford considered alarms the most intrusive disturbances. The secondary analysis found many patients reported that alarms prevented sleep and were a source of confusing and disturbing thoughts [36]. Other studies have also indicated that alarms are considered highly stressful in the ICU [184,185]. Patients were also concerned about sleep deprivation and constant disturbance, both for their own clinical care and from other patients and their visitors. Staff felt that high noise levels were a necessary consequence of the required equipment and activities associated with patient care and there were limits to what they were able to change.

Staff appeared to operate conservatively within the precautionary principle[21] [186] and alarm parameters were not often obviously adjusted to the individual patient, despite a widespread belief that alarm limits were always adjusted to the individual patient. This suggests a local practice of normalised deviance [96] which probably stems at least in part from limited understanding of how sounds affect the environment and those in it. Ad-hoc attempts by staff to reduce noise levels demonstrate a desire to improve the environment for patients but also a limited understanding of effective noise control strategies. Effects were rarely formally monitored so quantifying change is almost impossible.

During the pre-AEBCD period (April – July 2015) the median recorded LAeq24 was 57.0dBA (IQR 3.2). This is lower than the average of 59.2dBA measured in June 2012 [4] but in this previous study we measured sound levels over a single 24-hour period which may not have been fully representative. In spite of the lower overall sound values in the current study we observed no peak value below 100dBA (a level equivalent to a pneumatic drill or live rock music). The highest recorded peak value was 124.8dBA, loud enough to cause physical pain [187,188].

Historically most patients in ICU were heavily sedated to facilitate mechanical ventilation [189], but it is now much more common for non-sedated or minimally sedated patients to be treated in the ICU [189,190]. Round-the-clock working practices in ICU, coupled with the variety of devices needed to care for patients result in a noisy and unnaturally lit environment coupled with a professional team culturally acclimatised to constant activity. The environment has been described as an 'ergonomic nightmare' [191] with little integration between devices. This creates a workplace with a wide range of potential sources of disturbance, even during routine tasks.

The clinical workplace, generally, is not designed for the patient. Even during 'quiet time', staff were seen to continue with patient care tasks; some of which they acknowledged probably could have been delayed. The priorities of staff, and their need to complete tasks on their schedule, can conflict with unseen patient benefits, such as rest. This was often defended as clinical need in real time, but when reflecting on practice (for example during the focus group) nurses felt that sometimes patients' needs did not always come first.

The limits of understanding around sound, noise, and disturbance perhaps lead staff to the view that change is not possible. A subject of this complexity cannot be addressed using quantitative

[21] The precautionary principle is primarily used by policy makers for protection when evidence is lacking. The background philosophy is that the safest action should be taken where there is a plausible risk of harm. Evidence-based action should replace the precautionary principle as more information becomes available.

or qualitative methods alone. The added information gained from evaluating data from multiple sources is invaluable. It was observed in this study that staff (and study personnel) consistently rated the ICU in the Churchill hospital less noisy than the John Radcliffe AICU. This was not supported by the sound levels measured in each location. Field notes taken at the Churchill ICU refer to soft-close bins, quieter apron rollers, and less disturbing trolleys. The unit is also much brighter, with higher ceilings and large windows. This is where the psychology of noise perception (explored in more detail in chapters six and seven) is fundamental to understanding the environment, and requires an awareness of the whole environment and an understanding of the limitations of human cognitive awareness [192]. It may be that the larger, more brightly lit unit with newer equipment presents an impression of modernity and order, leading to a feeling of calm. Perhaps also perception of 'noise' is a reflection of acoustic peaks, or frequency of higher frequency sounds (such as alarms) rather than overall noise level reflected in LAeq. It is plausible that patient populations differ, with patients admitted to the Churchill being sufficiently less acutely ill to make a difference to the number of alarms activated.

There were other instances where perception did not match observed behaviour. Some of the busiest and noisiest observation sessions were in areas where most patients were sedated and ventilated. We also noticed an apparent desire to be quieter when patients were more aware of their surroundings. This contrasts with nursing perceptions that awake patients cause higher noise levels. Ventilated patients are likely to be more seriously ill than their neighbours, who may be more aware of their immediate surroundings, and this results in a higher acuity of care. Activity levels therefore rise but the care team are unlikely to be aware of this whilst they are in the act of delivering treatment to their patient. It may also be that staff concentrate on noise differently when they are conscious of being observed by patients, or alternatively that awake patients are perceived as being more demanding as they can (and do) interrupt staff during their planned activities. There was strong evidence that staff felt higher noise levels directly associated with perceived workload.

Attention paid to noise hygiene varied in different critical care areas. We observed these differences most notably in the neo-natal ICU. Sound management was integrated into environment design, with structured walkways deflecting activity from bed spaces and an electronic alert flashing to highlight noisy activity. These environmental features created raised awareness of high sound levels, although understanding of how to reduce them was still limited. It is well-known that pre-term babies are susceptible to physiological changes related to poorly developed processing of noxious stimuli such as noise [193,194]. Noise management has therefore been an important consideration in the care of pre-term babies for over 40 years [195]. Physiological effects of noise on adults is not well understood [196], and this may partly explain the environmental investment in noise reduction in neo-natal versus adult units. It is possible that blankets placed over cots serve as visual clues that the patients need protecting. This might go some way to explain why neo-natal patients seem to be viewed differently from adults when admitted to intensive care.

Background noise levels have a tendency to continue to rise once they begin to escalate. This is because intelligible speech needs to be approximately 15dB louder than the baseline level. This is known as the 'Lombard effect' [94] and was recognised during the observation sessions, particularly at handover times. Increasing background noise levels are not just a matter of patient comfort, but can also have demonstrable effects on staff. Mental capacity is a finite resource and increasing cognitive demands adversely impact performance in mental tasks [197]. Essentially, attentional focus narrows as mental workload increases [198] leading to a high risk of important information being overlooked. This effect has been demonstrated in clinical [199] and non-clinical settings [200,201], and the phenomenon is termed 'error of perception'. Vulnerability

to such errors is directly linked to the number of distractors in the environment [202], and the cognitive demands made of an individual [203].

This failure in auditory awareness is termed 'inattentional deafness' [204]. The phenomenon of failing to hear something because of mental workload, which under other circumstances would appear highly conspicuous is analogous to 'inattentional blindness' as demonstrated by Simons et al [203], and further explored in a (simulated) clinical setting of a resuscitation scenario [98,205]. It has also been demonstrated that inattentional deafness can be induced under conditions of high visual load without auditory distractors [206]

This may be another explanation why staff caring for the most acutely ill patients fail to accurately report noise levels. It is likely their brains are unable to process all the sensory stimuli in their environment. We were clearly focussed on a variety of things during the observation sessions, visual and auditory, but it was surprising how quickly we 'tuned out' and stopped registering individual alert tones and how we recognised they had just become part of background hubbub. While it may be valuable for teams to 'tune out' extraneous noise, such as the radio, it would be much more serious should they fail to perceive a critical alarm tone. A high alert tone will be part of the ICU staff 'attentional set' [207]. As such it is predicted to be less prone to being ignored, but unfortunately such events have occurred, and have resulted in patient death [208].

A poorly controlled acoustic environment can therefore adversely affect staff. Inattentional effects were witnessed during data collection. Preoccupation with tasks was common, and there were several instances where staff had to be specifically alerted to attend to their patient. The units were not always unusually loud at the time, nor were the alarms at any lower volume than usual. This is consistent with psychological data that shows these effects can occur during relatively mundane and simple tasks. Fortunately other team members retained awareness of developing situations, and no patient came to harm as a result of missed alarms.

It is commonly claimed by staff that noise and activity are protective against inattention, particularly during night shifts. However, given the known psychological effects of distraction (described above), simply increasing alarm volumes is likely to lead to worse outcomes for both staff and patients. There is some plausibility to the suggestion that some noise is essential. The Yerkes-Dodson relationship predicts performance improvements with increasing workload. However, this only holds true up to a point and performance degrades steeply as distractions increase beyond a critical level [209].

As part of the SILENCE study, nurses were asked to predict what factors patients would find most disturbing. Patients were also asked to identify what did disturb them during their stay. There was little parallel agreement between the lists generated by the patients and nurses. This may then reflect sources of distraction that nurses themselves felt most important and might be attributable to the 'false consensus effect' [210] whereby individuals have a tendency to assume that others hold similar views. It appears that nurse predictions particularly highlight distractors that affect staff personally, whereas the patient perception of disturbance seems to originate from a fear of the unfamiliar or unknown. The psychological disturbance of an unfamiliar activity such as ward round and handovers, although a similar sound (acoustically) to general chatter, is likely to be felt much more deeply than general conversation.

There is a well understood difference between what people say and what they do [211]. In order to understand the situated knowledge implicit within the ICU, it was necessary to observe the unit in action. The ideal method of participatory observation (observing from within the culture) was not feasible in this case as the primary researcher (JD) is not clinically trained. The secondary observer (EJ) is however a nurse and so shared some common ground with the team in the

observed environment. The existing close links between the ICUs and research group also helped build a sense of familiarity, thus limiting significantly altered normal behaviour in the presence of a stranger.

Whilst we made every effort to remain unobtrusive during the observation sessions, we recognise that examples of modified behaviour were observed. Being truly invisible is hard to achieve and during almost every session piqued interest and led to a discussion about the observations, the programme of work, and noise levels in general. We chose to view these interruptions as opportunities to acquire additional information which led to deeper understanding of the issues surrounding patient care in the intensive care unit, but they could equally be seen as negative events that sabotaged the reality of the observed environment.

Keeping patient experience of care central to the project purposively focussed attention on the full multi-disciplinary team, including support staff. We felt we were not perceived as targeting a particular clinical group.

3.7. Strengths and Limitations

Strengths

- AEBCD has been shown to be an effective method to drive quality improvement
- Secondary analysis of the patient and relative interview transcripts was an efficient way to beginning the project that maximized value of an existing resource
- Non-ICU trained observers brought fresh eyes to activities that ICU staff would not have thought to question
- Bringing staff and patients together to discuss and resolve a problem was a novel approach for the local team
- Presenting both qualitative and quantitative data allowed for more comprehensive discussion with stakeholders

Limitations

- Secondary analysis sources are limited by the intent of the original data gathering process
- Neither researcher conducting ethnography sessions was an ICU-trained nurse and neither had detailed working knowledge of clinical tasks under observation
- It was impossible to remain invisible during the observation sessions
- The pragmatic choice to host only one focus group may have restricted the breadth of professional participation and engagement
- Sound level monitoring for this initial phase was limited to single daily average values

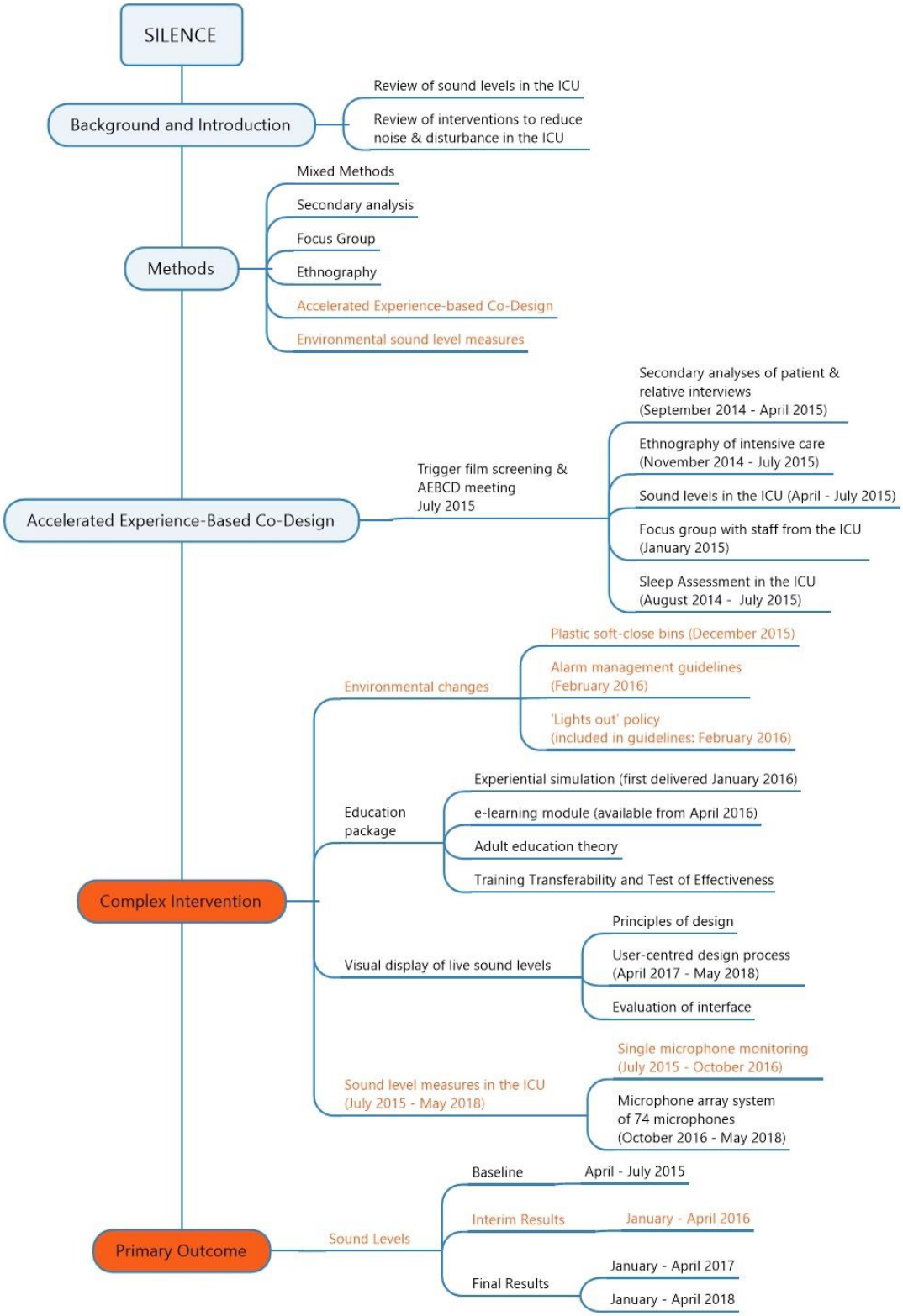
3.8. Conclusions

The strength of the mixed methods approach is that it can offer rich sources of information and insight which can lead to a better and more complete understanding of a topic.

Through this presentation of patient and staff voices and perspectives combined with sound level measures it is possible to shed light on key aspects of the ICU environment that may underlie increasing noise levels. It is also possible to begin to understand the perception of noise in the ICU and how this impacts both the staff working environment and the patient experience.

4. Chapter Four: Accelerated Experience-Based Co-Design

4.1. Chapter summary



This chapter covers the accelerated experience-based co-design (AEBCD) phase. The previous chapter explored background work completed to generate material for the AEBCD meeting. By the end of the meeting (July 2015) the group identified a number of key areas to improve noise levels in the intensive care unit (ICU) and proposed a plan for a complex intervention designed to reduce noise and disturbance in the ICU.

Briefly, this chapter describes the structure of the AEBCD event, preparatory work to create presentation materials, and post-event intervention development and subsequent implementation. Results following this initial phase are also presented. The development of teaching materials and design of the teaching package are described in chapter five. The design and development of the sound levels display is described in chapter seven.

4.2. Aim

The aim of the AEBCD exercise was to develop a noise reduction intervention that could be deployed locally as part of the National Institute of Health Research (NIHR) Research for Patient Benefit (RfPB) funded SILENCE feasibility study (RfPB ref: PB-PG-0613-31034; NRES Ref: 14/SC/0164; OUH R&D Ref: 10664). This participatory approach offered opportunities for local staff and patient involvement that was hoped would lead to good engagement with, and adherence to, any change introduced to the AICU.

4.3. Background

Preparatory AEBCD work is explored in chapter three but a brief overview is included here by way of background to the post-AEBCD work.

4.3.1. Sound levels

Sound level data were collated from continuous environmental monitoring recordings. These data were presented to provide quantitative context to discussions during the mixed staff/patient co-design event in July 2015. Levels were consistently higher than World Health Organisation guidelines, with LAeq24 values 55-60dB and peaks up to 124dB.

4.3.2. Patient experiences

Five clear themes relating to noise and disturbance emerged from the secondary analysis of patient and relatives' interview transcripts. These were alarms, lights, being disturbed by people, being disturbed by equipment, and feeling overwhelmed. Quotations were collated and merged with thematically matched quotations from the staff focus group.

4.3.3. Sleep disturbances

Data collected from the sleep assessment phase of the RfPB project were summarised and included in the AEBCD presentation to highlight sounds that seemed to be most disturbing to patients. Alarms and patient care activities were found to be the most disturbing.

4.3.4. Staff perspectives

Staff members from the Oxford University Hospitals NHS Foundation Trust (OUH) Adult Intensive Care Unit (AICU) participated in a focus group to discuss environmental noise in the ICU. New themes identified from this included staff perception of noise, the effect noise could have on staff (for example as a distraction or source for increased stress), and the futility that staff can feel about lack of control over noise levels.

4.3.5. Ethnography

In-situ ethnographic observations conducted between November 2014 and July 2015 generated insight into the working of the intensive care unit. Two overarching themes were identified; sources of noise in the ICU, and noise reduction strategies attempted by staff. Nights when lights were left on were louder, mapping to patient comments about disturbance from inappropriate lighting.

4.4. Methods

4.4.1. (Modified) AEBCD

The SILENCE project ran as a modified version of the AEBCD approach.

Secondary analysis of patient and relative interview transcripts, and informal feedback from the local ICU follow up clinic had already identified noise and disturbance as a patient concern. These results also formed the background and rationale for the NIHR RfPB grant application and award. It was obvious that discussion needed to focus on these areas.

Using the principles of Accelerated Experience-Based Co-Design (AEBCD) [153] the trigger film was created using clips from a large research archive of patient interviews held by the University of Oxford Health Experiences Research Group (HERG) and a local focus group held with AICU staff. Observational data from ethnography sessions were presented alongside data from sleep disturbances questionnaires, and sound level recordings. These data were presented separately from the trigger film to inform discussion rather than being part of the trigger film itself.

This phase of the project was run as a local service evaluation/quality improvement project (OUH Datix ref: 3247).

4.4.2. Trigger film[22] development

Example quotations from each theme (alarms, lights, being disturbed by people, being disturbed by equipment, and feeling overwhelmed) were selected initially by a patient with experience of intensive care. Some minor changes were made by the research team to ensure that all themes were appropriately represented. A series of short narratives of about five minutes per theme was created (appendix B). When selecting representative quotations from each theme, consideration was given to diversity of both subject matter within each theme and patient demographic. The 'scripts' were also reviewed by a member of the SILENCE Advisory Group with professional media experience to ensure coherence.

The trigger film was created by the DIPEx (Database of Individual Patient Experiences) Charity technical team using their standardised format. This was an iterative process that allowed minor content and technical changes to be made before a final version was confirmed. This was delivered both as a single film and as five shorter segments to allow flexibility of use. The terms and conditions of the usage agreement allows electronic presentation of films for educational, non-commercial purposes. It was confirmed with DIPEx that proposed use for quality improvement was within these constraints.

[22] Trigger films include short clips (in this case from patient and relative interviews and a staff focus group) that illustrate key discussion topics (or 'touch points') and are used to stimulate discussion in a wider group setting enabling identification of priority areas for change

4.4.3. Joint staff/patient event

Patients and relatives from the established OUH ICU Patient Forum were invited to attend. This group (which also includes nursing and medical staff from the AICU) also had input into the location, date and time. Posters (appendix B) were also displayed in the AICU visitor rooms. No speculative interest was received. Staff members were invited via a similar poster, and personal contact.

Sixteen people (patients, their advocates, intensive care nurses, doctors, and researchers) attended the meeting which was held at a neutral site (Eynsham Hall, Oxfordshire). This neutrality had two clear benefits. Firstly, it was not a place which patients or relatives would associate with their own experiences, thus limiting negative or post-traumatic feelings. Secondly, it ensured that clinical professionals would not be called away and would be able to give their full attention to proceedings.

For ease of viewing, the trigger film was presented as five segments, selected to match themes identified through secondary analysis of patient interviews: alarms, lighting, equipment, other people, and feeling overwhelmed. These were discussed individually and a flip chart was used to make notes of conversations between each segment. Comments and suggestions from each discussion were summarised and collated during the second half of the meeting to enable a comprehensive review of issues, risks, and potential solutions to the problem of high noise levels in the ICU.

Summary results from in-situ observation sessions, sound level measures, and patient and nurse completed sleep disturbances questionnaires completed as part of the NIHR RfPB funded study (described in chapter three) were presented separately. These data formed additional information to supplement the trigger film and enrich discussions.

Attendees were offered the option of dividing into groups to address individual key target areas but there was clear consensus to discuss all aspects under consideration as a single group. It was agreed that all follow up development work and local implementation would be undertaken by the research team. The senior members of the ICU staff team present confirmed they would encourage local support.

4.5. Results

The meeting attendees agreed unanimously that a cohesive package of changes was required to enable the ICU to become "quiet". Discussion focussed on the need to raise awareness of noise levels across all staff groups, associated effects on patients, and best ways to achieve this. It was also agreed there should be recognition that the intent was not to eliminate all noise, but to reduce *modifiable* noise that had been shown to affect patients.

It was universally thought that any intervention should be a multi-disciplinary collaboration with a high-visibility multi-modal approach that encouraged critical reflection on both an individual and team/organisational level. In particular it was felt that any measure introduced should encourage all staff to adopt an empathetic approach to environmental noise levels and patient sleep.

The group was keen to focus on objective sound levels as the primary outcome measure of any intervention introduced. Due to limitations of the physical environment only one bay in the AICU at the John Radcliffe Hospital could be actively monitored. However, it was clear that any measures introduced should be transferable to all ICU areas where possible. It was also agreed that any intervention should be easily sustainable and able to achieve results without frequent updates or reminders.

The group felt strongly that the participatory method (AEBCD) behind the decision-making process should be widely communicated during implementation to promote inclusivity. There was unanimous agreement that knowing patients and multi-disciplinary staff members had been involved would alter general staff perception, improving engagement with changes introduced to the ICU.

4.5.1. Suggested Interventions

A number of suggestions to reduce noise levels were put forward and discussed. These were:

Environmental

- Install commercially available illuminating screens to provide live noise level feedback
- Consider developing an improved display screen to visualise different aspects of environmental noise
- Replace metallic bins and apron rollers with plastic alternatives if available

Behavioural

- Encourage use of eye masks and ear plugs for patients as appropriate
- Re-orientate patients (remind them of time/date/where they are and why) frequently (possibly using the electronic record system checklist as a reminder)

Educational

- Raise awareness of how different activities create noise in the ICU
- Develop an alarms management policy to encourage critical thinking around individualising patient care within the context of the whole environment
- Enable staff members to experience the ICU from the patient perspective

4.5.2. Suggestions for implementation

The AICU is a busy and demanding environment with many conflicting priorities. Implementation of changes, delivery of teaching, and on-going monitoring would not be straightforward. Any new activity would therefore need to be easily incorporated into an already hectic schedule.

It was agreed that any electronic training resources should be incorporated into internal web-based systems to facilitate ease of use during a busy shift. This process would mirror access to other teaching materials available to staff, such as the OUH Trust mandatory training and ICU specific procedures and guidelines. Another common format for training delivery in the ICU is a series of short sessions delivered to small groups. This is known locally as 'espresso' teaching and is usually delivered during the mid-afternoon. This was a potential opportunity to deliver new noise-based training to staff.

It was agreed that any training package introduced needed to accommodate the different preferred styles of learning (active, theoretical, pragmatic, and reflective) [212] Suggestions to achieve this included use of statistics and evidence-based information, recordings of real ICU sounds, and patient interviews. A simple tutorial, whilst convenient to develop and deliver, would not have been sufficient, so a more sophisticated training package was needed. There was also a strong feeling that teaching should be grounded in the observations of local practices and sound levels.

The senior ICU staff members present at the meeting were keen to incorporate noise monitoring as part of daily assessment planning. Their suggestion was to use the 'group hug' (individual team briefing session held each shift) as an opportunity for discussing noise levels with a focus

on patient requirements. Proposed future changes to the 'group hug', which at present only involves the nursing staff, included bringing the full multi-disciplinary team together and using the time more efficiently to discuss patient needs and plans for treatment.

There was recognition that the AICU layout at the John Radcliffe is a barrier to good sound hygiene. It was built to different standards and building regulations in the 1970s and has since outgrown the original remit. It has many hard surfaces with little concession to acoustic management, and it is difficult to separate patients by level of care. Consequently, less unwell 'level 2' [213] patients will be in close proximity to those patients requiring 'level 3' [213] care. The clinical team were aware it was likely that level 2 patients experience higher levels of disturbance due to the care needs of more acutely unwell patients. It was agreed that organisational change on this level was outside the remit of this project but that information from this project may be put forward as supporting evidence for future changes in the clinical service in the Trust.

4.6. Follow up work

In the weeks immediately following the joint staff-patient event several work streams were progressed.

4.6.1. Replacement bins



Figure 4-1: SILENCE-branded plastic-topped bins

Waste bins with plastic lids were sourced almost immediately (Figure 4-1). These were procured from the Trust's usual supplier and adhered to all necessary fire and safety policies. For a small additional cost the study logo was printed on the lids. The purpose of this is two-fold. There is a constant visual reminder to be mindful of unnecessary noise, especially when using bins which were particularly mentioned by patients in their interviews and were witnessed to be unnecessarily noisy during in-situ observation sessions. The logos also raise awareness of the project as a whole. This was intended to help with local acceptance and adherence to later interventions, such as teaching sessions and engineering work associated with installation of the new sound monitoring and display system.

These bins were introduced to bay 'A' at the John Radcliffe Hospital adult ICU shortly before Christmas 2015. Local feedback was immediately positive with both staff and patients reporting a subjective improvement in the sound environment.

4.6.2. Alarm Management Guidelines

Nearly 20 years ago operating theatres were denounced as "*an ergonomic nightmare*" [214] and arguably this is still true of critical care environments today. Complexity lends itself to error because humans are fallible, particularly when under stress, in unfamiliar environments, or faced with pressured situations. The brain is a limited resource with a finite processing capacity. As sensory or cognitive demands increase, task-overloading can contribute to fixation bias or loss of situational awareness [215].

It has been recognised that increasing auditory stimuli impacts task performance. This is consistent with perceptual-load theory [216,217]. It is perhaps surprising that increasing workload in one sensory modality adversely impacts perceptual ability in another [218-220]. That perceptual resources are not modality-specific but seem to be spread across all incoming stimuli is highly significant in the ICU where relevant information can originate from multiple sensory sources. Simultaneously reducing distractions from unnecessary noise may make care safer as well as more pleasant.

In the context of increasingly complex patient care needs and multiple alarms in the ICU, which have increased significantly in recent years [221], the concept of inattentional deafness [204] is a reality, and was witnessed during observation sessions (chapter three).

Alarm management guidelines are recommended by a number of organisations including the American Association of Critical-Care Nurses (AACN) and the Association of Anaesthetists of Great Britain and Ireland (AAGBI). Their primary purpose is to reduce alarm fatigue and improve patient safety [222]. Alarm guidelines have also been shown to reduce noise levels [223]. Guidelines that encouraged customisation of default limits lowered critical monitor alarms by 43% from baseline, reducing opportunity for alarm fatigue to become established [224]. Desensitisation [225], the effect of being in a constant barrage of noise, and corresponding reduction in alarm response has been recognised as the leading hazard faced by hospitals in the United States [105]. This is clearly not solely a North American problem as evidenced by examples of inattentional deafness witnessed during observation sessions for this project.

Following the joint staff-patient event, a nurse based in the Critical Care Research Group (EJ) drafted alarm management guidelines. This was supervised by the lead researcher (JD). To ensure appropriate clinical input, senior members of the AICU nursing team reviewed and amended the draft guidelines before releasing the final version in early February 2016 (appendix E).

4.6.3. Teaching package

The observations and discussions (chapter three) revealed that staff had only superficial understanding of sound levels in the ICU. To maximise engagement, a comprehensive teaching package was developed in line with best practice in adult learning. The teaching package combines an online module and an in-situ experiential simulation exercise. The combined package focuses on the patient experience of ICU.

The online module includes excerpts from the patient interviews and a journal publication about sleep in the ICU. Staff are also encouraged to reflect on their own practices in relation to how their patients might experience their stay in the ICU.

The experiential simulation offers staff the opportunity to experience the ICU from the perspective of a patient. This part of the training has been particularly popular.

The design and development of teaching materials and curriculum is explored in full in chapter five.

4.6.4. Noise level display

A new noise level monitoring display was created for the ICU following recommendation from the AEBCD group. Acoustics expertise to build the data collection system was contracted from the University of Southampton (Institute of Sound and Vibration Research). The data collection system and sound level results are described in chapter six.

Specification for the display included identification of the originating source (location) of noise and an indication of how sound levels change over time. The interface was designed using

industry standard user experience methods. Software programming expertise to translate the design specification into a working prototype was contracted from Oxford Computer Consultants. The design and development of the AICU sound levels display is explored in more detail in chapter seven.

4.7. AEBCD 'celebration'

The final stage in the AEBCD process is to report, evaluate, and celebrate success [153,183]. Post-intervention data were presented to the OUH ICU Patient Forum on 21 June 2016. This included all patients and relatives and two of the members of staff who attended the meeting in July 2015.

The presentation included a description of how the teaching package had been developed, how it was being delivered, and feedback that had been received. The group was also presented with 'before' and 'after' sound level data (Table 4-1). These show a demonstrable reduction in both average and peak sound levels during the day (06:00 – 21:59) and overnight (22:00 – 05:59).

The group was delighted that their input had been so well received, had been relatively straightforward to implement, and, perhaps most importantly, appeared to have contributed to reduced noise levels in the intensive care unit. Plans for the noise level monitoring display were also outlined.

	Baseline	**Post-intervention**
No of days	86	70
LAeq median (IQR)	57.0 (3.2)	53.2 (5.1)
LAeq min	53.0	44.4
LAeq max	63.3	91.8
LC peak median (IQR)	110.3 (5.8)	78.0 (2.2)
LC peak min	104.6	68.5
LC peak max	124.8	115.3

Table 4-1: Interim sound level results after implementation of complex intervention

Non-parametric tests of independent samples indicate a significant reduction ($p<0.001$) in both median LAeq and LCpeak values[23] between baseline (April – July 2015) and post-intervention (January – April 2016) periods.

[23] LAeq is the A-weighted sound level for a given period of time. The 'A' weighting adjusts the raw decibel value to more accurately reflect how humans perceive sound (higher frequencies seem louder). 'C' indicates an alternative weighting system appropriate for sudden loud sounds, appropriate for reporting peak values.

4.8. Strengths and Limitations

Strengths

- Delivering interventions that had at least in part been designed by patients and staff increased local acceptance
- Environmental modification is a stronger intervention than simply providing more training
- The training delivered was designed and developed in line with adult education theory

Limitations

- Sound level analysis for this initial phase was based on environmental health guidelines and was therefore limited to comparison of simple values
- The clinical team were not allocated time outside of their routine clinical rota to participate (either in preparatory sessions or follow up work). This lack of facilitated engagement meant the intervention development and delivery became the responsibility of the research team. Ideally this is work that would have been taken on and owned by sub-groups of staff and patients.

4.9. Conclusions

The principles behind the AEBCD method were strongly supported. Including patients and staff in discussion encourages 'buy-in' from hospital management. Both staff members and patients (informally) reported high levels of satisfaction after the half-day meeting. The AICU readily accepted the implementation of suggestions from the AEBCD session. The AEBCD process shows promise as a method for change in the intensive care setting. It may be a successful method for quality improvement in the NHS more widely.

4.10. Dissemination and impact

4.10.1. The Kings Fund

Lisa Hinton presented the AEBCD work at The Kings Fund: Transforming patient experience (November 2015), *Patients and staff join researchers to design environmental changes in the Intensive Care Unit*, Julie L Darbyshire, J Duncan Young, Carolyn Barrett, Peter Edmonds, Lisa Hinton.

4.10.2. British Association of Critical Care Nurses

Julie Darbyshire delivered an oral presentation to the 31st Annual British Association of Critical Care Nursing Conference (September 2016), *Patients and staff help design experiential teaching for the Intensive Care Unit*, Julie L Darbyshire, Peter Edmonds, Nadeem Khan, Lisa Hinton.

4.10.3. Intensive Care Society

Julie Darbyshire delivered a poster to the Intensive Care Society State of the Art conference (December 2016), *"Deep experience is never peaceful": Raising awareness of noise sources in the Intensive Care Unit*, Julie L Darbyshire, Peter Edmonds, Lisa Hinton, J Duncan Young.

Julie Darbyshire was invited to speak at the Intensive Care Society State of the Art conference (December 2017) ***Lights, sound, action!*** *Noise in the ICU and the SILENCE trial* (panel session with Hugh Montgomery and Danny Bryden, chaired by Dorothy Wade)

4.10.4. DIPEx International

Lisa Hinton presented the AEBCD work at the International Conference on Narratives of Health & Illness (Tenerife, November 2016)

4.10.5. Journal of Health Design

The Journal of Health Design published a short article written by Julie Darbyshire and Lisa Hinton based on using the DIPEx patient narrative interviews as a springboard for service improvement in healthcare (June 2018). Darbyshire JL, Hinton L., Using patient narratives to design an intervention to reduce noise in the intensive care unit. JHD. 2018;3(2):109-112. doi: 10.21853/JHD.2018.51.

4.10.6. Local adoption

The Oxford University Hospitals NHS Foundation Trust Patient Experiences Group requested assistance in the development of their own 'noise at night' intervention. This was initiated in the local Trust as a response to the results of the national patient feedback questionnaire [226] in which patients consistently reported that the wards were unacceptably noisy, especially overnight.

The experiential session and e-learning module were both made available to other intensive care units in OUH. These cohorts of staff from the Cardiac ICU and Neuro-ICU have contributed to ongoing assessment of knowledge transfer and acceptance of training materials.

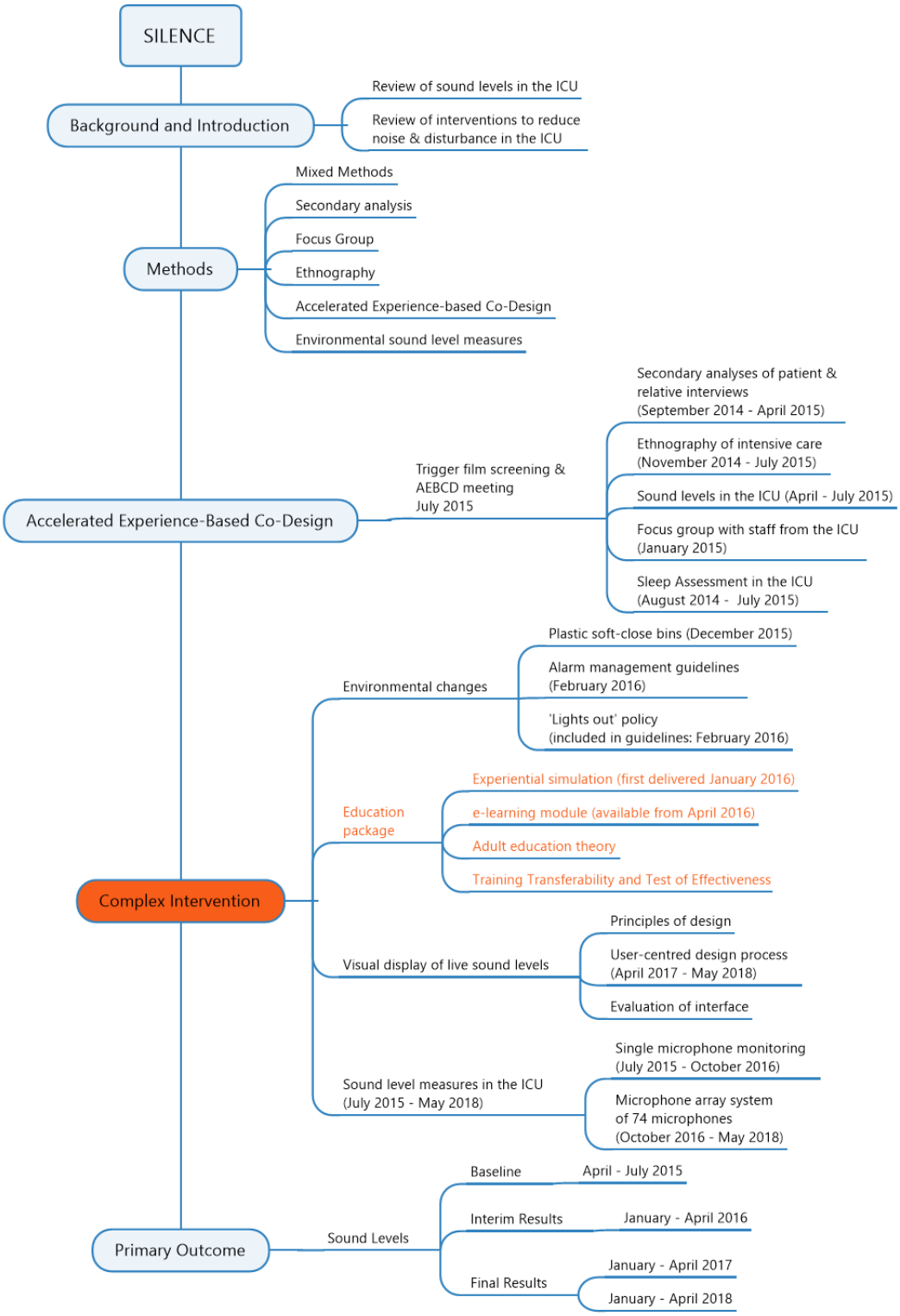
4.10.7. External interest

CW+ (the charity for Chelsea and Westminster Hospital NHS Foundation Trust) are in the process of redeveloping their intensive care units at the Chelsea and Westminster Hospital. They approached us to discuss how we might be able to share both the teaching pack, and the bespoke noise visualisation display.

Kings College, London invited the SILENCE team to their multi-disciplinary HPNoSS (Hospital Project on Noise Sound and Sleep) symposium in September 2017 to explore environmental noise reduction possibilities in more detail [227].

5. Chapter Five: Design & development of teaching package

5.1. Chapter summary



This chapter describes the development of teaching materials and training programme suggested at the AEBCD meeting in July 2015. Other practical outcomes from that meeting have been outlined in chapter four.

This chapter starts with an overview of adult education theory and the importance of having a well-defined course structure and purpose (section 5.3). Sections 5.5.1 to 5.5.4 describe how these background principles influenced the design, development, and implementation of training.

Finally sections 5.4.4 and 5.5.5 address the value of considering course evaluation, assessment of impact, and gathering evidence of knowledge transfer or behaviour change.

The educational materials were also trialled in a naïve population at another institution (Yeovil District Hospital). This enabled insights into their transferability and generalisability and also included sound level monitoring to test efficacy of the training. The evaluation at Yeovil is described in sections 5.4.5 and 5.5.6.

5.2. Aim

The teaching package was developed in response to the AEBCD request for wider staff awareness of the problems of high noise levels in the intensive care unit (ICU). The aims of the teaching were to increase knowledge of noise levels in the ICU, to help staff understand the effects that high noise levels can have on patients, and also how to modify personal contributions to overall noise levels.

5.3. Background

In contrast to children, adults require internal motivation to learn. They are independent and tend to be self-directing in their learning. Modern adult education theory is underpinned by constructivist philosophies which support multiplicity of meaning and understanding [228]. For adults the teacher role is to guide and facilitate learning, rather than to transmit knowledge. This requires curricula to be 'learner-centred' [229], placing the focus of teaching on student needs. This allows learners to take an active role in their own education but requires the use of a range of teaching modalities to enable effective learning across the diversity of adult learners. A variety of approaches accommodates differences in individual needs and preferences.

Adult educational theory [230] advocates a problem-centred approach and acknowledges the social processes that facilitate active engagement [229,231,232]. Adult teaching utilises prior experience as a resource for learning [233].

The process by which adults assume new information can be visualised using Kolb's learning cycle (Figure 5-1). This describes a cyclical progression of experience during which learners assimilate knowledge through reflection. This reflection might include consideration of how successful they were at achieving goals, what enabled success, or what barriers were faced. Learners then experiment with new approaches before attempting the experience again; identifying gaps in their knowledge, understanding, or experience, and methods to overcome these. Importantly, this process can begin at any of the four steps.

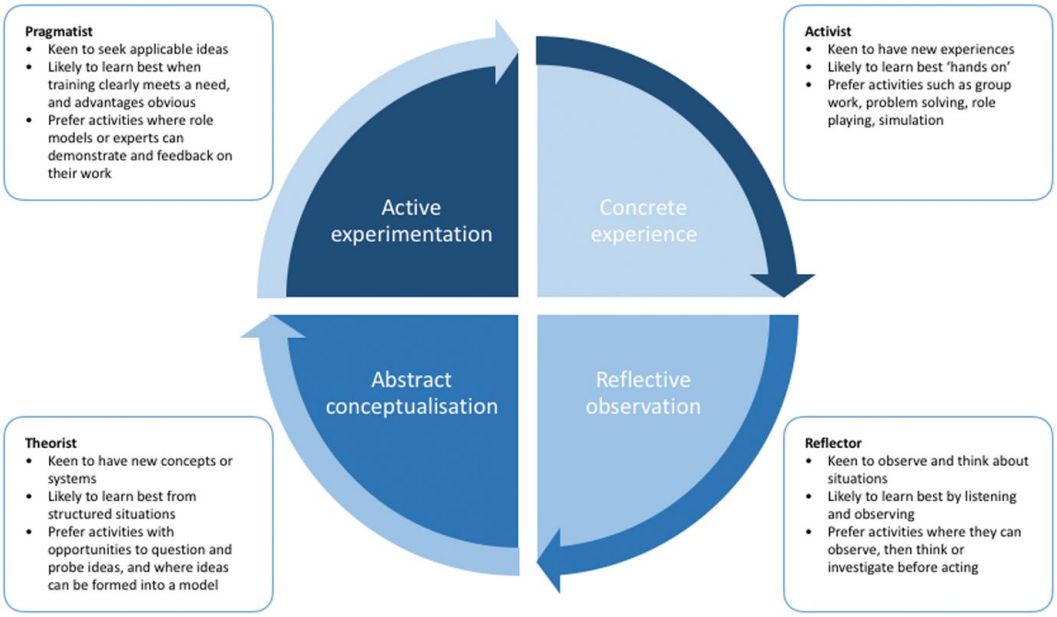


Figure 5-1: Kolb's learning cycle (reproduced from Greig PR, Darbyshire JL Medical Educational Theory in Practice *BJA Education* 2019; 19(2): 40-46)

Adult learners approach learning in different ways. One of the most widely used descriptions of learning styles was created by Honey and Mumford [212] which categorises learners into activists, pragmatists, theorists, and reflectors.

Few learners fall solely into a single category, but most exhibit a preference. Although learners can adopt non-preferred learning styles, understanding innate preference is useful to inform teaching styles for different audiences. Stereotypically, activists prefer 'hands-on' learning, will quickly engage and explore materials to discover potential application and limits. Pragmatists need to understand advantages of a new approach, and how to integrate knowledge into working practices. Theorists need to understand underlying principles or scientific theory, while reflectors benefit from time to observe or consider how to adapt knowledge for themselves. These preferences map to Kolb's learning cycle where each learner-type is likely to feel most comfortable (Figure 5-1).

Extending the Honey & Mumford concept, Fleming's 'VARK'[24] system [234] also describes preferences for learners' interaction with learning materials. As with Honey & Mumford learning style preferences these are not mutually exclusive, and learners can benefit from receiving materials in non-preferred formats, but providing materials in a range of formats will maximise inclusivity and engagement.

It is important to consider these preferences when designing education packages because undue focus on one preference may cause disengagement, boredom, or discomfort amongst learners with different, or opposing preferences. A key barrier to delivering training for adults in

[24] VARK: 'visual materials' (images, diagrams, or graphs); 'auditory materials' (lectures, podcasts, discussions); 'read materials' (textbooks, journal articles, blogs); and 'kinaesthetic materials' (simulation, part-task trainers, supervised practice)

healthcare is that clinical staff have limited time for tasks outside of their clinical duties. It is essential that new training packages are designed to meet needs as efficiently as possible.

The first step in developing training is to consider the intended aims, and from there develop a curriculum (sections 5.4.1 and 5.5.1). The curriculum describes a programme of study in detail for both learner and trainer [235]. It incorporates an overview of the materials, the ethos and purpose of the course and an indication of how information will be shared, and how learners will be assessed. A curriculum includes the aims, objectives, and outcomes of the course. Aims are high level statements of intent. They guide both learner and educator to understand the purpose of a learning exercise. Objectives describe how aims will be achieved. Outcomes are focused on the learner and explain specifically what the learner will be expected to be able to do on completion of the training.

A clearly documented curriculum offers confidence that teaching delivers a suitable breadth and depth of knowledge, whilst also demonstrating the range of material covered. This allows learners to judge if the training course is suitable for their needs, and sets expectations for teaching and assessment.

The importance of the curriculum on assessment development is often overlooked, but it is a critical tool that enables robust development of the educational package, and is required to create reliable, valid assessment. A well-written curriculum facilitates decisions to be made about how achievement will be measured. This process of assessment-creation is visualised most often through 'blueprinting' [235,236]. This provides a structure by which curriculum content is mapped to levels of knowledge that learners are expected to achieve. More specifically, blueprints outline the scope, complexity, and cohesion of the curriculum. It also allows systematic assessment of the curriculum and can be used to ensure a representative breadth of the curriculum is sampled at appropriate depth for assessment.

In addition to its role in measuring educational attainment, assessment can also motivate learners [237]. Most healthcare professionals have a revalidation process for which they must demonstrate engagement with continuing professional development (CPD). Robust assessment tools benefit both educator and learner; educators can have certainty of demonstrable progress, and learners gain evidence they are engaging with and meeting training and CPD requirements.

Defining objectives and outcomes for a course is not necessarily straightforward. When drafting statements of intent the level of depth expected of learners in each area needs to be considered, and also how learners might be expected to demonstrate increased knowledge or skill. Bloom's Taxonomy can be used to match intent of an objective with the wording of its associated outcomes (Figure 5-2).

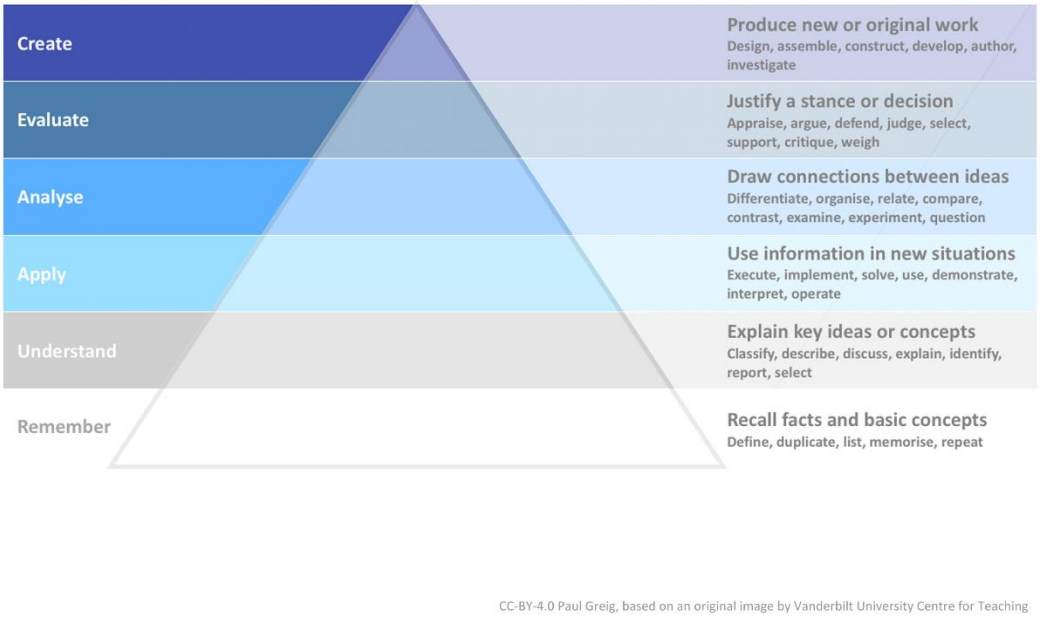


Figure 5-2: Bloom's taxonomy (reproduced from Greig PR, Darbyshire JL Medical Educational Theory in Practice *BJA Education* 2019; 19(2): 40-46)

The taxonomy was originally developed to facilitate demonstration of knowledge acquisition more broadly than simple factual recall [238]. Learning linked to professional competency requires students to apply knowledge to new situations. They should be able to analyse and evaluate data appropriately, and possess sufficient familiarity with a topic to create new material, or practical application of new knowledge. Choosing to frame learning outcomes using verbs from higher levels of the taxonomy communicates these requirements to learners.

5.4. Methods

5.4.1. Curriculum development (Learning aims, objectives, and outcomes)

Multimodal techniques were used to design the educational intervention. Understanding that adult learners prefer to define their own learning requirements, the aims of the teaching package were defined using those specified by the AEBCD group, which included both staff and patients.

The research team consulted an adult educationalist (PG) to set individual learning objectives and outcomes to meet the broad aims. These were to improve understanding of noise and to develop possible interventions to mitigate its effects (section 5.5.1).

After appropriate learning objectives and outcomes had been written, a blueprinting exercise was undertaken to ensure the breadth and scope was appropriate (Table 5-2). This mapped each learning objective to course content, then weighted each according to the frequency with which the topic was encountered in clinical practice and the degree of supporting scientific rationale This enabled objective assessment of individual item importance.

5.4.2. Developing the training package

Training materials were developed once learning objectives and outcomes had been specified. Two main components to the educational materials were specified: an e-learning module and an experiential learning session.

The e-learning module

The e-learning module presented a summary of environmental sound monitoring with specific reference to hospitals and presented a graph of sound level data recorded at the John Radcliffe AICU. These data were collected in the early stages of sound monitoring work (chapter three). The data provided a realistic context drawn from local, UK-based NHS practice. Also included was a brief summary of sleep science (specifically how it can differ between healthy people and critical care patients), a journal article about the impact of sleep disturbance on patients in the ICU, summary results of the observations completed in OUH ICUs (chapter three), five short film clips created for the AEBCD trigger film (chapter four), and an image of an ICU patient monitor highlighting how to control volume. The module also included free text responses to encourage mental and emotional engagement with the exercises: staff are encouraged to reflect on their own clinical practice and suggest ways to reduce sound levels to improve the patient experience of their stay in ICU.

The e-learning module also included self-assessment questions. Answers (and explanations) were provided to facilitate 'reflection in action'[25] [239].

The experiential simulation

A short experiential session was an attempt to mirror the patient experience as closely as possible for a healthy volunteer, whilst remaining psychologically and physically safe. It also had to be time-efficient, and practical to deliver in the busy clinical environment. This catered for activist and kinaesthetic learners in particular, broadening the reach of the training. See appendix C for guidelines produced to enable third party delivery of the simulation session.

Participants were asked to lie on a bed in the ICU to experience a series of simulated interventions typical of patient care. Individuals were slightly restricted by a simulated peripheral venous line (an IV giving set secured by tape to their arm and bedside). The participants' knees were raised to reduce freedom of movement, and some physiological monitoring was attached. Typically this was a finger-worn oxygen sensor and blood pressure cuff on the upper arm, both connected to standard bedside pendant systems. Whilst attachment of ECG leads might have added realism, this was impractical and unduly intrusive for staff wearing normal workplace clothes.

Those in normal physical health would not expect monitoring alarms during their experience. Alarm limits were manipulated to ensure they triggered during the experience. The oxygen alert was, for example, set to alert at 99%. This was intended to mirror the patient experience of uncertainty, related to unpredictable alarms possibly indicating a developing problem.

Participants wore glasses (Optima Low Vision Services Ltd, Totnes, Devon) to replicate visual impairment experienced by many patients admitted to the ICU. They also listened (through earphones) to common sounds associated with preparing for an intra-hospital transfer. This soundtrack was created initially using a standard mono recording captured by non-directional microphones, and later re-recorded using a binaural recording system (R-05, Roland UK, Swansea) in response to feedback from early participants. The binaural system captured spatial localisation of sound sources enabling accurate simulation of sounds moving around when played through stereo headphones. The recording was scripted from common tasks witnessed during ethnographic observations, or drawn from patient reports, and was recorded in the simulation suite at the Oxford Simulation, Teaching, and Research Centre.

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[25] The conscious act of thinking about processes and activities, recognising positives and negatives to inform improvement

While this recording played, those delivering the training moved around the bed space mimicking nursing care and related tasks. Examples of disturbances included: running water/paper towel use, bin-lid operation, doors/drawers opening/closing, opening of packaging, aprons pulled from a dispenser, trolleys moving, bed rising/lowering, lights switched on/off, and 'patient' re-positioning, sometimes without explanation. The 'patient' could hear live activities, including their own alarms, alongside the recording playing through their earphones.

The AICU in Oxford supports workplace-based teaching, and has created a window (15:00 - 17:00) each day which can be used for training. This generally coincides with lulls in clinical workload, when clinical staff have finished early afternoon care activities and before afternoon ward rounds begin. These training opportunities are subject to the demands of clinical need but provide a practical opportunity to capture clinical staff in their own environment. The nature and duration of the experiential package made it ideal for these ad-hoc sessions.

5.4.3. Developing assessment materials

For this training package, assessment comprised an initial series of questions designed to focus thoughts on the ICU environment, followed by true-false type multiple choice questions (MCQs). There were no limits to the number of attempts or time taken to complete assessment, and it was not negatively marked. The assessment scored up to 31 marks and was formative [240]. It was intended that the assessment take less than 10 minutes to complete.

Questions were mapped to learning outcomes (Table 5-1) according to the blueprint (Table 5-2), and reflected learning intent derived from Bloom's Taxonomy.

5.4.4. Course evaluation

Following experiential sessions participants were asked to complete a short questionnaire (appendix C). This provided feedback and facilitated reflection on learning. The questionnaire comprised five questions and took less than five minutes to complete. Participants used five-point Likert scales calibrated from 'strongly agree' to 'strongly disagree' to respond to statements such as 'I found the session useful', and 'I felt the immersive session recreated the patient experience well'.

The questionnaire also included a 'word cloud' derived from words patients have used to describe their experience in the ICU. These were extracted from interview transcripts that formed the basis of the secondary analysis (chapter three). Participants were asked to indicate which, if any, resonated with them following their experience. A final free text box invited suggestions for improvements to the experience.

5.4.5. Independent site evaluation

A sub-study was conducted at Yeovil District Hospital NHS Foundation Trust (YDH). This tested the complex intervention at a naïve site. The e-learning was available electronically, and local staff were trained to deliver the experiential session.

Sound levels were measured using a single point environmental monitoring microphone. This was fixed to a central location in the unit from 7th February to 7th May 2018. 'A' weighted decibel values were taken in 'fast' mode using CEL-630 portable sound level monitors with integral recording fitted with a CEL-495 preamplifier and a CEL-251 microphone (Casella Measurement, Kempston, UK). The environmental monitor was calibrated (CEL-120/1; Casella Measurement) and recorded continuously in 24-hour 'blocks' for the full duration. Every minute, the device recorded peak noise levels (LCpeak) and an averaged sound level (LAeq) from the preceding minute.

The e-learning module (without simulation or sound level monitoring) was offered to the AICU staff at the Queen Alexandra Hospital, Portsmouth. This increased numbers of participants completing the online module.

5.5. Results

5.5.1. Learning aims, objectives, and outcomes

It was agreed by the AEBCD group that the practical 'problem focus' for training should be 'sleep' as this was consistently the key complaint raised by patients through the interview transcripts (chapter three). The primary intent of the training was to raise awareness and increase knowledge of noise levels in the ICU, and to improve staff understanding of the effect that noise can have on their patients. Secondary aims were to provide specific information to enable staff to reduce their personal contributions to noise levels and construct their own systems to monitor and manage noise levels in the ICU.

Using recommendations with regard to course aims, learning objectives were planned (Table 5-1). The verb (in **bold**) specified in the learning outcome determines the level of understanding expected.

Learning objectives for the learning package

Objectives	Learning outcomes
• Increased knowledge of noise levels in the intensive care unit	• **Define** the World Health Organisation (WHO) guidelines for sound level limits in the intensive care environment • **Explain** what is meant by 'LAeq' and 'LCpeak' • **Interpret** LAeq data from the OUH AICU sound monitoring data provided and compare how local ICUs perform against the WHO standard
• Understand the effect that noise can have on patients	• **Describe** the ways in which patients can be affected by noises in the ICU • **Define** the five stages of sleep described by Rechtschaffen and Kales • **Compare** normal healthy sleep with the sleep experienced by the AICU patient
• Understand how to reduce personal contribution to noise levels	• **List** ten sources of loud noise in the AICU • **Describe** five practical changes in delivering care that can reduce noise levels • **Design** and conduct a noise risk assessment in the AICU

Table 5-1: Course learning objectives

The blueprinting exercise grouped learning objectives into one of three content areas; environmental monitoring (EM), local noise patterns (LNP), and sleep architecture (SA) (Table 5-2). This indicates the importance allocated to each area of the curriculum.

Blueprint of the course curriculum

Domain or Content Area	Importance	Frequency	Importance x Frequency	Weighting	Learning outcomes		
					Basic science	Working practice	Practical Measures
Environmental Monitoring (EM)	1	3	3	19%	Define LAeq	Define WHO guidelines	List environmental features that can be monitored
					Define LCpeak	List examples of simple working practice changes to reduce noise levels	
Local Noise Patterns (LNP)	2	2	4	25%	State local values for LAeq	Conduct a noise risk assessment in the ICU	Explain which noise sources could be most disturbing
Sleep Architecture (SA)	3	3	9	56%	Define the five stages of sleep	Describe how to maintain a normal circadian rhythm	List methods of measuring sleep
					Describe the effects of sleep disruption	Describe how to minimise sleep disruption overnight	

Importance		Frequency	
3	Conclusively proven effect on patient	3	An everyday task
2	Suspected effect on patient	2	An occasional task
1	Possible effect on patient	1	Seldom performed task

Table 5-2: Blueprinting the course learning outcomes

5.5.2. e-learning

The e-learning module was made available to staff at three participating sites: Oxford University Hospitals NHS Foundation Trust (OUH); Queen Alexandra Hospital, Portsmouth Hospitals NHS Trust (QAH); and Yeovil District Hospital NHS Foundation Trust (YDH).

The e-learning was accessed on 239 unique occasions. Nurses (registered and student) were the largest staff group (n=209) to access materials, followed by doctors (n=9), healthcare assistants (n=7), and non-clinical staff (n=4). Ten members of staff did not specify professional background.

The system was accessed for at least one minute by 229 [96%] individuals. Access time was not normally distributed (Shapiro-Wilk test $p < 0.001$). The median access time was 18 minutes (IQR 7 - 43.5). Access time did not significantly differ between professions (p=0.7). Usage statistics are summarised in Figure 5-3.

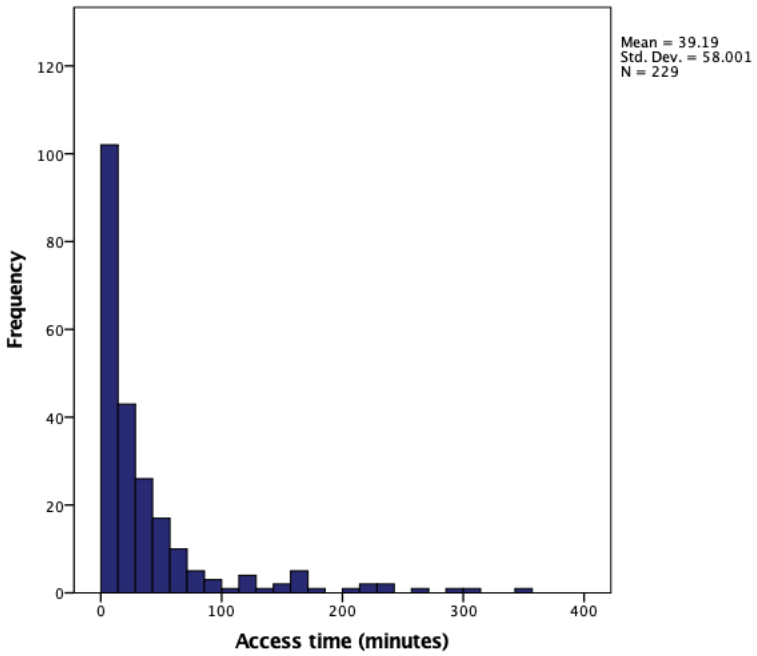


Figure 5-3: E-learning usage statistics

5.5.3. Experiential simulation

Due to limited local resources, experiential teaching was delivered only at OUH and YDH. In total 182 members of staff were trained, 173 (95%) of whom at least partially completed an evaluation questionnaire (section 5.5.5). This equates to approximately 45 hours of training delivered.

5.5.4. Assessment

The assessment was accessed on 256 unique occasions, with 207 [81%] people following through to completion. There was a significant association between site and assessment completion rate (p=0.002), with staff at YDH most likely to complete the assessment on their first attempt. Completion rates by Trust are detailed in Table 5-3. There was no significant association between professional background and assessment completion (p=0.461)

Course completion rates by organisation

Trust	Complete	Incomplete	Total
OUH	127 [74.7%]	43 [25.3%]	170
YDH	67 [93.1%]	5 [6.9%]	72
QAH	13 [80.9%]	1 [19.1%]	14

Table 5-3: Completion rates by Trust; OUH = Oxford University Hospitals, YDH = Yeovil District Hospital; QAH = Queen Alexandra Hospital

Of the assessments that were completed, the system was accessed most frequently by registered nurses (n=162 [69.2%]). There was a significant association between site and professional background of participants ($p < 0.001$) with a greater proportion of non-nursing professionals completing the course in Yeovil. These data are summarised in Table 5-4.

Course participants by professional background

Trust	Registered Nurse	Healthcare Assistant	Doctor	Other AHP
OUH	110 [86.6%]	2 [1.6%]	13 [10.2%]	2 [1.6%]
YDH	43 [64.2%]	6 [9.0%]	4 [6.0%]	14 [20.9%]
QAH	9 [69.2%]	0 [0%]	4 [30.8%]	0 [0%]

Table 5-4: Participants by professional background

The time taken to complete the assessment was not normally distributed (Shapiro-Wilk test $p < 0.05$) so non-parametric methods were used to evaluate data. The median (IQR) time to complete the assessment was 7 (5 - 11) minutes. This did not vary significantly between professional groups (p=0.167). The minimum time to complete was 2 minutes, while the maximum time was recorded as 1201 minutes[26].

There were 31 questions in the assessment, each worth one mark. The assessment was not negatively marked. The final assessment score was not normally distributed (Shapiro Wilk p=0.03), so comparisons were made using non-parametric methods.

Test score varied with participant background, with the highest scores achieved by non-nursing allied healthcare professionals, while healthcare assistants achieved the lowest scores ($p < 0.05$). These data are summarised in Table 5-5. No candidate answered all questions correctly.

Assessment scores by professional background

Professional Background	Median	IQR
Nurse	19	12 – 26
HCA	18	17 – 20
Doctor	20	15 – 25
Other AHP	21.5	18 – 28

Table 5-5: Assessment scores by professional background

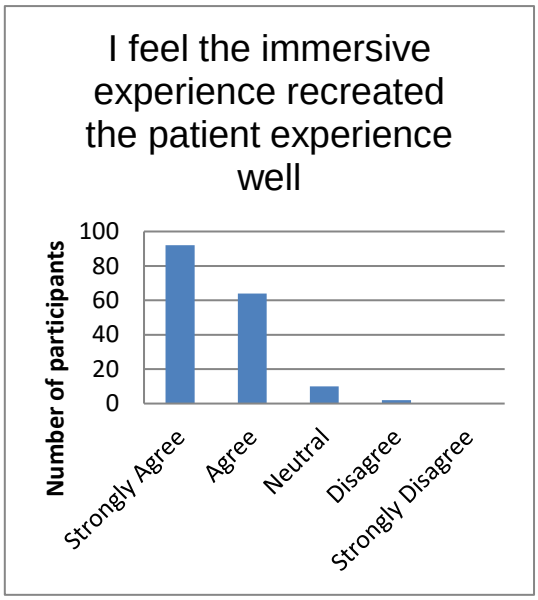
There was a significant increase in scores after completing training (p=0.01). The median pre-course score was 19 [IQR 12 - 26] versus 21.5 [IQR 18 - 28] post-course. Participants who completed the assessment having only completed one of the two training modules also saw their scores increase, although not significantly. Those who completed only the e-learning module achieved a median score of 20 [IQR 15 - 25, p=0.003], while those who completed only the experiential session achieved a median score of 18 [IQR 17 - 20, p=1.0]

[26] This is likely to be someone who left the browser open rather than taking 20 hours to complete the assessment. Non-parametric statistics were used to account for outliers.

5.5.5. Course evaluation

A total of 173 feedback questionnaires were at least partially completed after experiential sessions. Numbers of responses varied by question. All staff (168/168) reported they thought patients undergo significant stress whilst in the ICU and 161/169 (96%) thought staff could do more to reduce stressors in the environment for their patients. The majority [156/168 (93%)] felt the experience recreated the patient experience well and 167/169 (99%) reported they found the experience useful; 165/169 (98%) said they would change their practice having had the opportunity to experience the ICU from the patient's point of view. Part of the questionnaire asked staff to indicate how they felt. Almost half of those responding felt stressed (n=77 [45%]), confused (n=78 [45%]), and uncomfortable (n=82 [47%]) during the experience and more than a third were worried (n=64 [37%]), frightened (n=72 [42%]), and thought the experience was distressing (n=49 [28%]), reporting they felt afraid (n=44 [25%]) and alone (n=72 [42%]).

Staff were asked to suggest specific ways in which they would consider changing their behaviour. Of the 277 responses (multiple responses per participant), 12% were to reduce unnecessary patient interaction and 36% were to reduce disturbance from noise (specifically 9% to reduce alarm volume, 8% to reduce verbal volume, and 4% referred generically to reducing noise from equipment). Almost a third of responses (29%) were suggestions to reduce the startle effect of loud noises by increasing reassurance to patients during their ICU admission. These data are summarised in Figure 5-4 and Figure 5-5.





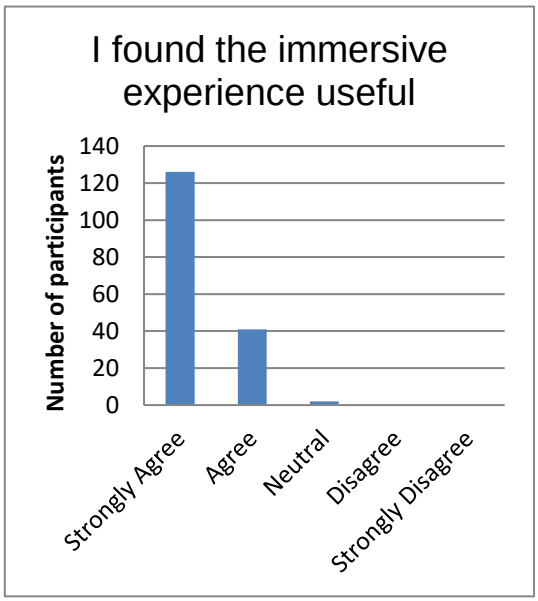


Figure 5-4: Feedback from the immersive educational experience



Figure 5-5: Word-cloud responses from 173 participants after the immersive educational experience

5.5.6. Independent site evaluation

Yeovil District Hospital NHS Foundation Trust (YDH) undertook a local quality improvement project using the teaching materials developed for this project. The overall purpose of the quality improvement project was to reduce sound levels in the ICU. The sound level results are presented here.

The overall mean (SD) LAeq24 for the YDH ICU over the full monitoring period was 59.1 (7.0). The lowest sound recorded was 46.3dB. LCpeaks were regularly >100dB (Figure 5-6). The highest peak sounds occurred at the start of the recording period in February. The loudest LCpeak was 142.3dB at 18:23 on 20th February. The mean (SD) peak value during the day (06:00-21:59) was 81.3 (4.7) vs 79.5 (4.1) overnight (22:00 – 05:59).

Of the 7.2 million data points, approximately 2.4 million were overnight. Over the full recording period mean (SD) sound levels overnight were 56.97 (6.6). This is significantly quieter ($p<0.001$) than during the day when mean (SD) levels were 60.2 (7.0) (Figure 5-7).

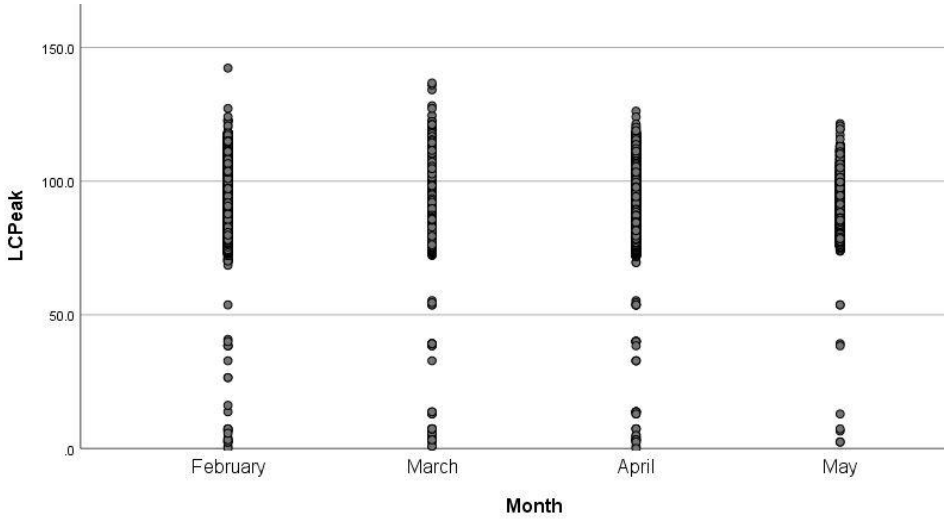


Figure 5-6: LCpeak values by month

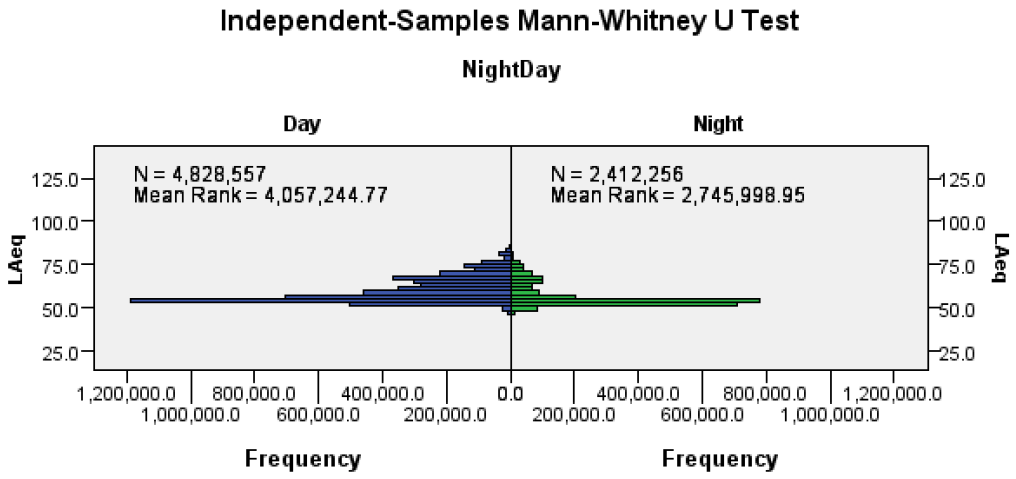


Figure 5-7: Comparison of sound levels (LAeq) by day and night

Sound levels differed significantly (p=<0.001) between each month (Table 5-6):

Sound level monitoring results (dBA)				
Month	N	Mean (SD)	Minimum	Maximum
February	1,782,641	58.05 (7.19)	47.7	110.6
March	2,505,576	60.57 (7.55)	49.5	103.8
April	2,409,309	58.57 (6.39)	46.3	94.9
May	543,287	58.34 (4.98)	49.4	90.4

Table 5-6: Outline results of decibel values

Sound levels also differed significantly by day of the week (p=<0.001) with mean values being higher midweek (Table 5-7 and Figure 5-8).

Sound level by day of week		
Weekday	n	Mean (SD) dBA
Sunday	1,241,632	58.93 (7.04)
Monday	933,909	58.68 (6.60)
Tuesday	760,559	59.68 (7.14)
Wednesday	1,271,137	59.67 (7.31)
Thursday	802,217	59.53 (6.83)
Friday	1,143,857	58.98 (6.90)
Saturday	1,087,502	58.50 (6.98)
Total	7,240,813	59.12 (7.00)

Table 5-7: Number of sound level values and comparison of means (SD) by day of week

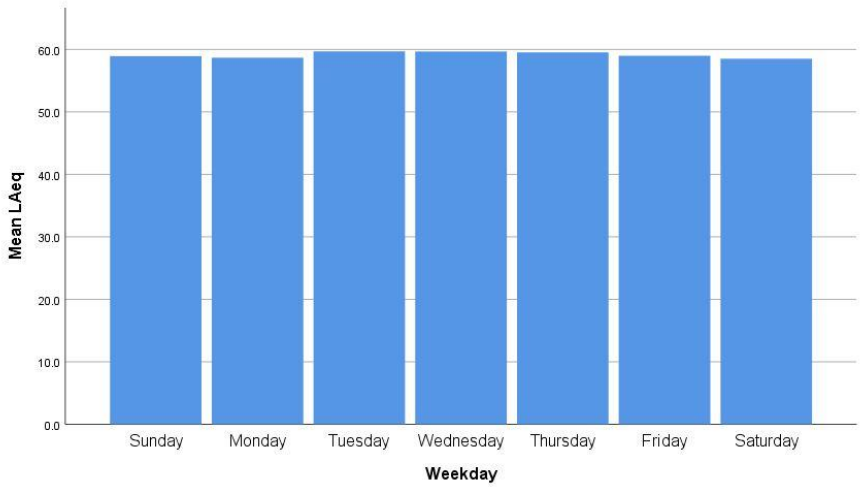


Figure 5-8: Mean LAeq by day of the week

The training delivery team at YDH also created their own alarm management guidelines (appendix E).

Feedback from the YDH team was that the quality improvement project was both fun and worthwhile. There was considerable enthusiasm from the general staff group to take part in the training sessions leading to good rapport and morale boosting within the team. Although the number of staff who completed the assessment after training was low, the increase in demonstrated knowledge for those who did attempt the quiz seems encouraging.

5.6. Discussion

To ensure training was focussed appropriately, considerable effort was put into determining aims, objectives, and outcomes for the programme as a whole. In this context, aims set out the high-level intentions of the intervention. These were established by the staff and patients in the AEBCD group. Their input ensured the training was relevant to, and met the needs of, both the patients and those caring for them.

However, aims alone are not sufficient to frame teaching. More specific learning objectives and outcomes need to accompany the broader 'aim' statements. These highlight the exact areas of knowledge, skills, or attitudes (KSA) that students are expected to develop, and how achievement will be demonstrated [241]. Objectives and outcomes are necessary when developing materials and delivering teaching as they explicitly state behaviours and skills that training is intended to modify.

The learning outcomes (Table 5-1) use action verbs from Blooms Taxonomy (Figure 5-2) at a range of levels. These make it clear that learners are expected to be able to demonstrate skills and abilities beyond the relatively simple recall of basic facts.

Blueprinting (Table 5-2) confirmed that curriculum and associated domains were appropriately diverse, and that topics were covered in adequate depth. With >50% of the material focussed on 'sleep architecture', the blueprint demonstrated the focus of the curriculum and assessment mapped to the priorities identified by the AEBCD group. This satisfies the classical concepts of content and construct validity when thinking about in-curriculum assessment [240], and also instils confidence that the assessment has sampling validity.

5.6.1. Development of teaching materials

Both 'Honey and Mumford' [212] and 'Fleming' [234] systems were considered when creating teaching content. Using the blueprint a range of materials support teaching objectives, whilst presenting users with a variety of different methods of content delivery.

Preparation for patient transfer was chosen for the experiential learning. It was important for staff engagement that activities simulated were clinically plausible. It was not feasible to simulate an emergency for healthy volunteers, so the situation had to be a busy but elective situation. Transferring a patient is a common scenario in the ICU, where a patient is prepared to be taken to another area of the hospital (for example operating theatres, the CT scanner, or discharged to a standard ward). It can be a complex exercise, requires planning and preparation, and was recognised during ethnography sessions as a situation that created unexpected increases in sound and activity levels. It was therefore highly suitable for simulation.

While this set the background scene, additional activities were required to provide participants with a more inclusive experience. For example, glasses created a blurred and restricted visual field, intended to replicate that visual disturbances are a common feature reported by patients [36] and corrective lenses are not worn by many patients in the AICU.

This experiential 'learning in context' feeds into Knowles' principles of adult learning [230,242]. Through experience the learning is contextualised, and becomes meaningful and personally relevant. It can also be revelatory, and a key stage in the experiential learning process is that individuals are encouraged to reflect on their experiences. The experiences of participants before, during, and after the simulation exercise inform their practice, and knowledge gaps identified by the encounter can motivate learners to seek out new educational opportunities.

Although not explicit, this internal feedback model incorporates elements of Kolb's learning cycle [243-245]. It seems likely that reflections in- and on-practice, facilitated by debriefing of

a 'real' experience, will be of greater quality and depth than could be achieved by theory-based teaching alone.

The nature of providing a realistic patient experience meant there was limited opportunity to include factual and scientific aspects of sleep and noise in the session. The e-learning module therefore complemented the more emotive aspects of the simulated experience. The module was developed to be easily accessible, and to be completed in a relatively short amount of time such that busy staff could complete it without excessive disruption to normal working practices. More than two-hundred staff successfully accessed the module; the median access time of 18 minutes suggests the module is an appropriate length.

The experiential session and the e-learning modules are self-contained, each with their own opportunities for reflection and self-identified learning points. This module independence was important because it could not be predicted which order staff would complete each section. The experiential learning requires a free bed, so there were practical challenges to delivering it, even when sufficient numbers of interested staff were available. Training sessions were delivered opportunistically, with clinical research staff from the Critical Care Research Group (LB, JD, CH, EJ, BL, CR, AS) rostered to provide training, but 'stood down' if clinical workload was unsuitable.

The e-learning and experiential learning session interlock to create what Harden describes as a spiral curriculum [246]. This is a structured, iterative revisiting of the same topics and themes using varied approaches that complement each other. The spiral curriculum allows learners to build their knowledge and understanding at each stage. This enables better connection of concepts and a deepening understanding of the wider problem.

A true spiral curriculum will increase in difficulty at each stage. The two modules developed for this project can be completed in either order. This was a pragmatic requirement, since the unpredictability of clinical work makes it impossible to assume learners will encounter materials in a fixed order. This meant the modules could not necessarily increase in complexity from one to the other. However, learning points from each module do directly relate to each other, and learners are able to link information from both stages. Progressive competency, the conceptual purpose of the spiral curriculum, is therefore likely.

5.6.2. Assessing the assessment

Assessment can be either formative or summative [240]. A formative assessment is intended to guide ongoing learning, whereas a summative assessment represents a test that must be completed before an individual can progress.

Given the nature of this training package, and the context in which it was delivered, assessment was entirely formative in nature. The purpose of assessment is twofold. It allows learners to measure achievements against learning outcomes. This is useful for adult learners as identified gaps in knowledge guide future learning. It also allows an opportunity to identify gaps in educational materials to refine teaching content.

Questions addressed varying levels of knowledge [238,247] and all sections were designed to provoke reflection-on-action [248]. A potential drawback of the true/false type question is they can be a test of factual recall only. But significant advantages to the format are that it can be administered to large numbers of people with minimal administrative overhead, is convenient to deliver and mark electronically and, with careful design, can explore higher-order thinking. An appropriately designed test can therefore be both highly efficient and cost-effective. MCQ examinations allow a large number of questions to be put to candidates in a short amount of

time which is useful as a larger cross-section of the curriculum can be sampled, and learning can be tested more widely.

It is essential that assessment is reliable and valid [249]. This confirms the test can successfully discriminate between candidates of varying levels of expertise, that it appropriately reflects course content, and produces consistent results. There are several elements to consider when evaluating performance of assessment instrument(s).

Validity describes the extent to which a test measures what it claims to measure. A challenge in test validation is that, unlike physical characteristics such as height or weight, there is no single measurement that will conclusively prove a test is valid. 'Assessment of assessment' therefore requires evaluation of multiple pieces of evidence which suggest a level of validity when considered together.

Although the assessment was designed using classical concepts of validity and reliability testing, more modern and nuanced concepts of validity are gaining increasing interest in medical education [250]. This more modern view frames validity as an argument for which evidence is needed to confirm or refute test appropriateness. This approach addresses the key inferences and assumptions that are made when designing a test process. Five sources of evidence are required to validate a new assessment method. These are listed below and in Table 5-8.

1. Content: the relationship between the educational materials, test items, and the underlying educational construct of interest
2. Internal structure: the degree to which items sampled in the test relate to the educational construct and each other
3. Relationships with other variables: the degree to which the test produces the same outcome as other tests purporting to measure the same educational construct
4. Response process: the appropriateness of the test instrument to the behaviours or knowledge under scrutiny
5. Consequences: the implicit and explicit effects on examinees having taken the assessment

Sources of evidence used to support validity argument

Source of evidence	Evidence available
Content	Results of blueprinting exercise Expert/patient review of content Pilot testing and revision
Internal structure	Testing of internal consistency
Relationships with other variables	Comparison of pre- and post- course test results
Response process	Post-course participant feedback
Consequences	Demonstrable fall in ICU sound levels following training delivery Post-course participant feedback

Table 5-8: Evidence base for validity arguments

The body of evidence gathered to support validation of the assessment is explored in further detail in appendix C.

Assessment participation was good. The improvement in scores when comparing pre- and post-course results demonstrates that the training materials were effective in transferring knowledge, and engagement statistics demonstrate that the time to complete both the training (18 minutes) and assessment (seven minutes) is relatively short. Time is a consideration when introducing new sessions to the suite of training sessions available to the AICU staff. A total time of around 25 minutes suggests this would not be an onerous addition.

Completion certificates were issued to everyone completing the online module. Certificates demonstrate CPD commitment that individuals can include in training portfolios, and provided a worthwhile incentive for staff to engage with training.

To improve sustainability, in latter stages training was delivered by local nursing educator teams following a 'train the trainer' session delivered by the project team (LB, JD, CH, EJ, BL, CR, AS). This experience enabled training sessions to be offered to other ICUs involved in the wider SILENCE work. At YDH local teaching was delivered by the local team who were initially trained by the Oxford-based research lead (JD). A practical guide to delivering the session is included in appendix C.

5.6.3. Course evaluation and impact

The Kirkpatrick Model [251] is widely used to evaluate training effectiveness. There are four basic levels which can be assessed; reaction, learning, behaviour, and results. Learners' reactions and acquisition of new knowledge are usually evaluated through relatively simple before/after questionnaire assessment. Changes in individuals' behaviours and/or organisational practice need to be identified through observation.

Observation sessions as part of the display assessment described in chapter seven offered useful insights into workplace changes since deployment of the teaching. These enabled judgement on behavioural and cultural change, the penultimate aspects of the Kirkpatrick Model [251]. Although these observations were not primarily intended as teaching follow up, during these sessions staff spontaneously volunteered information about responding to disturbances in the ICU in a new way after the training. In one specific example a senior sister approached the observer (JD) to describe how she was using examples such as the apron dispenser to raise awareness of noise, and was encouraging colleagues to do the same.

The final Kirkpatrick assessment would be demonstrable results leading to direct patient benefits. These would be the gold-standard for medical education but are difficult to detect because of other cofounders, especially in a complex intervention. Updated patient interviews might highlight changes in the subjective patient experience of an ICU admission and these qualitative data could be matched to quantitative data such as length of stay or sedative/analgesia prescribing. However, these data would be blurred by confounding factors difficult to control for in analysis. The quality improvement project at YDH (February – May 2018) yielded some interesting sound level results with a reduction in peak values after the training.

To ensure confidence in any future use of the teaching package effectiveness of the teaching materials was evaluated. This process also facilitated opportunities for learners to influence curriculum development.

Course evaluation is distinct from individual assessment. Individual assessment measures the impact of the training on the learner. Course evaluation is an opportunity for learners to affect future iterations of training. Participants can suggest which parts of the training were most useful and relevant, and where materials should perhaps be revised.

Candidate feedback was particularly valuable for this course. It was used primarily to refine content and delivery of experiential sessions. The experiential sessions were updated in line with ideas received from staff who completed feedback forms during the first three months. The session was approximately three minutes in its first iteration. The new session (delivered from Summer 2017) is closer to six minutes, with more physical interaction between trainers and the simulated 'patient', and the transfer soundtrack was updated. This increased reality for the 'patient' as the recorded activity sounds now appear to come from the left and the right. The

practice of using participant feedback to refine teaching methods conforms to best educational practice [252].

5.6.4. Generalisability

Although noise level changes seen at YDH are statistically significant, the differences are relatively modest. A change in 3dB is usually considered the minimum that would be detected by the human ear. Where significant and real change has apparently occurred is that peak values dropped by 20dB between February and May. It is important to be aware that these will be single high value occurrences during each month but it does suggest a trend that indicates raising awareness of the effects of loud noises in the ICU can have a measurable effect on the 'signature' of the ICU soundscape.

The AICU at Yeovil was selected from sites that recruited patients for the SILENCE sleep assessment study [52]. It was a motivated and interested site but (importantly) had not attempted any local intervention programme to reduce noise levels in their AICU. As such, they were a naïve site with limited background understanding of noise monitoring practices. The value of results from a naïve site is that they can indicate potential for transferability and generalisability across the NHS. That a relatively simple intervention seems to have generated positive results is encouraging.

Results from the YDH sub-study (section 5.5.6) indicate there may be quantifiable, measurable changes seen after introducing simple environmental changes in combination with an experiential education exercise. This is in addition to increasing understanding about the effects of high sound levels can have on patients admitted to the ICU.

5.7. Strengths and Limitations

Strengths

- Use of adult learning theory to develop a robust training package
- Support from local teaching faculty facilitated in-situ delivery of simulation sessions
- Hosting the e-module alongside other NHS Trust training materials standardised the mode of delivery
- Analysis evaluated training, assessment, and impact (including at an independent site)

Limitations

- Limited project resourcing resulted in post-intervention ethnography sessions being largely opportunistic
- More detailed observation of routine practice in the ICU immediately following periods of training might have recognised subtle changes in practice
- Independent site evaluation was relatively short in duration

5.8. Conclusions

The training package designed and implemented as part of this project can be described as good quality in that:

- Original aims were identified by the learner group (the AEBCD group)
- The curriculum blueprint indicated coherence to the original aims.
- Staff feedback indicated engagement with the training materials.
- Before and after assessment of the e-learning module confirmed an increase in knowledge in those completing the course.
- There was an indication that peak sound levels decreased after the training.

5.9. Dissemination and impact

5.9.1. Journal of Medical Education

Article published for The Journal of Medical Education 'Really Good Stuff' feature *Using the experience-based co-design method to design a teaching package*, Darbyshire JL, Hinton L, Young JD, Greig PR, Journal of Medical Education, Volume 52, Issue 11, 1198 (November 2018, first published 21 October 2018), doi: 10.1111/medu.13720

5.9.2. BJA Education

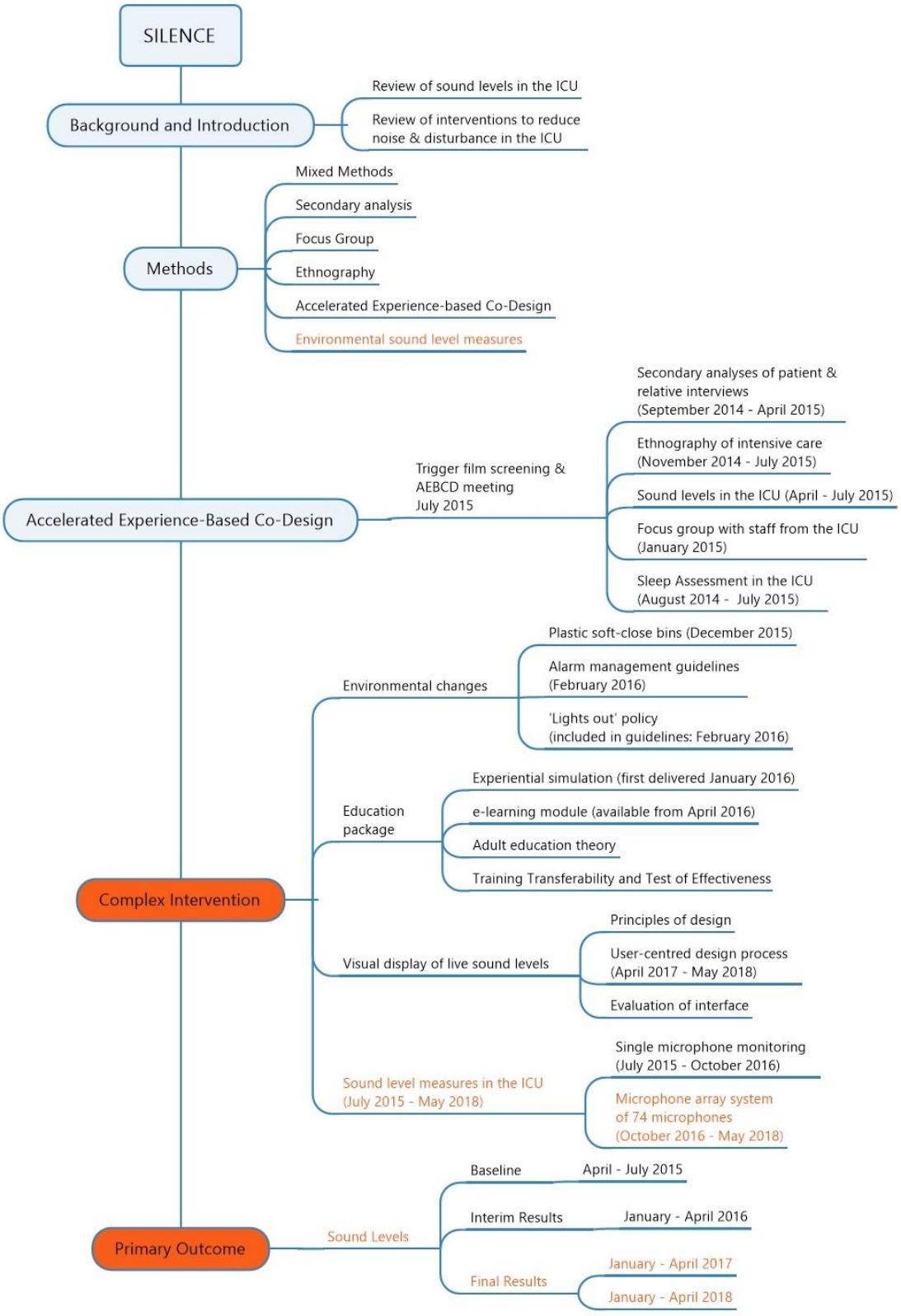
The BJA Education published *Medical education theory in practice*, Greig PR, Darbyshire JL, BJA Education, Volume 19, Issue 2, 40-46 (February 2019) doi: 10.1016/j.bjae.2018.10.003

5.9.3. Local adoption

Other intensive care areas within the OUH Trust have requested access to both the experiential sessions and the e-learning module, and, following discussion with the educational leads within the nursing faculty, the experience may become part of the general adult intensive care induction programme.

6. Chapter Six: Sound level measurements.

6.1. Chapter summary



This chapter reports sound level data collection and analysis.

The single point sound level monitoring and recording system used in the early stages of this project has been described in chapter four. In this chapter, standard sound level monitoring is described (section 6.3.1), the new multi-point sound level monitoring and recording system is briefly described (section 6.4.1), the process by which the high volume of data was aggregated and summarised is outlined (section 6.4.2), the purpose of data cleaning is explored (section 6.4.4), and data cleaning outputs are presented in section 6.5.1. Final analyses are reported in sections 0 (sound levels) and 6.5.3 (sound source localisation). The sound level data presented in this chapter is observational only. There were no formal interventions introduced to reduce sound levels (see figure 0-1, page x).

A visual monitoring display was designed to present real time noise levels and location of key noise sources to staff working in the intensive care unit (ICU). This used the multi-point sound level system as a data source. The design and development of this noise visualisation display is described in more detail in the following chapter.

6.2. Aim

The aim of this chapter is to describe, in detail, sound levels in the ICU environment.

Standard environmental monitoring uses a single microphone to report sound levels at a specific location. Results represent the sound level an individual would experience at the measured point but give no indication of the specific source of noise, nor its amplitude at origin, and do not identify sound levels at other locations.

In clinical spaces, such as an ICU, a variety of sound sources are distributed throughout the space. Spatial variation and differences in reflected sounds will result in significant and unpredictable differences in sound levels across the environment.

There are a variety of different techniques and metrics for reporting environmental sound levels. Sampling intervals, averaging periods and weightings applied to different frequencies vary considerably between approaches. The acoustic properties (hard/soft surfaces or free space volume) of individual environments will also affect perception of sound levels that are objectively similar in volume. Single-point monitoring is less meaningful in a complex environment because it is primarily intended to confirm compliance with health and safety regulations.

The ICU environment is subject to considerable diurnal variation. Working patterns, shift changes, and bed occupancy will all influence sound levels. This is particularly important for this project as the predominant interests are disruptive effects of sound in the ICU rather than health and safety concerns associated with occupational exposure to high sound levels.

This chapter reports sound levels for a single bay (bay ‘A’) of the general AICU at the John Radcliffe Hospital (OUH) over a period of eighteen months with high spatial and temporal resolution.

6.3. Background

6.3.1. Standard environmental sound reporting

The first widespread use of noise measurement was conducted in 1929 in urban New York by the Noise Abatement Commission [253]. Monitoring meters measure sound levels of the immediate environment in which they are placed and are predominantly used to assess the extent of noise pollution caused by industrial processes or aviation. Such is the importance of environmental noise pollution and the effects that high sounds can have on the human ear that its measurement is governed by international standards (IEC 61672-1:2013) [254].

The World Health Organisation (WHO) published Guidelines for Community Noise in 1999 [255]. Noise in the community (including working environments) affects individuals in four key areas; annoyance, communication, sleep disturbance, and adverse health effects. The rationale and foundations for each area are briefly summarised here.

Annoyance

Annoyance is not solely dependent on decibel level. Different noises cause differing annoyance responses, even at the same volume. Steady noise levels (for example road traffic) tend to be less annoying than those which vary (rail, air). Tolerance for noise is also time dependent. Volumes that would cause little intrusion during the day are much less tolerable overnight.

Speech intelligibility

Background noise affects communication. A signal to noise ratio (speech to background noise) of 12-15dB is needed to maintain good speech intelligibility, although this varies on type and volume of background noise [256]. Where reverberation levels are high, such as in spaces with hard floor/wall surfaces, speech intelligibility is impaired. At normal speech volume of ~50dBA, background noise levels should be 35dBA or less, although primary speech frequencies of 500, 1,000 and 2,000Hz can be understood fairly well with background levels up to 45dBA[27]. Increased vocal effort is required when background levels rise above 50dBA and ongoing conversation tends to continuously increase sound levels, which escalates the problem [94].

Sleep disturbances

Sleep disturbances can occur when background sound levels are as low as 30dBA, and peaks of 45dBA have been shown to induce awakening. The elderly, shift workers, and those with physical or mental disorders are particularly at risk of adverse consequences of awakening and disrupted sleep.

Health effects

Noise levels have been shown to affect cognitive performance both in laboratory studies and in the workplace. There is a suggestion that long-term exposure to values >65dBA may be associated with a slight increase in cardiovascular disease. This is because increased noise levels can result in higher sympathetic arousal leading to higher resting blood pressure levels. Direct effects of noise-induced hearing loss are well documented and noise monitoring in the workplace typically focusses on ensuring that environmental sound is within safe (non-physically-damaging) levels. The Control of Noise at Work Regulations 2005 [30] oblige employers to control sound levels (and/or provide hearing protection where lowering sound levels to a safe level is not

[27] Some sound monitoring equipment includes an option to measure speech intelligibility. This is known as STIPA and is governed by BS EN 60268-16.

possible). UK employers have a legal duty of care to protect employees' hearing if there is a risk of daily exposure values >80dBA or peak sounds of 135dBC[28]. Ear plugs and over-ear hearing protection can each provide up to 30dB protection.

Sound measurement conventions

The decibel (dB) is the most common unit of sound level measurement. It is a logarithmic unit that describes the ratio between measured sound level and an internationally defined reference level of 0dB [257].

The majority of environmental sound reporting uses the A-weighted scale (dBA). Sound level meters have a frequency response determined by sensitivities of microphones and electronics to different frequencies. These frequency-dependent sensitivities may not match those of the human ear and acoustic processing neural pathways. A-weighting adjusts raw sound levels to an approximation of sound levels mapped to the frequency response of human hearing.

Sound monitoring is reported as equivalent continuous sound levels, or time-averaged levels. This calculation is governed by IEC 801-22-16 [258]. LAeq is the A-weighted equivalent continuous sound level in decibels measured over a specified period of time. Most community and industrial noise measurements are A-weighted, and LAeq is widely quoted.

There are no maximum limits for environmental noise outside the workplace. However, the Health and Safety Executive in the UK recommends music concert event average sound levels (LAeq(event duration)) below 107dBA, with peak sound levels no higher than 140dBC [259]. Other examples of environmental noise monitoring are around airports. There is an assumption (in the UK) that if LAeq(07.00–23.00) is higher than 57dBA this will be "significantly annoying" for individuals living locally [260].

Globally, environmental noise in hospitals is measured against the WHO standards. The WHO guidelines recognise that the main effects of high sound levels in healthcare environments such as an ICU are disturbance and interrupted sleep, and problems with communication, rather than direct damage to hearing as a result of high volumes. The guidelines recommend that hospital ward environments should aim for average values between 30-35dB LAeq24 with maximum values of 40dBA overnight. These levels are consistently not achieved by intensive care units globally [4,93].

Sound levels are usually reported as single daily values reflecting mean sound levels (LAeq) over a 24-hour period. This is reported as LAeq24. For evaluation of sound exposure in the working environment, the LAeq can also be reported for the standard eight hour working day (09.00–17.00) as LAeq8. When sound levels are reported for the healthcare environment (chapter one) it is common to see LAeq(day) and LAeq(night); time periods (day) and (night) mapping to shifts, commonly twelve hour periods 07.30/08.30-19.30/20.30.

However, even A-weighted sound values reflect the human perception of loudness poorly. The perception of loudness depends on volume level, duration of exposure, pitch, tone, information content (of the sound), and frequency. Loudness therefore takes account of the likely psychological effect of sound on the individual which enables the human experience of sound to be quantified. The concept of loudness is subjective and will differ between individuals. What is unbearably loud for one will be tolerated by another [192]. Loudness can be calculated in a number of different ways, all of which result in a numerical estimate of an "average" perception

[28] "C" weighting is used for measuring sudden peak noises

of loudness of sound. The Zwicker method is recommended as the most appropriate method for calculating loudness for time-varying signals [261] and was used for this project.

6.3.2. Commercially available sound level measuring and display devices



Figure 6-1 : Image of SoundEar Classic sound level measuring/display [262]

There is some recent evidence that suggests visual displays of sound level, such as the 'Sound Ear' (SoundEar A/S, Soborg, Denmark) (Figure 6-1), can reduce ICU sound levels in the short term [263]. There is no evidence that lower sound levels can be sustained (chapter one). Current approaches for visualising sound levels in real time are imperfect for the clinical environment. It is likely this is due to a number of factors. These are discussed in more detail in chapters four and seven but briefly: commercial off-the-shelf monitoring displays are designed to prevent physical damage to hearing (rather than disturbance), have no indication of 'history', and are limited in their ability to provide real-time feedback. Retrospective analysis is sometimes possible but this offers no option for staff to reflect in action, limiting opportunities to provoke proactive behaviour change. As a result of their limited effectiveness, staff become habituated to these displays, and over time become blind to the almost constant alert.

The AEBCD group for this project (chapters three and four) were keen to see an alternative display in the ICU that addressed these issues.

The Institute of Sound and Vibration Research, University of Southampton were commissioned to build a sound recording system to feed into a new interface enabling real-time noise monitoring in the ICU. The design and development of this system is described in the following chapter (seven). This new system supported higher spatial and temporal resolution than would be available from standard commercial systems.

6.4. Methods

Sound level data were collected using two different environment sound monitoring systems. Initially (April 2015 – October 2016) data were recorded using a standard commercial system[29]. The early phase of the project is reported in more detail in chapters three (April – July 2015) and four (December 2015 – April 2016). This single-point monitoring system was replaced in October 2016 by a bespoke multi-microphone array that mapped sound levels across the whole AICU bay. This chapter focusses on this new system. No new interventions were introduced during this later period (October 2016 – May 2018) of sound level monitoring. Data are

[29] CEL-630 sound level monitors with integral recording fitted with a CEL-495 preamplifier and a CEL-251 microphone (Casella Measurement, Kempston, UK)

reported as they were recorded from each system. Results from the immediate post-AEBCD period are fully reported in chapter four.

6.4.1. New system design and build

The system used to collect and report sound level data for the latter stage of this project was built by the Institute of Sound and Vibration Research, University of Southampton. Funds from the NIHR RfPB grant (ref: PB-PG-0613-31034) were transferred to the University of Southampton to facilitate recruitment of an acoustics engineer. This engineer was employed to build a sound monitoring system including real-time display in the ICU. Data collection and recording equipment had to be unobtrusive to both patients and staff, and sufficiently robust and reliable to require no ongoing maintenance or significant ongoing operating costs. The system is described more fully elsewhere [264] and appendix E.

Four spiral arrays of sixteen microphones (left image, figure 6-2) were installed in bay 'A' of the adult ICU at the John Radcliffe Hospital, Oxford University Hospitals NHS Foundation Trust (right image, figure 6-2). This system of 64 microphones enabled source location software to identify sound origin, as well as reporting sound levels with a high degree of temporal resolution. The location algorithm relies on time delays for sound reaching different microphones. Differential spiral spacing allows localisation of multiple frequencies.

The spatial software was programmed by the Southampton engineer to identify sources of sounds >35dB, the WHO threshold for patient environments. All sounds above this level will contribute to escalation of overall sound levels [94].

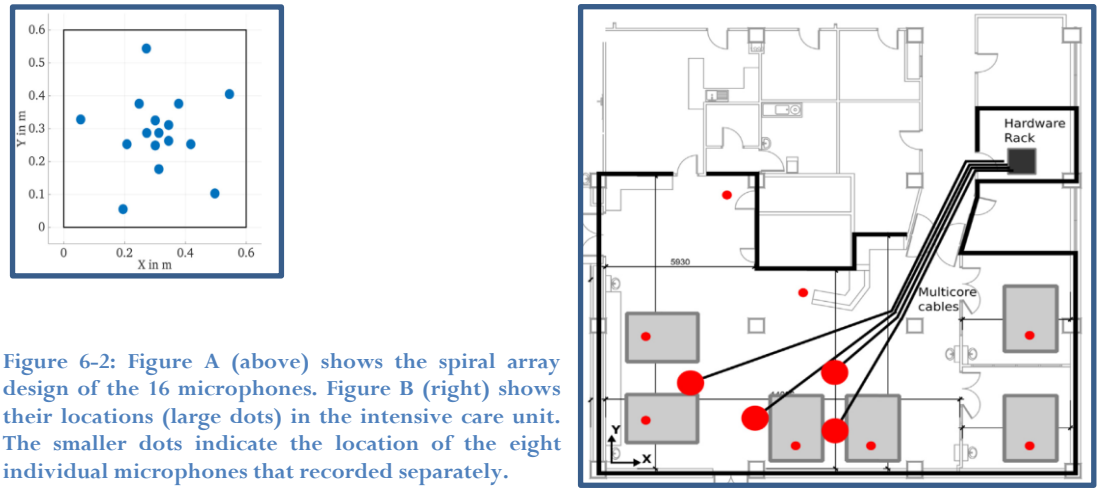


Figure 6-2: Figure A (above) shows the spiral array design of the 16 microphones. Figure B (right) shows their locations (large dots) in the intensive care unit. The smaller dots indicate the location of the eight individual microphones that recorded separately.

Eight additional microphones were also installed. These were situated above each bed in the intensive care bay (Figure 6-2). Microphones 65 and 66 were in side-room ceilings, and microphones 67-70 were installed over the main patient treatment area. These microphones were placed to approximate the patient experience of sound in the ICU. The final two microphones (71 and 72) were positioned to capture sound levels at the nursing station and outside the sluice room. These locations were identified as 'noisy' during ethnography sessions (chapter three).

System testing

The system was tested under simulated conditions in the laboratory in Southampton before installation in the ICU. The testing identified some minor issues with limited clarity of location mapping and allowed optimal microphone patterns to be determined. This testing and preparatory work is outlined elsewhere [264].

System installation

The system was installed by the local NHS Trust Estates Team. Four pre-prepared ceiling tiles, each with sixteen microphones, replaced standard ceiling tiles [264]. Power banks were housed in the void above the ceiling. These units were physically connected to a central analogue to digital (ADC) converter which was located in one of the intensive care administrative offices outside the main unit (right image, figure 1-2). This ADC connected to the processor in the AICU 'hub room'.

6.4.2. Description of the data

The system recorded data from all 72 microphones. At each timepoint the system captured sound levels of third-octave frequency bands [265], an overall average sound level (LAeq), and a converted 'loudness' value.

The array ran from installation in October 2016 to the end of the project in May 2018. Each day could theoretically generate >215 million data points (3,024,000 data points per microphone), but temporal resolution was variable with actual recordings every 2-4 seconds due to varying computing overheads. Data processing occurred after each sample of sound had been saved, and computing time varied. As a result, daily data capture in reality varied between 1-1.5 million data points per microphone. This is still a minimum of 72 million data points every day.

6.4.3. Data aggregation

The 2TB dataset meant that conventional statistics programs would require computational resources not available on standard university equipment. A cluster computing framework (Apache Spark) was used to overcome these limitations[30]. The Spark system was able to process the entire dataset using relatively modest resources without the need for data sampling.

The system consisted of a single Dell Precision workstation (6 cores and 32 GB of RAM) running Ubuntu 18.04 LTS (Bionic Beaver), Oracle Java 1.8, Apache Spark 2.3, Scala 2.11, R Core 3.5, R Studio 3.5 and sparklyr 0.8.4. The sparklyr package running inside the integrated developer environment (R Studio) ran R code on the dataset using the dplyr package [266]. Aggregate data were exported back into R Core for analysis and visualisation using ggplot2 [267][31].

Data frames were created in R to facilitate subsequent analysis. These data frames grouped results by time (minute, hour, and day of the week) as well as summarising by sound level (both

[30] The benefit of Spark is that the system splits the dataset and runs analyses in parallel batches which means less processing memory is needed. This contrasts with other systems where the entire dataset needs to be accessed at one time. Spark is therefore more efficient and is ideal for processing very large datasets. This cluster framework was built for this project by Robert Hatch, research clinician based at the University of Oxford Critical Care Research Group

[31] R packages are organised collections of code, functions, and tests that run within the core R programme. They extend the functionality of base R and are essential for efficient data management and processing to enable analysis.

dBA and 'loudness'), and by maximum, minimum, and average (mean/median) values at each time point.

These aggregate data sets enabled more detailed analysis of the sound environment of the ICU than is reported routinely. This in turn enabled more opportunities for exploration and understanding through comparison with other data sources.

6.4.4. Data cleaning and initial data visualization

Possible quality issues [268,269] at this stage were implausible values (outliers or contradictions), inconsistent values (unexpected results), and irregular reporting (lack or excess data).

Implausible and inconsistent sound level values might indicate sudden microphone failure or gradual calibration drift. Irregular timestamps might indicate a wider, more generic and pervasive problem with the software and/or hardware.

Data cleaning was an iterative process [270]. Raw data were visualised (section 6.5.1) to enable assessment of data quality [268]. Visualisations were rendered using the ggplot2 [267] package within R Studio.

Summary statistics confirmed distribution, range, and density of sampling frequency and sound levels.

6.4.5. Data analysis

After data cleaning, the final data sets were interrogated.

Descriptive statistics and data visualisation (section 6.5) allow more detailed review of the sound environment of the ICU than single daily mean values (LAeq24) reported as standard.

Of specific interest for this study was the difference between usual metrics (dBA) and 'loudness' values. Loudness also takes account of the likely psychological effect of sound on the individual which enables the human experience of sound to be quantified. The LAeq of the AICU is unlikely to ever be high enough to be harmful to hearing but the qualities of sounds in the AICU are likely to be highly disturbing for both patients and staff. As discussed earlier, for in-hospital assessment of sound and noise, it is the experience of sound that is perhaps more relevant rather than physically damaging effects.

Exploratory data analysis

Data cleaning or early profiling [271] of large datasets offers opportunities to review data as a whole and identify potential inconsistencies. Common visualisations include distribution analyses, range checks, and assessments of correlation.

Summary statistics were computed using the dplyr package [266] algorithms within R [272]. Outlier values were identified through box and whisker plots. Background understanding [268,269] of the expected normal range for environmental sound levels guided simple lower limitation of the decibel values to be included in the analysis dataset.

The number of samples recorded each day was plotted as both a time series and histogram. Having determined the dataset was non-normally distributed, specific values considered outside 'normal range' were identified as those above and below the upper and lower 5% confidence interval of the median.

Where applicable, the number of distinct values per variable ('minute', 'day', 'hour', or other determinant of time) were calculated to enable filtering/selection of data sub-sets. The number of values per variable was standardised to exclude the upper and lower 5% of the data points.

Final data were compared at two time points (January – March 2017 and January – March 2018) using non-parametric tests of comparison.

6.4.6. Sound source localisation

The microphone array identified originating sources of the five loudest sounds above 35dBA for each time point. Loudness was calculated automatically within the multi-point microphone system using the Zwicker method as per the ISO standard [261]. Full details of the sound monitoring system have been published elsewhere [264].

Data for source location analyses were collated from 7th April 2017 to 16th April 2018 inclusive. These data were a sub-set of the full data collected between October 2016 and May 2018. From the total 381 days, complete data were available for whole days from 248 days. Data were analysed using MATLAB R2018a (MathWorks, Massachusetts, USA). The area monitored was 14.1 by 12.7 metres with a spatial resolution of approximately 1cm.

Decibel levels for each location point were summarised and loudness levels averaged and plotted to a floor plan using colour to indicate sound levels. Full methods for this sub-study have been published elsewhere [273] and included in appendix E.

6.5. Results

6.5.1. Data cleaning

The higher fidelity sound monitoring system designed and built for this project ran from 26 October 2016 – 24 May 2018. During this time data were collected across 426 unique 24-hour periods.

The number of data points recorded each day varied considerably (Figure 6-3).

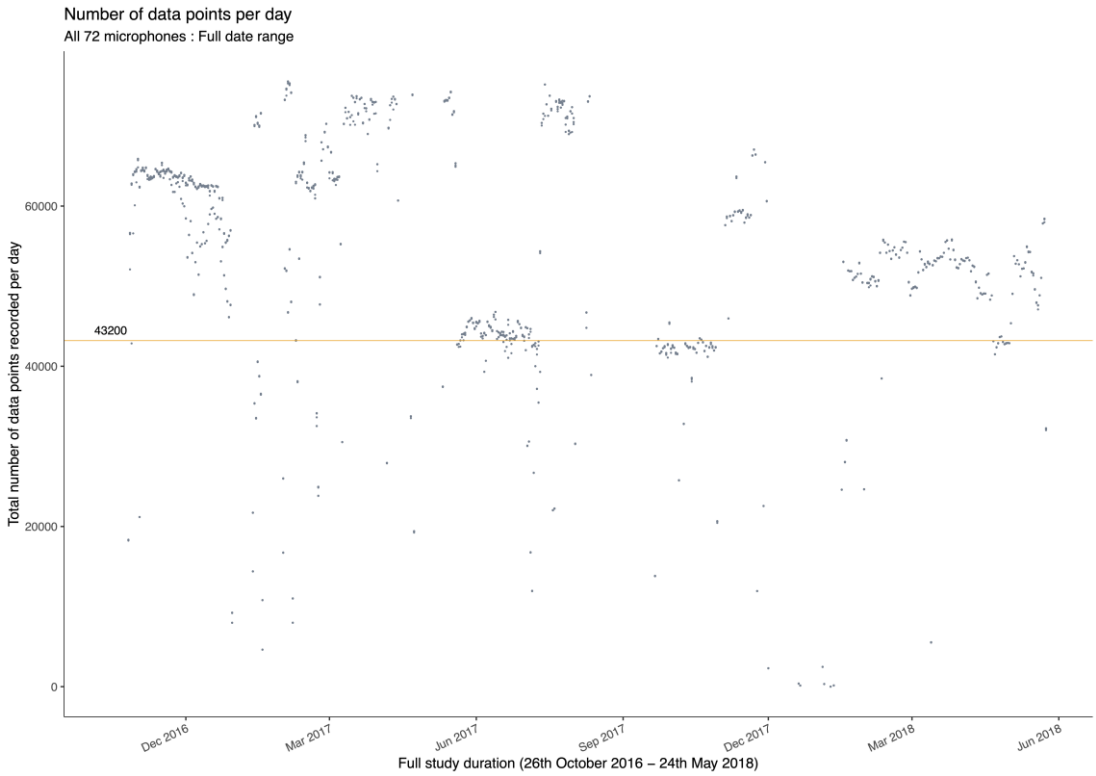


Figure 6-3: Plot of first date to last date with number of sound level values recorded each day. The orange reference line at 43200 indicates a theoretical sampling rate of two seconds.

Figure 6-4 shows from about half-way through the recording period there were clear outlier LAeq24 values. Each day includes 72 datapoints, one for each microphone. From August 2017 eight microphones (later identified as 65-72) consistently reported implausibly low values. The graph indicates a catastrophic failure in August 2017. Consequently, data from these eight microphones were discarded.

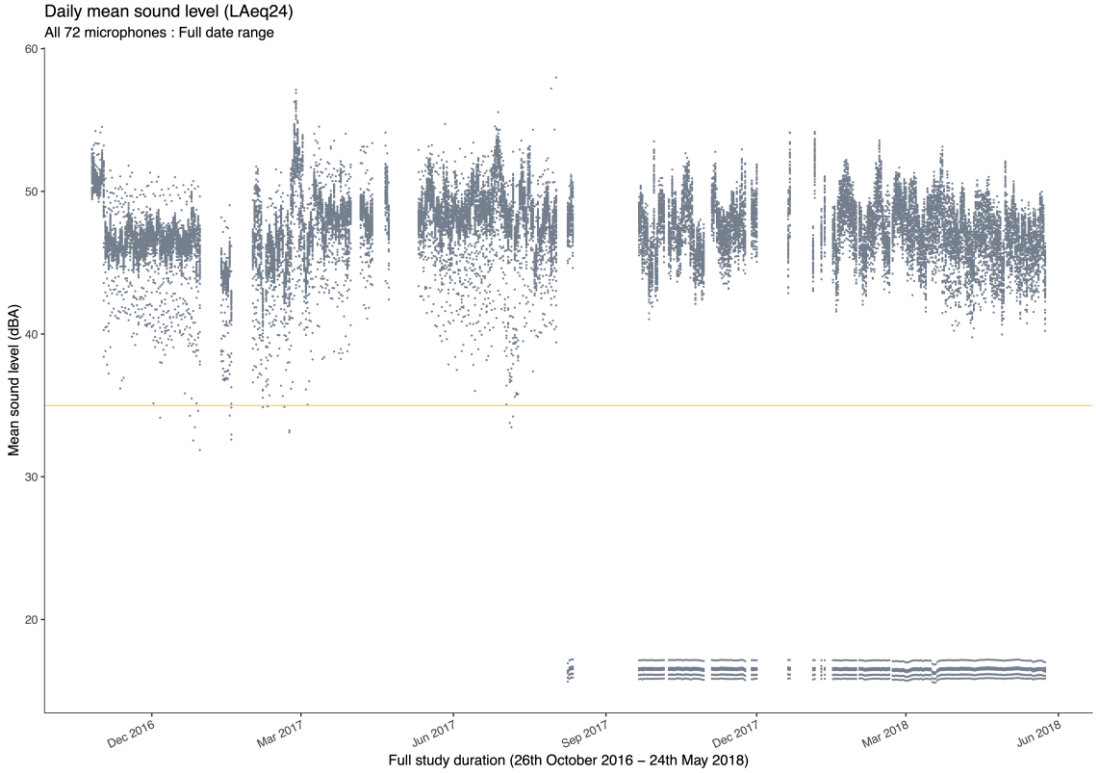


Figure 6-4: Plot of first date to last date with average daily sound level values per day from all microphones[32] The orange reference line at 35dBA indicates the WHO guideline sound level.

These initial visualisations identified several problems. In particular it revealed the number of data points recorded each day was inconsistent and that individual microphones (numbers 65-72) reported differently from the array (numbers 1-64). The 64-microphone array routed through one analogue to digital converter (ADC). The eight individual microphones were processed through a second ADC. Although both ADCs were calibrated and set the same (SILENCE Project Report, appendix E), there were clear differences in values reported. These eight microphones affected overall values considerably.

Summary of data cleaning process

Having established and excluded measurements due to hardware failure, the next stage was to examine for erroneous outliers. The remaining dataset was reviewed and assessed for quality issues and potential data bias. Final analysis data frames were created by filtering to remove implausible outlier values of dBA (below 20dB[33]) and all data from the eight individual microphones (numbers 65-72). Limits applied ensured consistent datasets, and recordings distributed evenly across hours. Days were excluded where the system had been interrupted (for example switched off deliberately for system upgrade, or random failure) and only days

[32] Each day reports 72 values, one mean average for each microphone

[33] The average decibel value of an anechoic chamber is between 10-20dB, reported values <20dB were removed as likely to be erroneous

with values from all 24 hours were included for analysis. Additionally, days were excluded where the number of data points per hour were outside 5-95% percentiles.

The system had a theoretical temporal resolution of two seconds. Local processor burden on computational power meant that this resolution varied between two and four seconds. The median (5^{th}-95^{th} percentile) number of data points per hour (across all days of recording) for microphones 1-64 was 145,851 (109,823 – 199,017). Hours with numbers of data points outside this range were excluded from analysis. Per individual microphone (example microphone 40, Figure 6-5) these figures become 2,279 (1,716 – 3,110).

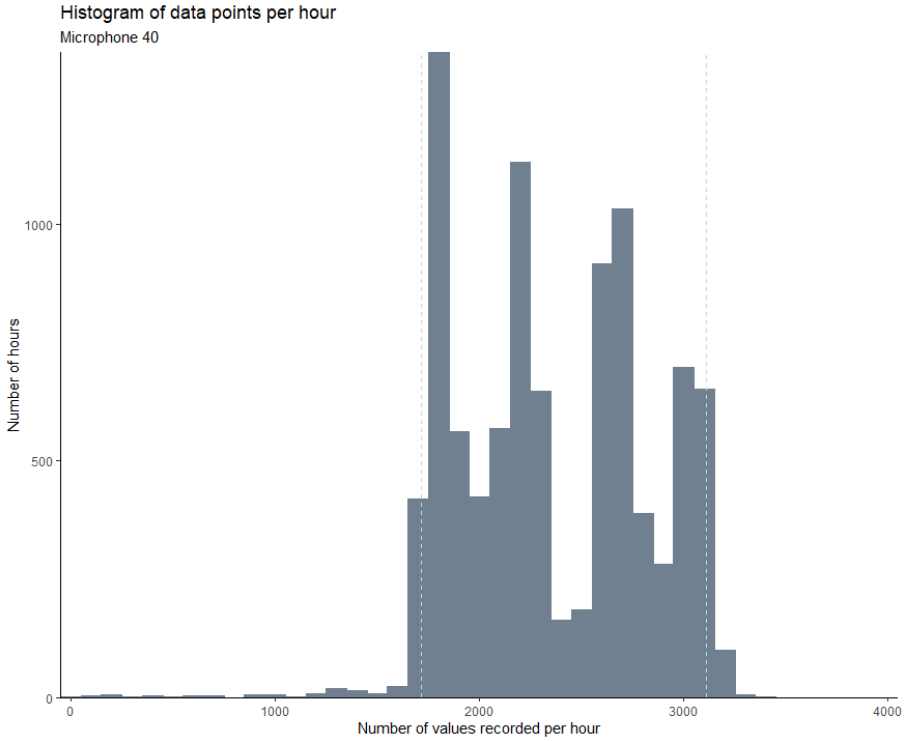


Figure 6-5: Histogram of the number of data values recorded per hour (for single microphone (40) only). Dashed vertical lines indicate the upper (95%) and lower (5%) percentiles. Hours with numbers of records outside this range (1716 – 3110) were not included in the final analysis dataset.

For the purposes of reporting loudness, data were extracted in minute intervals to avoid premature averaging of high values. Due to limitations of processing memory, loudness values were extracted and processed for a single microphone only. Microphone 40 was approximately central to the ICU and positioned similarly to the original single microphone used April 2015 – October 2016. Data outside upper (95^{th}) and lower (5^{th}) percentile limits (<29 and >52 data points/minute) were excluded and only days with full 24-hour coverage were included for analysis.

More detailed analyses were conducted to assess changes in the sound environment across the duration of the project. These are reported below.

6.5.2. Final analyses

The final analysis dataset comprised data collected over 275 full (but not contiguous) 24-hour periods between 28th October 2016 and 21st May 2018. This represents data from 65% of the 426 days on which data were captured between 26th October 2016 and 24th May 2018 (Figure 6-6).

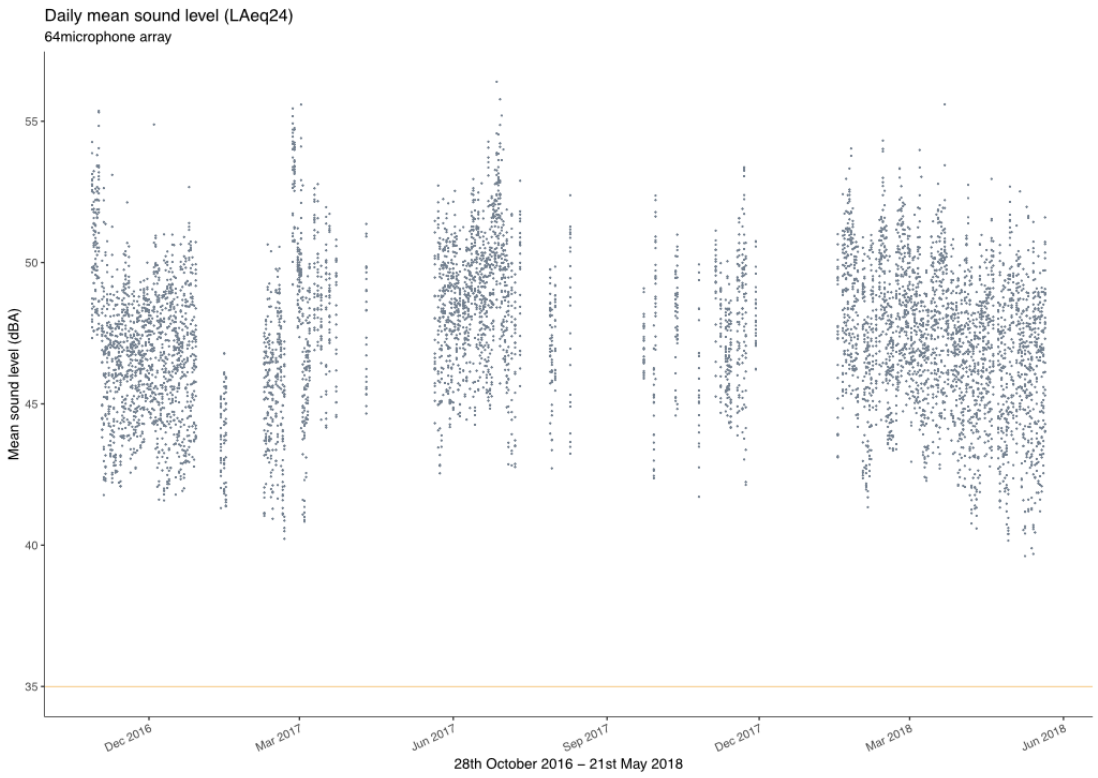


Figure 6-6: Plot of first date to last date with average daily sound level values per day from the 64 microphones used for the analysis set[34]. The orange reference line at 35dBA indicates the WHO guideline sound level.

On no day was the daily mean sound level (LAeq24) below the WHO guideline limit of 35dBA. No night had maximum levels below the WHO overnight threshold of 40dBA.

Across the full timeframe (28th October 2016 – 21st May 2018) the daily mean sound level values (LAeq24) varied between 43.1dBA (19th February 2017) and 53.2dBA (26th February 2017), with an overall mean of 47.4dBA.

The hourly mean sound level values varied between a low of 39.6dBA (02.00 – 03.00 9th May 2018) and a high of 56.4dBA (07.00 – 08.00 27th June 2017), with an overall hourly mean sound level of 47.4dBA. The highest single value recorded in any hour was 101.7dBA (between 21.00 – 22.00, 29th September 2017. The lowest single value recorded during any hour was 21.6dBA (between 06.00 - 07.00, 3rd July 2017). Aggregated hourly mean sound levels are visualised in Figure 6-7.

[34] Each day reports 64 values, one mean average for each microphone

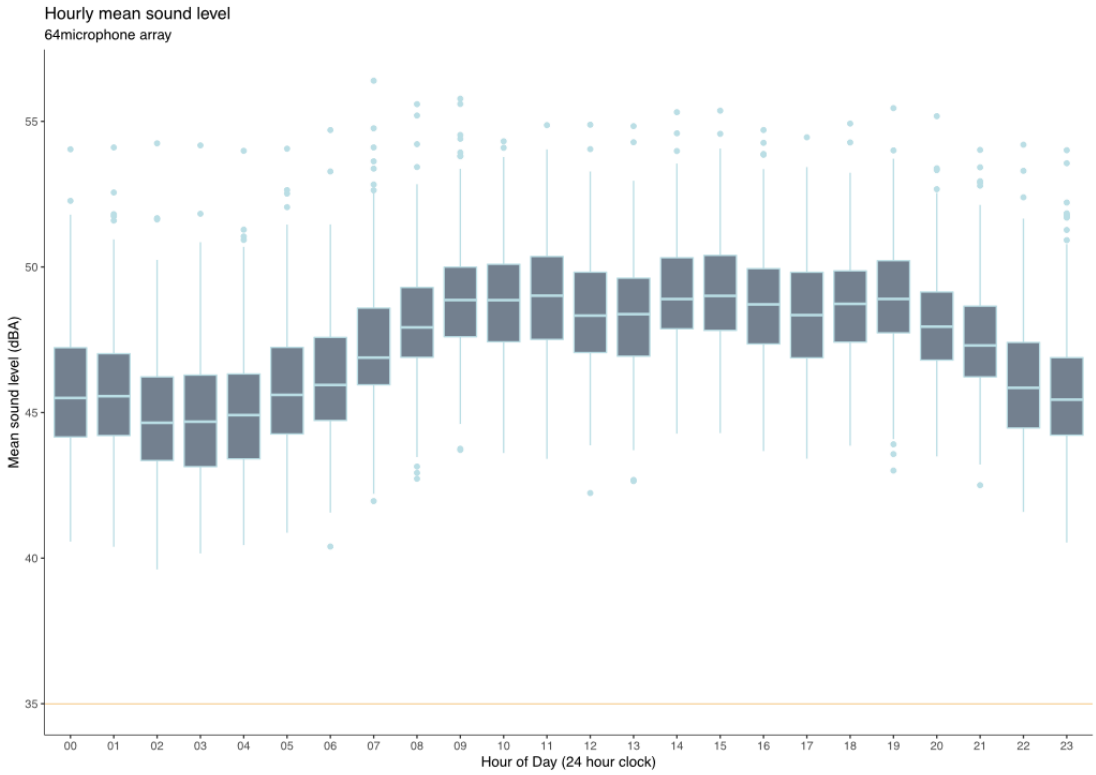


Figure 6-7: Plots of aggregate sound levels by hour from microphones 1-64 (28th October 2016 – 21st May 2018). The orange reference line at 35dBA indicates the WHO guideline sound level.

Noise level changes over time (64-microphone array)

Between 13th January – 23rd March 2017 (31 days) the daily mean sound level values (LAeq24) varied between 40.2dBA (20th February) and 55.6dBA (2nd March), with an overall mean across the quarter of 46.9dBA. The highest value recorded during any single day was 96.8dBA (between 09.00 – 10.00, 25th February). The lowest value recorded was 29.7dBA (between 12.00 – 13.00, 20th February).

Between 17th January – 31st March 2018 (65 days) the LAeq24 varied between 41.3dBA (4th February) and 55.6dBA (22nd March), with an overall mean across the quarter of 47.8dBA. The highest value recorded during any single day was 100.0dBA (between 09.00 – 10.00, 5th March). The lowest value recorded was 26.5dBA (between 23.00 – 00.00, 22nd February).

The plot below (Figure 6-8) shows aggregated sound levels from the 64-microphone array. This illustrates fluctuating 24-hour patterns and variance in hourly range from October 2016 – May 2018.

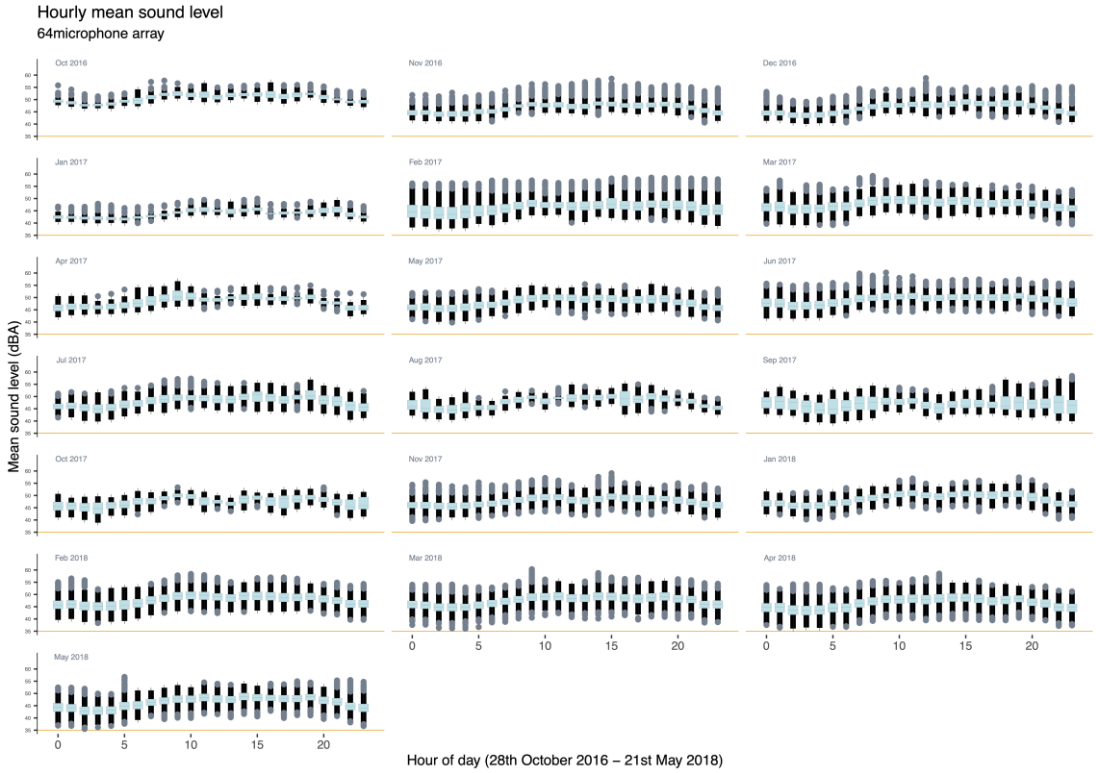


Figure 6-8: Plots showing aggregated hourly mean sound levels by month The orange reference line at 35dBA indicates the WHO guideline sound level.

When microphones are aggregated, there is an apparent increase in LAeq24 from 46.8 to 47.8 ($p < 0.001$) over time (Figure 6-9)

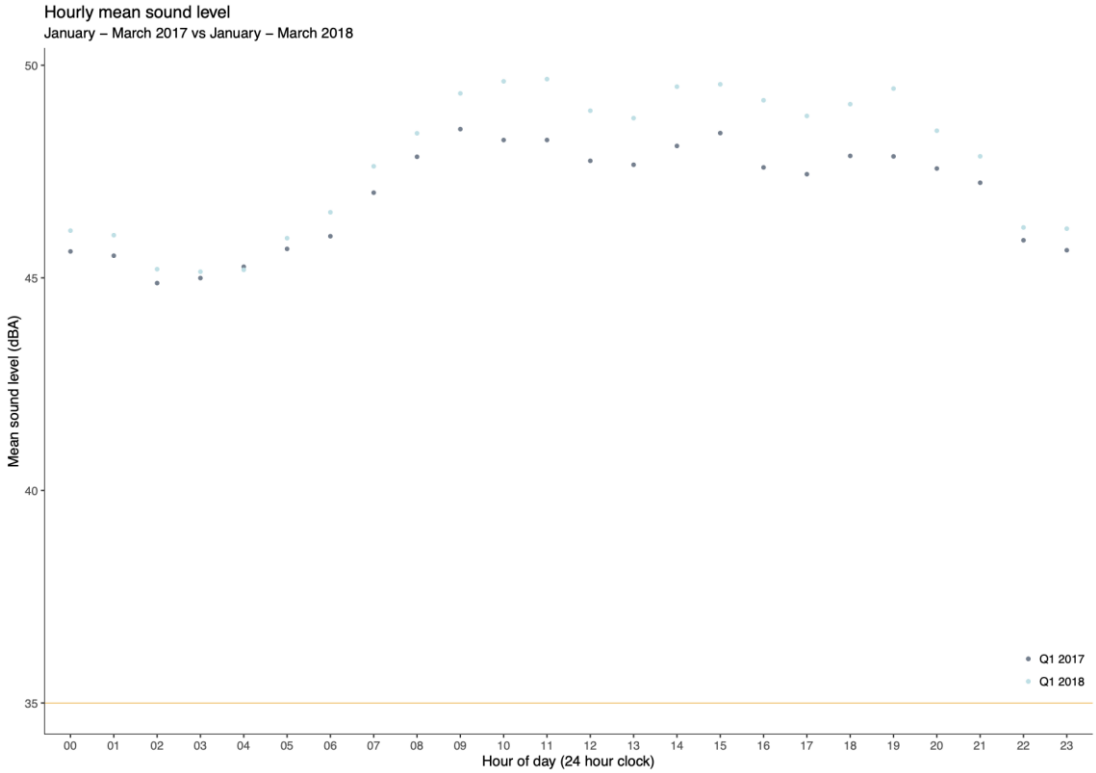


Figure 6-9: Plot of aggregate sound levels by hour from microphones 1-64 comparing January – March 2017 (Q1 2017) with January – March 2018 (Q1 2018). The orange reference line at 35dBA indicates the WHO guideline sound level.

Single microphone analysis

Baseline and interim sound levels[35] are reported in chapter 4 (section 7). Briefly though: mean LAeq24 (min-max) values between 19th April – 19th November 2015 (97 days) and 23rd December 2015 – 3rd March 2016 (70 days) were 55.1dBA (48.9-63.3) and 53.8dBA (44.4-91.8) respectively.

The initial results evaluation reported in the final project report for the NIHR [274] used data from a single microphone (microphone number 40). These results indicate a reduction of LAeq24 between the two time periods (January – March 2017 [31 days] and January – March 2018 [65 days]). Figure 6-10 shows this reduction clearly, particularly over the last six months.

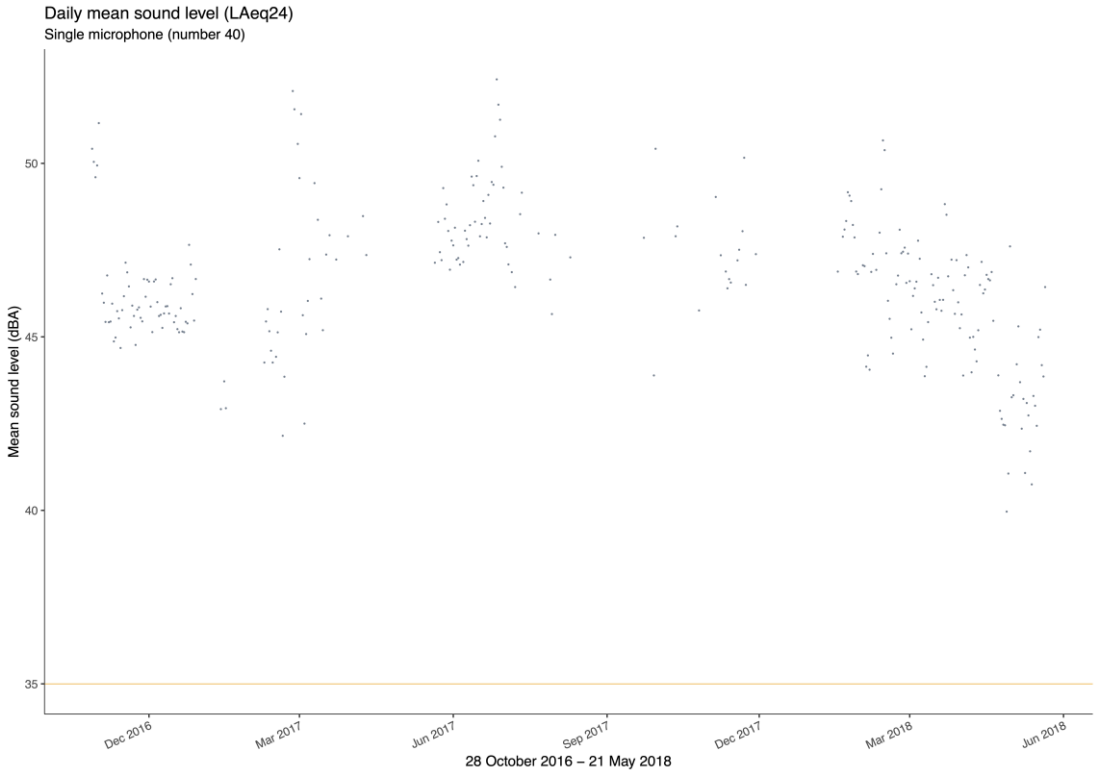


Figure 6-10: Plot of first date to last date with average daily sound level values per day from microphone number 40[36]. The orange reference line at 35dBA indicates the WHO guideline sound level.

[35] Data recorded using single environmental monitoring microphone

[36] Microphone 40 was positioned similarly to the original off-the-shelf sound level monitor, roughly central within the main patient area of the ICU

24-hour sound level by day of week

Clinical activity in the hospital reduces at weekends due to variations in staffing levels. It is reasonable to hypothesise this might translate into variable sound levels across the week. Figure 6-11 indicates this is not the case.

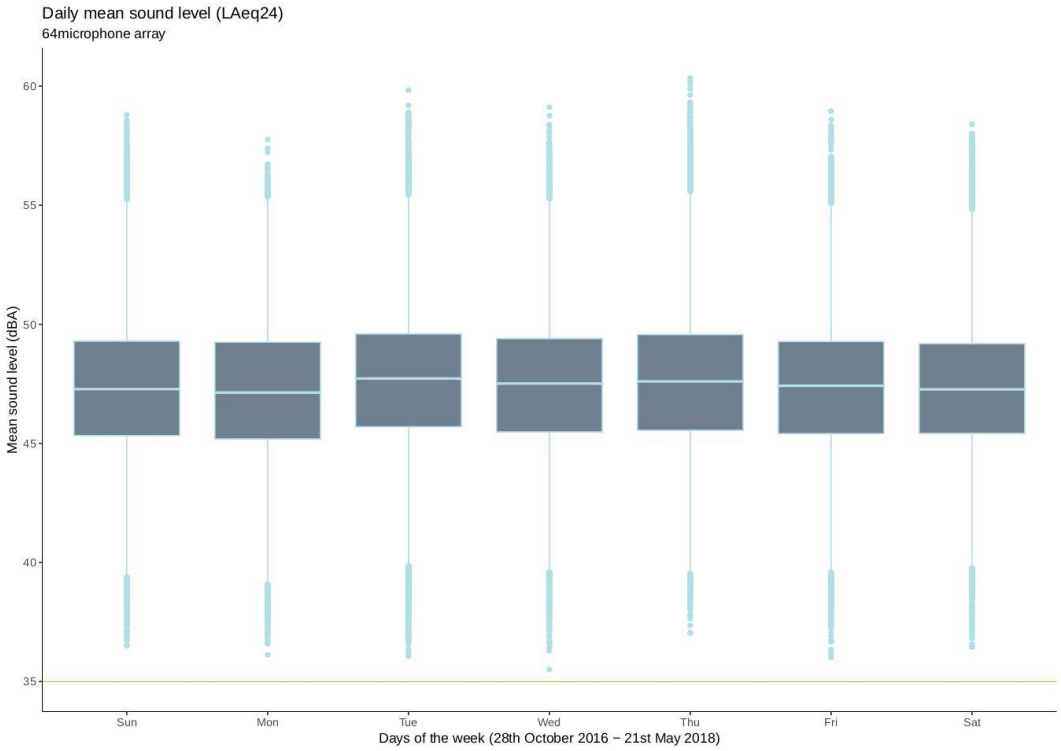


Figure 6-11: Plot showing aggregated daily mean sound levels by day of the week. The orange reference line at 35dBA indicates the WHO guideline sound level.

Simplified to weekday vs weekend, this becomes

Comparison of weekday and weekend sound level

	Weekday	Weekend	significance
Median dBA	47.5	47.3	<0.005
[min-max; IQR]	[35.5-60.3; 3.97]	[36.4-58.8; 3.86]	

Table 6-1: Weekday versus weekend sound levels

Although the difference in LAeq24 between weekends and weekdays is statistically significant (Mann-Whitney U test), this is not meaningful in the clinical context. The absolute difference in decibel values (0.2dB) is not discernible in practice.

Loudness

Loudness values represent sound as experienced by humans. In environments dominated by higher frequency sounds (such as alarms)[37], the loudness values will be considerably higher than routinely reported LAeq. Figure 6-12 shows the difference between daily mean sound level (LAeq24), equivalent mean loudness, and maximum loudness values.

This highlights that maximum loudness values are well above 90dB every day and frequently higher than 100dB. In all plots there is a visually noticeable drop in values recorded towards the end of the project.

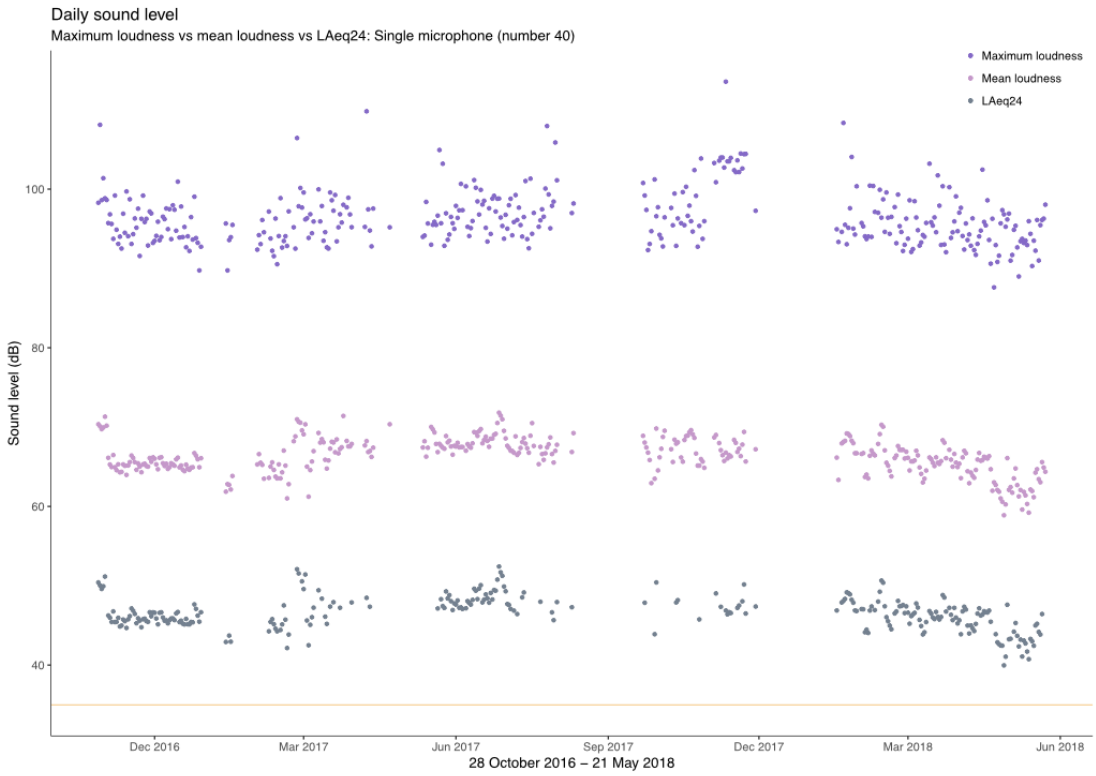


Figure 6-12: Plot of daily sound levels from microphone 40 comparing the standard reporting value (LAeq24) with mean and maximum loudness values. The orange reference line at 35dBA indicates the WHO guideline sound level (measured as LAeq24).

[37] Humans find higher frequency sounds more disturbing.

6.5.3. Sound source localisation

The source location sub-study has been published elsewhere [273].

The 64-microphone array was designed to accurately identify the source location for sounds above 35dB. For 248 days between 7th April 2017 and 16th April 2018 the system recorded 12,245,708 data triplets (X/Y co-ordinates with sound levels).

Mapping (Figure 6-13) shows clear areas of high noise level around patient bed spaces. This indicates most of the louder sounds in the ICU are generated close to patients' heads.

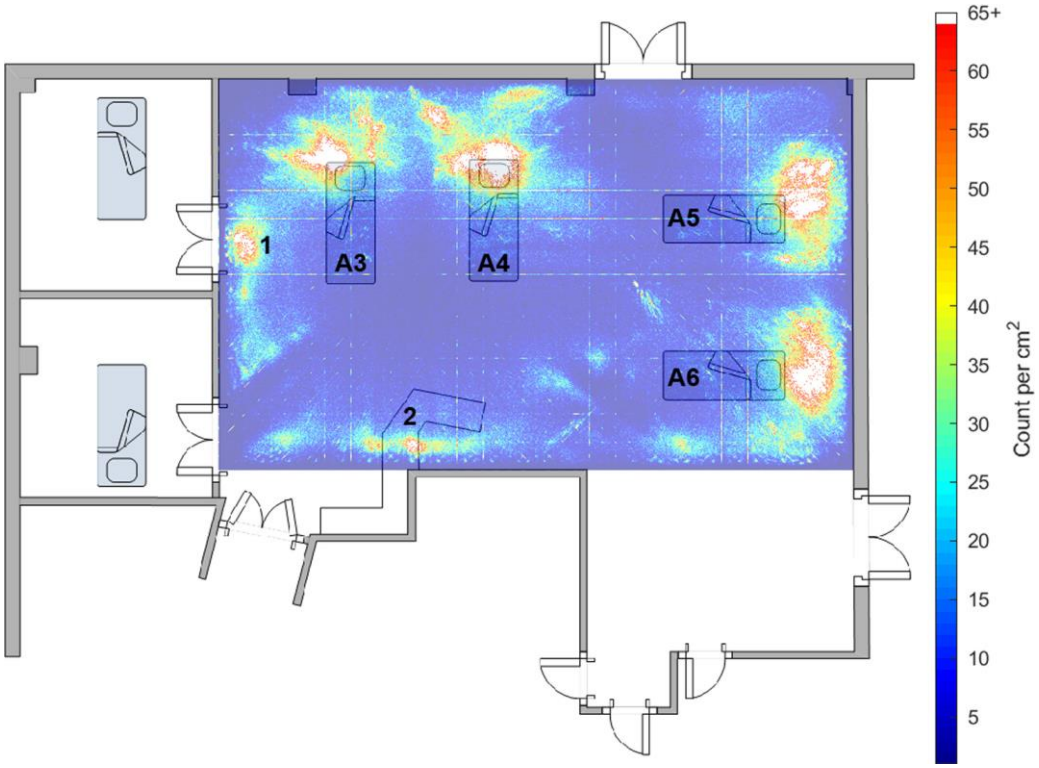


Figure 6-13: Plot of frequency of loud noises above 35dBA originating from each 1cm² of the ICU bay. The area marked '1' is outside the side room used preferentially for admissions. The area marked '2' indicates the location of telephones at the nursing desk.

Although overall sound level was lower in the early hours of the morning (Figure 6-7), the number of peak sounds was not discernably reduced between 04:00 – 05:00 when compared against early evening (Figure 6-14).

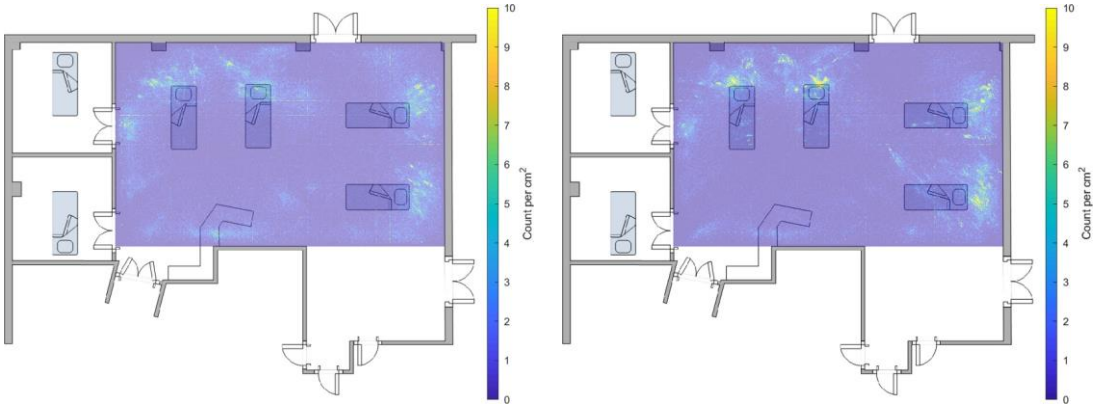


Figure 6-14: figure A (Left hand side) shows a plot of frequency of loud noises above 35dBA originating from each 1cm² of the ICU bay between 19:00 – 20:00; figure B (Right hand side) shows the same plot between 04:00 – 05:00

This suggests that patients may not experience the corresponding reduction in disturbance that the change in mean sound level implies.

6.6. Discussion

6.6.1. Summary of final results

No day LAeq24 was compliant with the WHO guideline limit of 35dBA. All single hour average sound levels were also higher. The lowest averaged hour level achieved was 39.6dBA. This was in the early hours of the morning.

Initial results were calculated using microphone number 40. This was one of the microphones in array three. Array three was positioned in approximately the same place as the standalone environmental sound level meter used early in the project. Results from microphone 40 formed the basis for the final study report submitted to the NIHR in April 2018.

Results from this single microphone demonstrate both statistical and practically meaningful differences in sound levels by the end of the project (May 2018)[38]. The final daily mean LAeq (30days) was 43.4dBA (SD 1.7). These results indicate a reduction of approximately 14dB from initial measures taken in summer 2013. These figures compare favourably with qualitative feedback from ethnography and ad-hoc discussion with staff that by early 2018 the ICU was a quieter, more restful place than it was in the latter months of 2014[39].

It is important to acknowledge this difference between results from the single microphone and microphone array.

It was a surprise when results from the full array were not in line with those from the single microphone. Microphone 40 was reasonably expected to provide data both broadly representative of the ICU (all microphones being omnidirectional) and comparable with earlier results.

The sound reduction seen with microphone 40 vanishes when data from the multi-microphone array are aggregated. Instead there is an indication the LAeq increased over time. The final LAeq (17th January – 31st March 2018) was 47.8dBA. This is consistent with other reports that ICUs (globally) are becoming louder over time [275] and that noise reduction interventions are difficult to sustain effectively for a prolonged period of time (chapter one).

Data quality checks confirmed that whilst each array differed statistically from each other (although not meaningfully in practice), individual data patterns were consistent within and between each array. Whilst this suggests data were likely accurate, it also suggests sound levels in the ICU are more variable and location-specific than expected. This has implications for the interpretation of standalone metres commonly used for routine environmental sound monitoring. It would seem that multiple sources of sound measures may offer a better reflection of sound level fluctuations within a defined environment such as the ICU. It is also important to recognise that the absolute difference between locations was quite small. A difference of just one or two decibels is not discernible to the human ear.

Given that sound level data appear sensitive to location and methods of recording and reporting, and that current standards seem inadequate for the ICU, new standards are perhaps needed. This would require central bodies such as the Department of Health or the Health and Safety Executive to engage and issue new guidelines.

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[38] Final results submitted to the NIHR as part of the project report were median(IQR) 46.1(5.7), maximum 99.3dBA. See appendix E for full report

[39] The full project ran from Spring 2014 – Summer 2018

6.6.2. Fidelity of data reporting

Increasing the fidelity of sound level monitoring demonstrated that sound levels fluctuate more than daily mean values indicate.

It was suggested (from a single microphone) that lower sound level values were more pronounced overnight. This overnight reduction has also been shown in another recent intervention study [263]. It is likely that focusing on the need to provide a dark, quiet environment (as much as this is possible in the ICU) to facilitate sleep is a key driver for change.

There has been much speculation on links between high noise levels, limited sleep, and developing delirium in the ICU. Outside of critical care there are known associations between poor sleep and disrupted psychological health [276,277]. Patients admitted to the ICU frequently attribute noise and disturbance overnight to their poor sleep [184,278-281] and a recent review has shown the risk of developing delirium in the ICU can be reduced by giving earplugs to patients [282]. This suggests that despite the development of delirium in the ICU being associated with severity of illness and some drug treatments [283], and studies recognising that just 11-17% of arousals overnight can be attributed to noise [284-286], sleep and noise do have a role to play in the physical and psychological recovery of patients admitted to the ICU [287].

It was unfortunate that data from the eight individual microphones were lost. During interface development (chapter seven), nursing staff specifically requested individual bed space sound levels. Their mental model [288] of the ICU centres on the patient. For nurses, bed space environmental sound level values are something they can equate directly to their patients' experiences of intensive care. It is also a physical space over which they can exert some degree of control.

The data demonstrate the ICU is significantly quieter at weekends. However, the difference between weekdays and weekends is just 0.2dB which is not detectable in practice. This similarity in sound levels suggests daily activity levels for the ICU remain constant which is perhaps not surprising as staffing levels are guided by the number of patients admitted. With reduced ancillary services available elsewhere in the hospital (scanning, x-ray etc) it might be supposed that interdepartmental transfers, reviews, and consultations would reduce at the weekend and that this might have an effect on sound levels. This assumption does not seem to be the case and sound levels are similar across the week; indicating that the soundscape of the ICU is principally affected by activities and behaviours within the ICU itself.

6.6.3. Sound source localisation

The spatial analysis suggests that higher decibel levels are likely to be generated by alarms and other equipment commonly at patient bedsides. Sound levels vary logarithmically with distance from the noise source [289,290]. The proximity of patients to noise source maximises the ill effects of high sound levels. Alongside the repeated sound peaks overnight, this may go some way to explain why the environment is not quite as 'restful' as average night-time sound levels suggest. With evidence that 90% of alarms are 'false positives' [291] and recognition that alarms can contribute to patient disorientation and distress [292], more needs to be done to reduce disturbance from patient monitoring equipment.

Relatively simple design changes to the environment are possible. Moving alarm speakers away from patients' heads, or even removing the alarm sounds from the environment altogether [293], would partially solve the problem by cutting patient proximity to loud sounds. Altering the 'systems design' of the ICU and other critical care areas by replacing auditory alerts with haptic devices worn by clinical staff is technologically feasible. However, when proposed as part

of the NIHR RfPB project, this was rejected by both patients and staff. Patients were concerned that staff would not react to a non-auditory alert and staff valued the in-built resilience that auditory alerts can be heard (and acted upon) by other clinical staff.

Noise cancellation (for example active headphones or ear plugs) might go some way to reduce the overall experience of sound but is most effective at frequencies below 500Hz. It is largely not effective for frequencies above 1,000Hz. Since alarm tones are high frequency (~2,500Hz), these would still be heard. Introducing white[40] or pink[41] noise may be effective and has been shown to improve working conditions in an open office [294] and to reduce annoyance in healthy volunteers [295]. It may also be possible to create individualised zones of silence [296] by manipulating the sound environment around patients' heads with acoustic masking or cloaking [297].

6.6.4. Loudness

The Zwicker 'loudness' calculation [261] produces a measurable value approximating the human experience of sound. Peak loudness values >90dB are frequent in the ICU. That these do not fluctuate much across 24 hours may go some way to explaining why meaningful changes in average sound level are hard to achieve.

As well as being high volume, the qualities of alarm sounds mimic the 'acoustic roughness' [298] of a baby's cry or human scream. A common sonic interval used for alarms is the tritone (two notes, three tones apart). The tritone is particularly dissonant and unpleasant to the human ear. This dissonance triggers an innate reaction within the amygdala, the area of the brain that process fear/danger responses [299]. Such is the visceral reaction to the tritone that it has been termed the devil's interval (*diablous in musica*) and was reportedly banned by the Catholic church during the Middle Ages[42]. Work is currently underway to reduce the harshness of alarms [300,301]. This is unlikely to reduce hospital LAeq24, but it may reduce disturbance and stress response.

[40] Broad-spectrum sounds resulting in a fairly high-pitched 'hissing'.

[41] Uses the same broad-spectrum as white noise but higher frequencies are modulated, reducing their prominence resulting in sounds that may be more pleasing to the ear.

[42] It is more likely that restrictive composition rules are the foundation of this urban myth. Early church music was strictly harmonious and the dissonant augmented fourth/diminished fifth was forbidden.

6.7. Strengths and Limitations

Strengths

- Using a microphone array was a novel method to analyse sound levels in the clinical environment
- Recognition of 'loudness' as an alternative, and potentially more appropriate, measure of noise and disturbance in the ICU

Limitations

- The array microphone system was not available early enough to allow detailed monitoring of changes in real time in response to interventions
- The technical complexity of the array system led to unpredictable failures; most notably this affected the eight individual microphones but also resulted in repeated complete system failure

6.8. Conclusions

The parallel processing features of Apache Spark meant data did not need to be down-sampled too early[43]. This preserved data fidelity and enabled more nuanced features of the sound environment to be explored.

Identification of 'loudness' seems a more meaningful measure of noise levels in the hospital environment. The daily mean (LAeq24) is particularly inappropriate for measuring sound levels in the ICU. The many high peaks influence the LAeq24, distorting the measure. Recognition of 'loudness' as a more representative value of noise levels as experienced by patients needs further investigation but is a promising alternative to the LAeq24 for environments such as the ICU where the problem is disturbance rather than hearing damage.

The multi-microphone array system identified that sound levels in the ICU are much more localised than perhaps previously thought. This has implications for future monitoring and potential interventions to reduce patient disturbance.

Nursing staff remain keen to see localised environmental monitoring (specifically individual patient bed space values) in addition to the identified principal areas of sound origination.

[43] Without Apache Spark the data would have needed to have been down-sampled ('averaged') at a much earlier stage. The more efficient use of processing memory within Spark meant that detail was not lost too soon.

6.9. Dissemination and impact

6.9.1. Acoustics

Müller-Trapet M*, Cheer J, Fazi FM, Darbyshire JL, Young JD, Machine listening in combination with microphone arrays for noise source localization and identification, 173rd Annual Conference of the Acoustical Society of America, Boston, Massachusetts, June 2017; The Journal of the Acoustical Society of America 2017; 141 3964 doi: 10.1121/1.4989025

Mueller-Trapet M, Cheer J, Fazi FM, Darbyshire J, Young JD: Acoustic source localization with microphone arrays for remote noise monitoring in an Intensive Care Unit. *Applied Acoustics* 2018, 139(October):93-100

6.9.2. International Symposium on Intensive Care and Emergency Medicine

The technical architecture used to analyse the dataset was presented at the 39th International Symposium on Intensive Care and Emergency Medicine (ISICEM), Brussels, March 2019.

The abstract was published in the Journal of Critical Care: Darbyshire JL, Young JD, Bedford J, Redfern O, Hatch RA, Understanding sound pressure levels in the intensive care unit, Critical Care 2019, 23 (Suppl 2): 72. doi: 10.1186/s13054-019-2358-0

6.9.3. Association of Anaesthetists

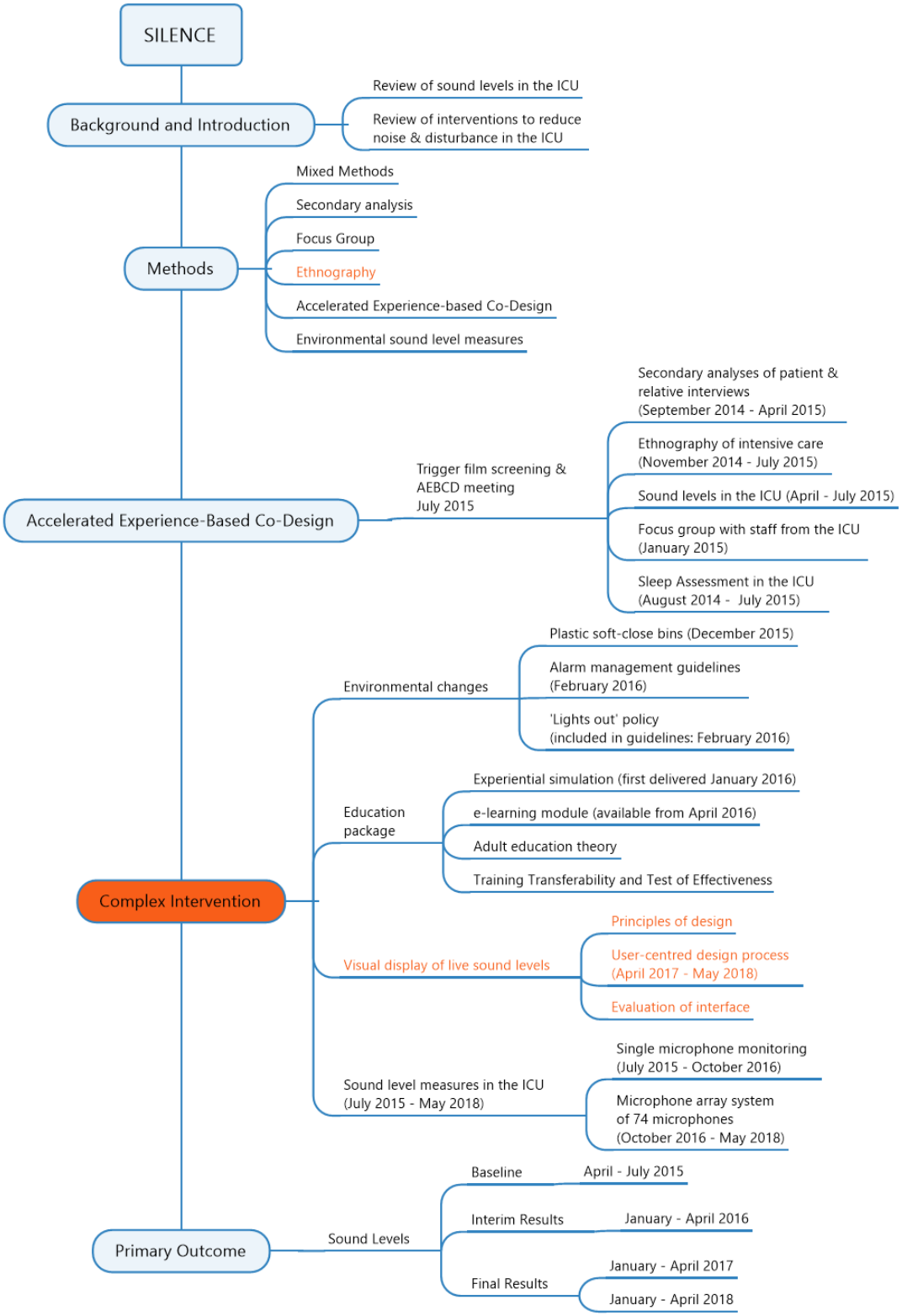
Findings from the source localisation sub-study were published in Anaesthesia, the official journal of the Association of Anaesthetists: Darbyshire JL, Muller-Trapet M, Cheer J, Fazi FM and Young JD, Mapping sources of noise in an intensive care unit, Anaesthesia 2019, 74, 1018–1025, doi:10.1111/anae.14690

6.9.4. Intensive Care Society

Julie Darbyshire is an invited speaker for the session 'Humanising the ICU/Building Better ICUs at the Intensive Care Society, State of the Art conference: Birmingham, December 2019'

7. Chapter Seven: Design and Development of interface

7.1. Chapter summary



The previous chapter explored the installation of a sound level monitoring system in the adult intensive care unit (AICU). This chapter describes how these data were presented to AICU staff. The needs and requirements for the interface were established by the qualitative phases of this project (chapters three and four).

A major focus of this chapter is the design principles required to ensure sound data are presented meaningfully. This chapter summarises graphical user interface (GUI) design and how this was applied to create a good user experience (section 7.3.3), and highlights weaknesses of existing systems (section 7.3.2). An overview of psychoacoustics (the experience of sound) is presented (section 7.3.1), along with human factors theories of user-centred product development (section 7.4) that are encapsulated in the 'agile'[44] design process (section 7.5). Finally, the chapter assesses the interface (section 7.6.3) and proposes future direction (section 7.8).

7.2. Aim

The aim of the GUI is to provide staff with real-time sound levels in the ICU to enable them to reduce noise and disturbance proactively.

7.3. Background

7.3.1. Measuring and reporting sound

Sound levels in the healthcare environment

A typical library is 35dBA, whilst a chainsaw is ~110dBA [259]. The current limit for road-legal car exhausts in the UK is 74dBA [302]. Sounds >200dBA can be instantly fatal [303]. Prolonged exposure >85dBA can damage hearing and requires hearing protection in the workplace [30]. By comparison, sound levels in hospital environments are typically 57dBA (chapter one, section 4.7). At these levels direct physical harm is unlikely but, as outlined in the previous chapter, the concern is that elevated sound levels will have more subtle effects, such as disturbing patient sleep, distracting staff, or hindering team communication.

It is known that ICU admission affects long-term mental health [74]. Patients can find the ICU highly distressing [36], and excessive noise related to staff activity and equipment are frequently cited contributors to patient anxiety.

Sound levels are difficult to manage in an ICU:

- An ICU has a semi-structured working pattern with superimposed periods of activity occurring randomly round the clock.
- Patients are closely monitored and supported by a wide variety of devices each with their own audible alerts, mechanical noises, and requirements for staff input.
- Alarms, by their very nature, are 'alarming' [298].
- The constant noise generated by staff and equipment places patients into a heightened state of alertness.

In an environment where peak sound levels >100dB occur up to 16 times every hour, even overnight [4], it is unsurprising that patients report alarms the primary barrier to good sleep [304].

[44] 'agile' design involves rapid prototyping and change which allows feature development to be evaluated quickly. The main advantage over more traditional linear product development is that features can be abandoned and replaced quickly if they do not perform as expected.

Reporting environmental sound: sound level weighting and loudness

The last chapter explained that the majority of environmental sound reporting uses the 'A-weighted' scale. This weights raw sound by frequency, excluding frequencies beyond the normal human hearing range. Despite this processing, A-weighted values still poorly reflect the personal experience of 'loudness'. Loudness is somewhat subjective, and depends on duration of exposure, pitch, tone, and information content of the sound [192]. The Zwicker method [261] is one method for calculating a loudness value which reflects a hypothetical 'average' person's perception of sound (chapter six, section 3.1). While the A-weighted scale is suitable for industrial settings where risk and assessment for physical harm is the objective, it is less suited to the needs of hospital patients where disturbances caused by sound are more subjective. The Zwicker loudness values[45] used in this project are thought to better reflect the human experience of sound.

Brief introduction to psychoacoustics

The AEBCD group felt strongly that commercial noise alert systems were not effective in clinical environments. They felt a better display of sound levels was needed to help staff manage noise and disturbances in the ICU. Both staff and patients thought it would be useful if this new display visualised qualities of sounds as well as reporting sound levels.

This is important because the human experience of sound described by psychoacoustics is more than simply volume. Two sounds of the same volume are likely to be found differently 'intrusive', 'annoying', or 'noisy' [192]. Sounds carry meaning in addition to the physical characteristics of the waveform, and meanings attached to sounds varies with culture and mental state. Higher frequency sounds are perceived as analogous to a scream or baby's cry. These can trigger startle responses or anxiety in ways that lower frequency sounds of the same volume do not. It is no accident that most alarms feature characteristics of these sounds [298]

While the words 'noise' and 'sound' are interchangeable in common use, they are not technically synonymous. 'Sound' is a generic term for an auditory stimulus; 'noise' usually indicates 'unwanted sound' which, by definition, must be perceived as either unpleasant or intrusive in some manner. To assess noise therefore requires a listener. Put another way, if a tree falls in a forest and no-one is there to hear, it could be said to make a *sound* but not necessarily a *noise*.

7.3.2. Interface design in the healthcare environment:

Twenty years ago, hospital environments were described as an 'ergonomic nightmare' [305], due in large part to poor integration between devices and systems in clinical workplaces. The NHS Long Term Plan [306] requires extensive assimilation of existing systems and new technologies. Whilst it is now relatively simple to record and export large datasets, storage and movement of data alone does not ensure success of electronic systems. Poorly designed systems can impair clinical team response [307] and new systems need to be designed and tested well. Frameworks for assessing new technology are still being developed and it remains unclear how best to evaluate new technology introduced into clinical use [308,309].

A key concept in the design of systems built to improve work flow, work conditions or efficiency is to minimise user cognitive load [310]. Displays should be clear, unambiguous and simple if they are to be effective. Each element in a visual display should be considered and reduced to its

[45] Calculated automatically within the new sound monitoring system built by the University of Southampton

simplest form whilst retaining desired functionality [311]. Antoine de Saint-Expury observed that 'perfection is achieved, not when there is nothing left to add, but when there is nothing left to take away' [312].

How information is presented on screen affects how users interact with it. Inadequately designed systems can worsen team actions, or make them slower [307]. The example screenshot (Figure 7-1) is typical of electronic patient record systems available within the NHS, and illustrates this point well. The image is taken from a simulated version of Cerner Millenium®, and illustrates display of clinical observations, such as blood pressure and heart rate. As a display it is highly complex and inefficient to navigate, especially for those unfamiliar with the system. This is not unique. Many systems have been shown to be suboptimal, with several usability "challenges" identified [313,314].

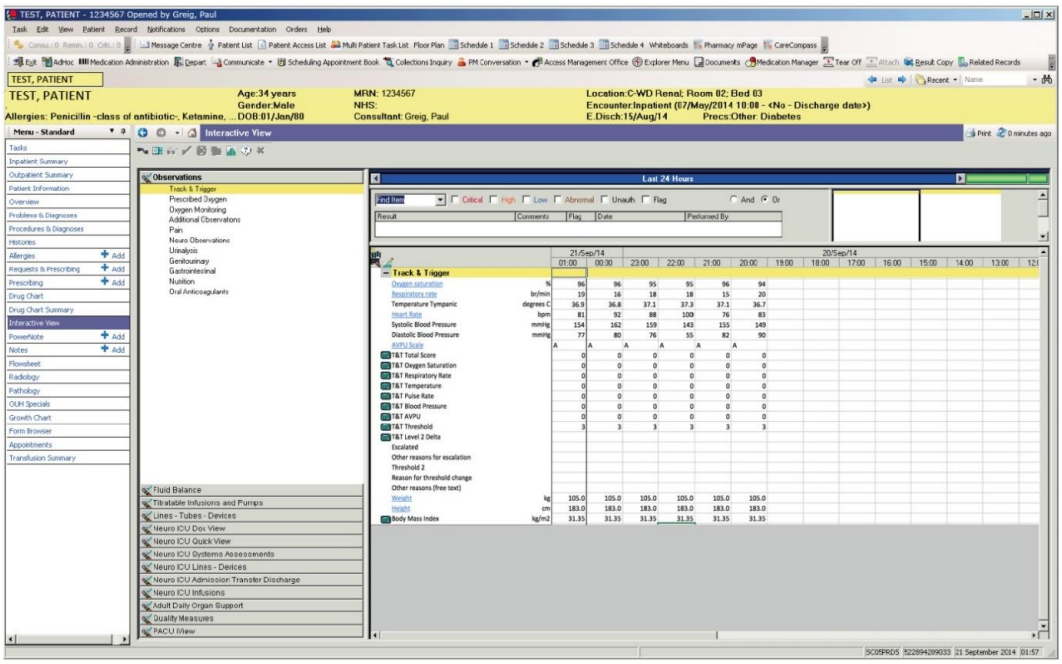


Figure 7-1: Screenshot of the Cerner Millennium® electronic patient record

In contrast, the simplicity of the patient monitor from AICU (Figure 7-2), displaying the same core data, is striking. It is quicker and easier to locate items of interest because of display organisation. There are well-established design reasons why user performance using these interfaces should be different. These are explored in the next section of this chapter (0). Briefly though, to ensure systems are usable in real working conditions, it is important that from early in the design process designers understand the purpose for which displays will be used, and the key features that users need from them.

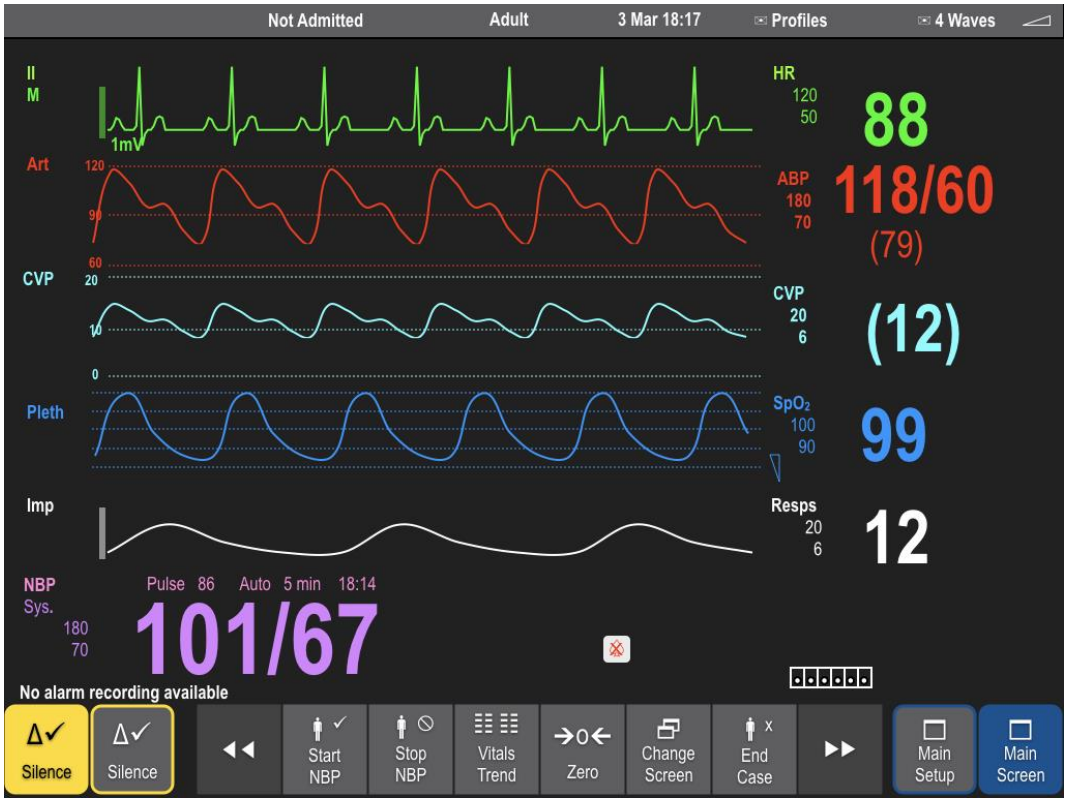


Figure 7-2: Screenshot of a Philips Intensive Care Unit patient monitor

The goal of good design is 'usability' (defined as 'effectiveness', 'efficiency' and 'user satisfaction' [315]) with minimal adaptation required of the user. Good design is achieved when a product (or object, or environment) is "usable" by as many people as possible without modification or detailed explanation. Many technological systems fail because their 'conceptual image' (the model that the user generates of how the system performs, what the information it displays means, and how they can influence the working of the system [316]) does not match reality. Through good design designers can communicate correct conceptual mapping to users more clearly [316]. This leads to an efficiency in use that encourages effectiveness. In healthcare this can be recognised in the pulse oximeter. A waveform indicates both pulse rate and signal quality and a corresponding pattern of rising or falling audible tones indicates change in clinical values. It would be baffling if falling tones indicated rising levels.

7.3.3. Principles of good design

There are six key principles of good design that informed this phase of the project. These ensured the system accommodated users' needs and requirements, that it was straightforward to use, and communicated information clearly.

Accommodate *users' expectations*

For users accustomed to reading from left to right, visual presentation should be mapped to a 'Z pattern' [317] (Figure 7-3).

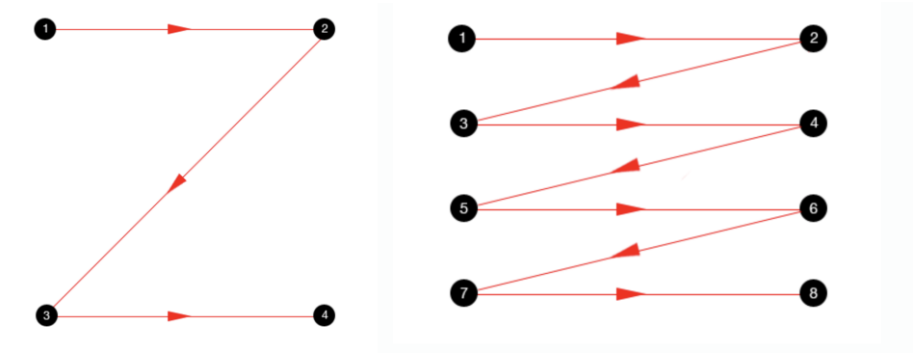


Figure 7-3: Z-pattern of information processing

There is a natural tendency for Western readers to look at a graphic-based display from the top left and scan right before sweeping to the bottom left and moving horizontally again. This can be manipulated into a zigzag by using strong horizontal elements, but these stereotypical scan paths mean that crucial information, particularly 'storytelling' elements, should be positioned predictably. The Cerner Millennium® system fails with excessive use of vertical lines coupled with misaligned text preventing natural z-sweeps. This requires more effort to interrogate, and makes visual search slower.

Information should be presented hierarchically, with critical information at the top, analogous to a headline. This ensures critical information is encountered first and frequently [318], and enables early comprehension of the gist, or purpose, of the display. Users can then interrogate remaining data as required.

Comprehension can be further facilitated by removing visual clutter. Design simplicity should aim to reduce "interference effects" [319] that can create conflicting mental processes and increase cognitive load. Designers describe the compulsion to fill all available space as *horror vacui* (a fear of emptiness). It creates excessive crowding of distracting interface elements making it difficult to identify essential information, and it becomes harder to signify how and where a user can interact with the system. Hiding non-essential information until requested by users is a common solution to achieving interface simplicity. The ubiquitous [320] (if not always intuitive [321]) 'drop down menu' is a simple but well-established method of progressive disclosure [322] that hides complex functionality behind an initially simple interface. This allows blank spaces around critical values to create local contrast, easing user recognition of key information. Clinical monitors do this routinely, hiding set-up controls behind touch screen menus. The Cerner Millennium® interface again fails by placing target parameters in a busy display with little blank space.

With an understanding of visual attention, it is possible to manipulate how users interact with an interface. Attributes such as distinctiveness, colour, or size are processed faster than semantic meaning, and this can be used to control attention to the 'target value' [323]. Objects that are locally distinctive 'pop' out of their background and users are primed to notice them rapidly

with minimal cognitive input [324]. Designers can control this by understanding how **typography**, colour, and rules of design can work together to direct the eye.

Wayfinding

It is important that areas where users can interact with the system are clearly signified [316] and that users know where they are in the workflow. This is termed 'wayfinding' [325] and is analogous to navigation through real physical environments. Complex physical systems such as the Transport for London (TfL) network handle thousands of unfamiliar users every day, generally with few route-finding problems. TfL achieve this by rigidly enforcing standardised typography and symbology [326], coupled with readily available system maps reassuring users of progress.

The digital equivalent means ensuring clarity of hierarchy, progression, and objective. Relationships between features can be conveyed by 'chunking' data units together, suggesting connectedness through proximity, colour palette, or framing groups of related items. Chunking data into groups of three to five, particularly in environments where concentration may be compromised will maximise user ability to use information to solve a problem [327]. This is consistent with theories of short-term memory capacity [328], and generally a small number of chunks is recommended [329].

Adding visual elements to group items is not totally risk-free, as seen with the Cerner Millennium® display which disrupts Z-scanning patterns [330]. Designs with fewer 'chunks' that are horizontally and/or vertically aligned are simple visually and require less cognitive processing [324]. This is one reason why clinical values in the patient monitor are easier to find than on the electronic patient record. Users are able to focus easily on relevant information faster, leading to a more efficient system.

Typography

Typography is a significant part of informational displays that serves two major functions. Firstly it creates visual identity, and secondly it helps convey relationships between different parts of the system. The font New Johnston, used by TfL, is a well-recognised example that unifies disparate components of a single network. More than just an exercise in branding, this reassures users as they move through the different parts of the network that they are still interacting with the same system.

There are also important usability concerns to consider. The choice of typeface can affect readability, and recommendations differ for electronic or print media. Whilst serif fonts such as Times New Roman are often considered more comfortable to read on paper, lower resolution digital displays can blur serif details. Sans-serif options such as Helvetica are generally recommended for digital displays [331,332].

Finally, humans generally find rounded shapes more visually appealing than those with hard edges [333], possibly because of a subconscious association between hard edges and danger [334]. It may also be related to the concept that most humans (and many other mammalian species) display a preferential bias towards 'baby face' features [335]. Rounded typefaces such as Verdana or Calibri may be more attractive to software users than more linear fonts, for example **Impact** or Arial [336].

Aesthetics should not be ignored. People perceive aesthetically pleasing designs more favourably, and products which are 'accessible by design' [337] are more likely to be successful and long-lived. Awareness of this can help engineer positive relationships between end users and the product. Cerner Millenium® undoubtably has a dated 'look' to the design. This will influence

perception [338] and may lead users to feel they are using old technology. This may trigger feelings of demotivation and lack of trust associated with a sense of low investment [339]. A poorly designed system is likely to have effects that reach beyond immediate usability and performance of the system itself.

Colour palette and cultural connotations

People are attracted to bright (as opposed to muted) colours, but excessive variety in colour appears garish and contributes to visual 'noise'. A restricted palette is recommended for application designers [340]. Distraction is a barrier to users achieving their desired action and a good rule of thumb is to design initially in greyscale and only add colour for emphasis. Use of a colour wheel aids choice of harmonious colours that complement or contrast [341]. Cerner Millennium® for example (Figure 7-1) has no obvious purpose in its colour use. Colours are neither complimentary nor contrasting and prediction of meaning signified by colour is limited, resulting in inefficient searches.

Colours can be used to convey messages. Red hues for example are often reserved for warnings, or to indicate heat. UK weather maps scale heat by colour from blue (cold) to red (hot), but these conventions are culturally dependent. In some parts of Africa the hot tap is coloured blue, while the cold is red [342], and in China red is specifically associated with good fortune [343]. Variations in cultural colour connotation are illustrated in Figure 7-4) [344] and it is important to understand local conventions to ensure appropriate design choices.

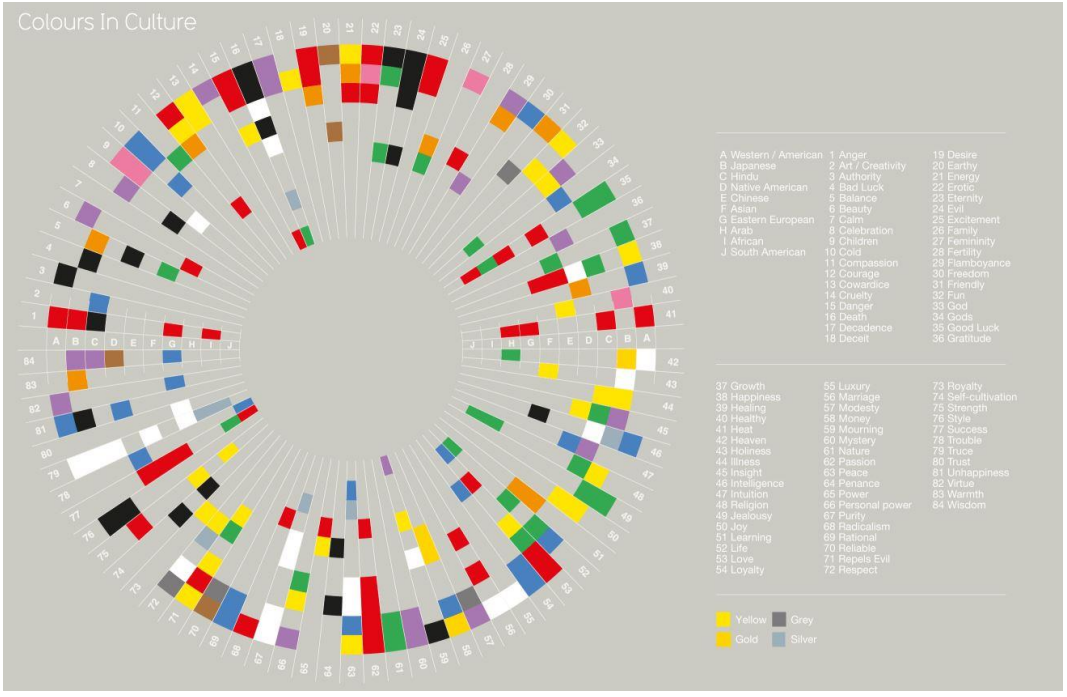


Figure 7-4: Colours in Culture, David McCandless, CC BY-NC 2.0

Consideration should also be given to how a display might appear to users with dyslexia[46] or colour blindness[47]. Commonly colour blindness affects red/green differentiation, sometimes extended to related colours such as oranges or browns. Other colour combinations are also affected so displays should avoid colours that can be commonly confused. Some colour

[46] Up to 10% of the nursing workforce admit to having dyslexia.

[47] The UK prevalence of colour blindness is approximately 8% in males and 0.4% in females

combinations can help those with dyslexia but this tends to be individual preference [345]. Generally, colour is better used as a categorical differentiator rather than as an indicator of a quantitative difference in data [346]

Iconography

Well-drawn graphics convey complex messages more efficiently than text, provided the meaning of the illustration is part of a shared mental model [288] between designer and user [347].

Icons that are visually similar to physical objects are common in graphical displays and are used to both communicate information and conserve display space [348]. It is common for new systems to use symbology associated with a familiar technology to support users' conceptual model. Using iconography that resembles physical devices ('skeuomorphism' [349]) is primarily intended as a short-cut to understanding the purpose of features in a new system. Examples are the 3.5" floppy disc (🖫) indicating document storage on a computer hard drive, or a telephone (☎) to show where to enter a phone number. These bear no functional resemblance to how modern systems actually handle these inputs, but this knowledge isn't necessary for successful operation, and iconography capitalises on understanding users already possess. The risk of skeuomorphic conventions is that they can become outdated as fewer and fewer users are familiar with the legacy system [350]. The floppy disc for instance has not been in common use for over ten years and is essentially obsolete.

As with colour connotations, it is possible to exploit conventions to simplify information transfer using iconography. The '+' and '-' symbols can denote a number of specific actions but generally '+' indicates more of something, and '-' less. More arbitrary symbols such as 🔍 need context and learned association to confer meaning. In a web-browser most users will interpret this as 'search', whereas next to an image it is likely to suggest 'magnify'. Iconography choices are fundamental decisions in any new design.

Convergence: people like what they already know

When Apple designed the iPad they used familiar conceptual features. This allowed them to explain 'you already know how to use it' [351] despite it being a brand-new device. Whilst people may not have seen a touch-screen before, the gestures used to manipulate the screen imitated actions in the physical world, and were intuitive. The majority of users did not need to be taught how to use the iPad. This, ultimately, led to satisfaction when using the device, and successful product roll-out.

A recent survey of anaesthetic monitors found users made fewer information search errors when using an interface configuration with which they were familiar. This was despite them not always being able to proactively identify their usual configuration accurately [352]. When thinking about a GUI, it is important to consider other interfaces in use in the intended environment. This is especially true for an ICU where there are perhaps more devices in common use than in other clinical areas. A new interface needs to be distinctive, but also familiar.

7.4. Methods

7.4.1. User-centred design

The design process for this project was iterative, beginning with definition of a user persona. User personas are theoretical constructs representing key or archetypal users [353]. They help contextualise the design in the real world [340]. The creation of this representative user was

mapped to the needs generated by the AEBCD group (described in chapter four) coupled with ethnographic observations (chapter three).

The staff group with the greatest numbers in the ICU is nursing. A 'goal and role' based user persona [354] of a typical nurse was created by five nurses with a range of seniority (NHS Bands 5-7) and experience of working in an ICU. This group members were asked to think about their goals during a shift, activities carried out, expectations, and frustrations.

Since 90% of the nursing workforce is female [355] the group created 'Suzanne'. Suzanne is a staff nurse of moderate experience working in a general adult ICU. For the purposes of developing the user persona and understanding how she might interact with the new system, a typical 'user journey' was planned using a hypothetical admission of a patient from the operating theatre. This event was chosen as a representative and commonplace activity associated with heightened workload.

The goals of the working system (understanding and contextualising changing sound levels in real time) were considered against each clinical task in the admission process (handover, transfer of equipment, drug requirements, patient assessment, washing and repositioning of patient). Predicted sound level changes associated with each stage of the user journey were mapped against how aware Suzanne is likely to be of these in real time, and how her stress levels vary during the tasks. The purpose of this user journey mapping is to identify 'pause points' [356] when Suzanne will most benefit from additional information about sound levels.

7.4.2. Iterative design

With this archetypical user's needs in mind, iterative cycles were undertaken to assess each new version of the interface according to the three dimensions outlined in ISO 9421 (effectiveness, efficiency and user satisfaction) [315]. Iterations were rapidly prototyped in response to user feedback (Figure 7-5) according to an 'agile' design process [357].

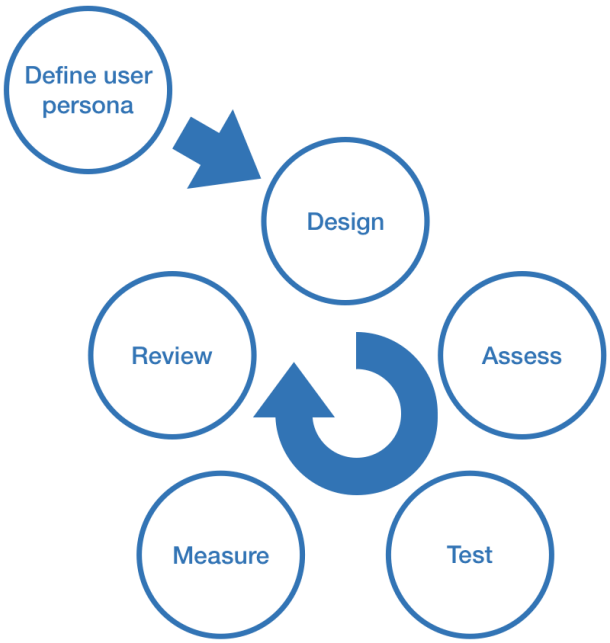


Figure 7-5: the iterative design cycle

Each iteration was explored primarily using the 'talk aloud' method [358]. Other methods included semi-structured discussion, including exploration of sound levels understanding and how users thought a new GUI of sound levels might integrate into workflow, and simple questionnaires. During talk-aloud sessions users were asked to describe their interactions with the system and verbalise their actions. They were specifically questioned about workflow, how they expected to achieve their objectives, and what their understanding was of each piece of data the system presented. Responses were summarised and benchmarked against intended goals of the interface.

Display use was assessed by in-situ ethnography. The display was active for the duration of the observation sessions only. Field notes captured a description of the environment with a particular focus on how people interacted with the GUI. Live sound levels were recorded alongside behavioural observations. Where clinical staff engaged and asked questions about research activities, opportunities were taken to explore their understanding of the display and how they felt awareness of sound levels in the ICU had changed since late 2014 when this project started.

7.4.3. Visual Clutter

Visual clutter can predict information search efficiency [324] related to screen complexity [359]. An example screenshot from each iteration was measured using the Feature_Congestion package [360] running in MATLAB (MATLAB r2014a (Mathworks UK, Cambridge, UK) as described by Rosenholtz et al [361]. This analysis produces two measures of visual complexity. The first (feature congestion) conveys clutter, and predicts the difficulty of locating a new variable if it were to be added to the display. The second (sub-band entropy) is related to the raw amount of information available and is influenced by the number of features, colours, and shapes. These values correlate well with real-world performance in visual search tasks [359]. Displays with higher values are less organised and more difficult to search.

7.4.4. Patient Involvement

Exemplar screens were taken to the OUH ICU Patient Forum meeting on 22nd May 2017. This group of ICU staff, patients, relatives, and members of the general public meet regularly with the aim of improving services delivered to patients. Membership fluctuates but some members in May 2017 had been part of the original AEBCD group (July 2015) that proposed noise reduction opportunities using a real-time display of sound levels in the ICU.

Feedback from the group was incorporated into final design/functionality, and the final working prototype was presented to the group 21st May 2018.

7.5. Results

7.5.1. User persona

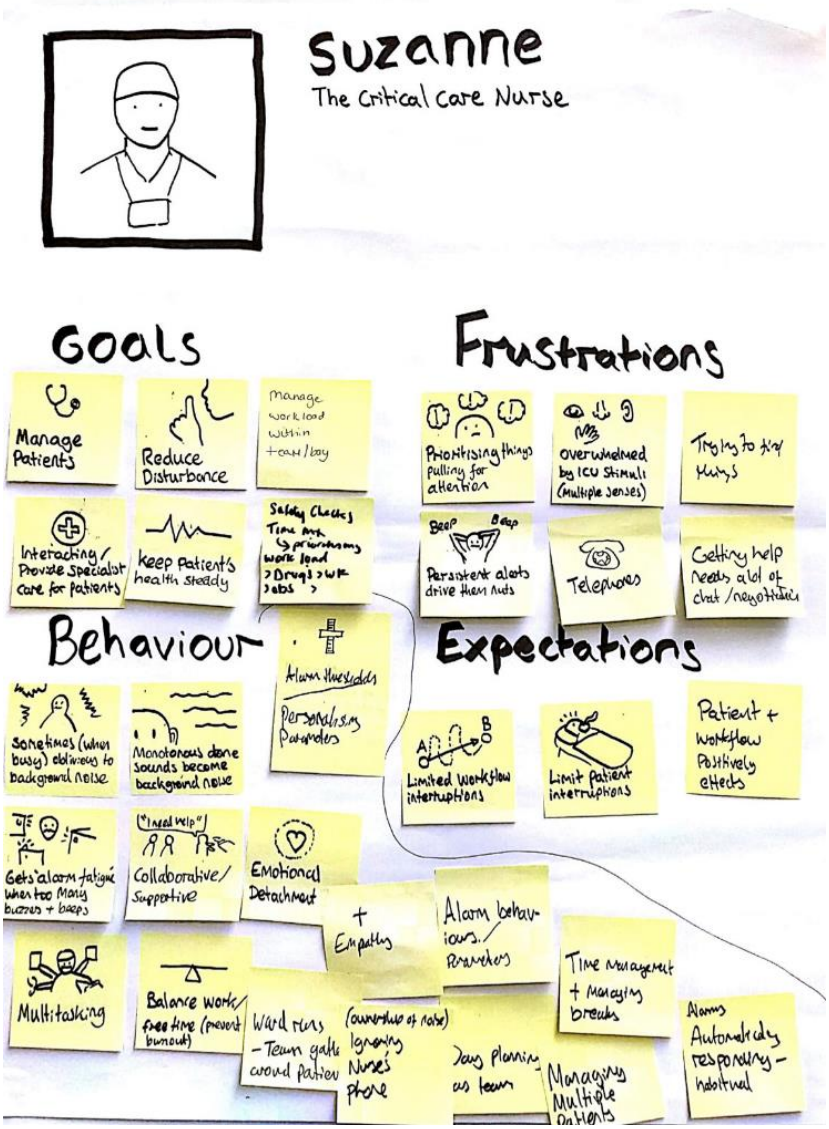


Figure 7-6: Suzanne – intensive care nurse & key user of interface

A realistic and detailed persona description helps the product design team understand the end user and how a solution to their real problem may be realised. By recognising the needs of a typical user, their expectations of the product, and how the product will fit existing tasks or processes, the design team can optimise the product and maximise chances of successful deployment and adoption.

From notes created during the group discussion (Figure 7-6) the persona description was created: Suzanne's primary goal is to manage her patient's wellbeing by providing specialist care to maintain a 'steady' state of health and reduce disturbance. To achieve her goal she expects limited interruptions to her workflow and does not want to disturb her patient more than necessary. She is frustrated by anything she perceives as preventing her from achieving her goals. Such barriers include being overwhelmed by the multiple stimuli in her workplace and the many demands on her attention. She is particularly bothered by telephones and persistent alerts from patient monitoring systems, finds it time-consuming to negotiate for help, and is irritated when unable to find equipment she needs.

Her 'sense of self' is that she is caring and empathetic, an integral part of a collaborative and supportive team, and effective at multitasking. She can also feel emotionally detached from her work and she worries about the balance between her work and free time. She is worried about burnout.

When thinking about sound and noise in the ICU Suzanne aims to manage her patient's alarm thresholds (thus limiting disturbances) by personalising parameters but admits she can habitually respond to alarms somewhat reflexively. She can also be oblivious to background noise which can feel like a monotonous drone. She is aware that when there are too many buzzes and beeps she can suffer from 'alarm fatigue'.

7.5.2. User journey

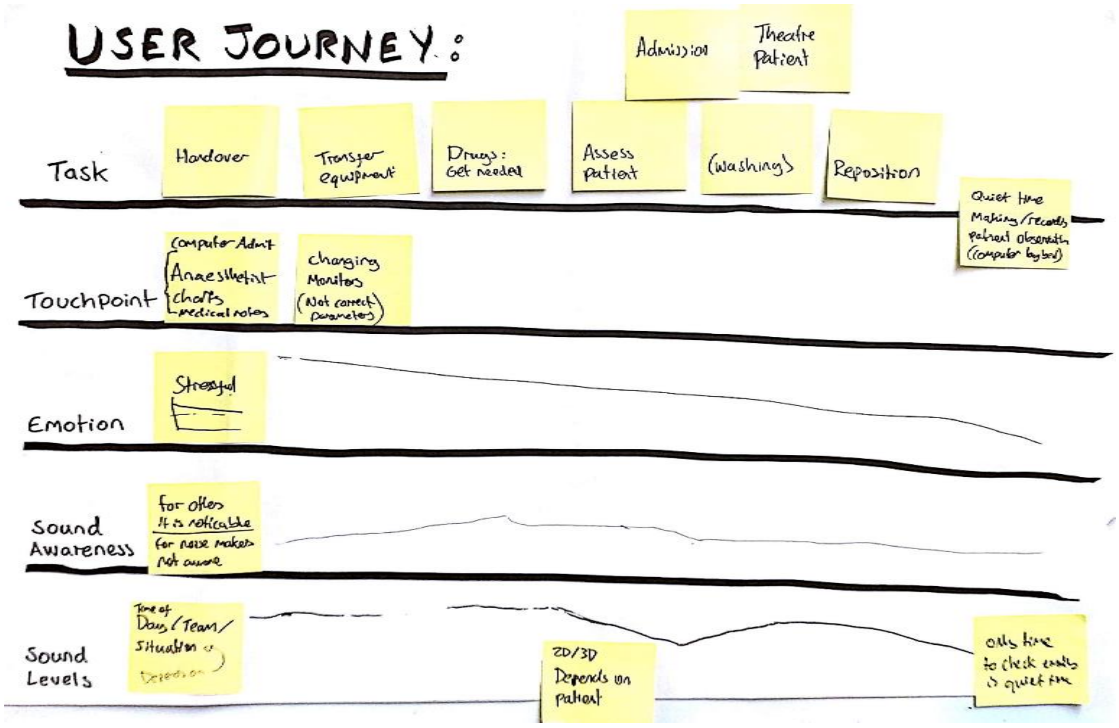


Figure 7-7: User Journey during admission of a patient to the intensive care unit from theatre

A user journey was used in combination with the user persona to identify how best the new technology might integrate into existing workflows. Admitting a patient from theatre is a common task for nurses in the ICU. The nurses reported Suzanne would be under stress during this journey (Figure 7-7). On the patient's arrival she does not know exactly what is needed and she needs to assimilate a lot of information from multiple sources. She needs to transfer the patient from one set of monitoring equipment to another, likely changing settings and triggering 'disconnection' alarms in the process. As she becomes more familiar with her patient, her anxiety levels fall and her situational awareness increases. Retrospectively, Suzanne is aware that the admission process was disruptive for other people, but she admits that "in the moment" she is unaware of the disruption her team is creating.

These findings were validated against ethnographic observations and staff focus groups reported in chapter three of this thesis.

7.5.3. Design iterations

There were four iterations of the GUI between April 2017 – April 2018 (Figure 7-8). These are outlined below.

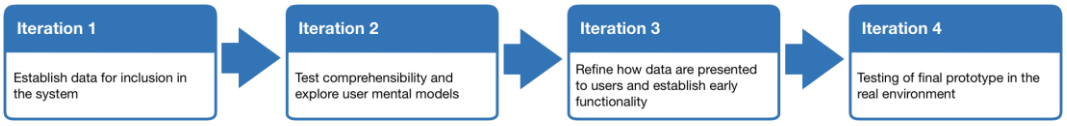


Figure 7-8: Iteration progress

Iteration 1

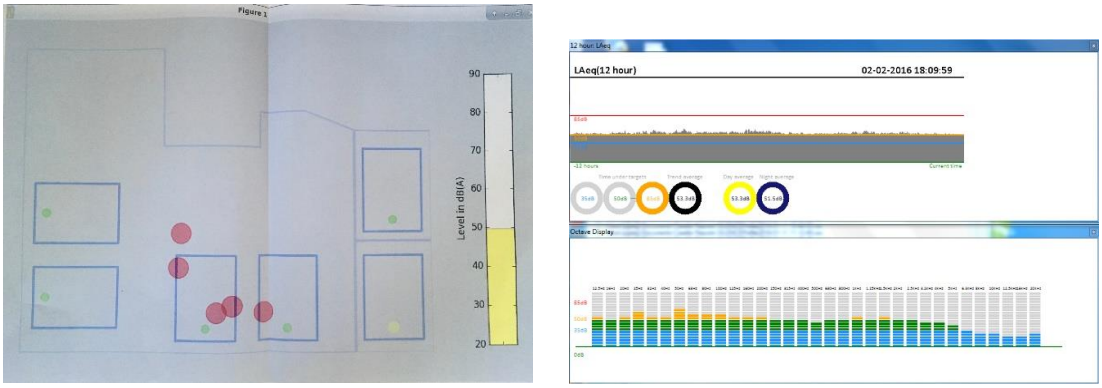


Figure 7-9: Iteration 1a (left) and Iteration 1b (right)

- **Format:** Paper
- **Functionality:** None
- **Priority:** Data for inclusion
- **Testing group:** 10 AICU nurses (seven female)

Two prototypes were developed (Figure 7-9) and presented for think-aloud review. The testing group was invited to make their own suggestions for the interface. Participants were also asked some general questions about their understanding and experience of noise levels in an ICU. This was to ascertain how much information could, or should, be displayed.

Of the ten individuals who reviewed these initial designs, only one was unaware of the SILENCE project. This was a new recruit (start date not recorded). Four individuals were also aware of the noise management guidelines developed as part of the SILENCE project (chapter four, section 6.2), but only two had read them. When prompted for detail of what they could remember from the guidelines, both individuals highlighted that reducing noise at night was especially important. Of those who hadn't read the guidelines, three also mentioned the importance of reducing noise overnight.

Three of the ten people had completed the experiential learning session and four had completed the online module. Six of the ten had completed at least one of the training options in the last six months, but four reported they were unaware of the teaching.

When offered a tick list of noise-related information they would want displayed on a screen, seven wanted 'noise level', five requested 'location', six thought 'source/type of noise' would be useful, and two were interested in the 'severity' level. When prompted for their own suggestions five people wanted "tips", "suggestions", or "reminders" about how to keep noise levels lower and four wanted to see "trends" or "comparison" data to assess current levels against a target.

Several thought this display would be best as a wall-mounted screen near the central nursing station. Six suggested it should be accessible from computers at each bed space.

Interface 1a:

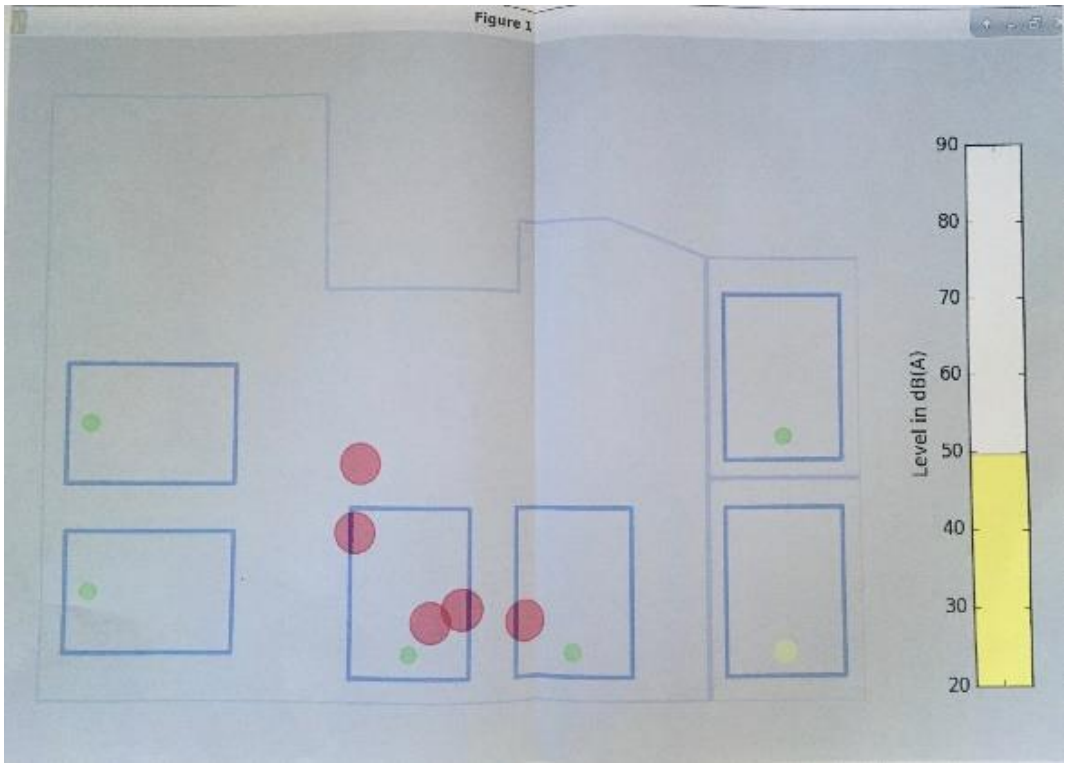


Figure 7-10: Interface 1a

Summary of comments

- The grey background was felt to be dull.
- Everyone recognised the floorplan as Bay 'A' of the AICU.
- Most people understood the red spots indicated 'hot spots' of high sound level.
- Some incorrectly interpreted the smaller green or yellow spots as indicating bed occupancy.
- Universal request for a 'key' to explain colour scheme associated with sound levels.
- Opinion on overall 'look' of the design varied.
    - Clarity and simplicity thought to be good
    - Needs more colour/interest to attract attention

Interface 1b:

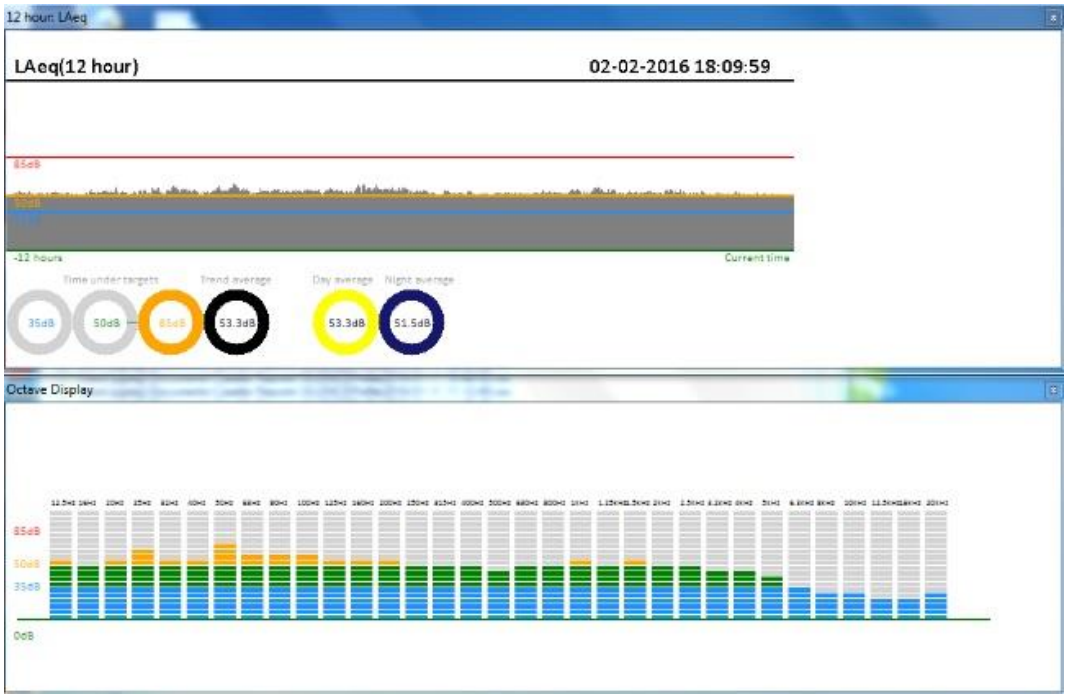


Figure 7-11: Interface 1b

Summary of comments

- Colours attractive & bright (although possibly too much use of colour).
- The 'time under target' circles were not understood.
- Frequency ranges and associated sound levels poorly understood.
- As with interface 1a, a 'key' was requested
- Overall it was felt this design presented too much information.

Staff-designed interface layouts

When staff were offered the opportunity to design their own interface results varied from the very simple (participant 4) to the complex (participant 8). All examples can be seen in Figure 7-12. Individual displays can also be found in appendix D.

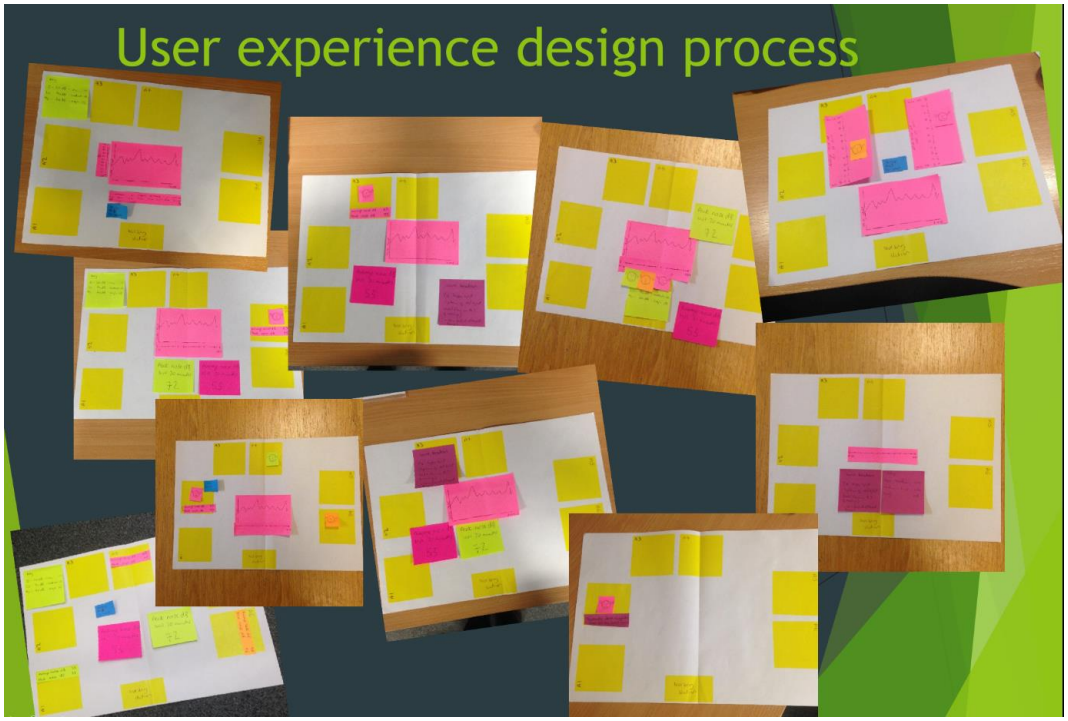


Figure 7-12: User-designed interface layouts

From these, elements of the interface were classified and grouped. This process identified elements frequently requested as well as outlier options that were each proposed by just one user (Table 7-1).

Features requested by staff for inclusion on display interface			
N ≥ 5	n = 4	n = 3	n = 1
Trend Graph (n=7)	Sound levels / shift timeline	Location of sounds	Text statement about sound levels over the last 15 minutes
Face icon with expression (n=6)	Peak sound level in the last 30 minutes	Average decibel level during the shift	Key to colour coding (without values)
Average sound level over the last 30 minutes (n=5)	Include a key to colour coding (inc. sound values)		Classification of sound
	Average & peak value from last 30 minutes		24 hour timeline of sound levels
			Peak & average sound levels over the last 30 minutes (with timeline)

Table 7-1: Features suggested for inclusion by staff

Based on the findings from this first iteration, two exemplar low-fidelity interface designs were generated for iteration 2, which (in addition to the basic floor plan [bed spaces marked A1 – A6 in the schematics]) varied in their level of information complexity (Figure 7-13).

Iteration 2

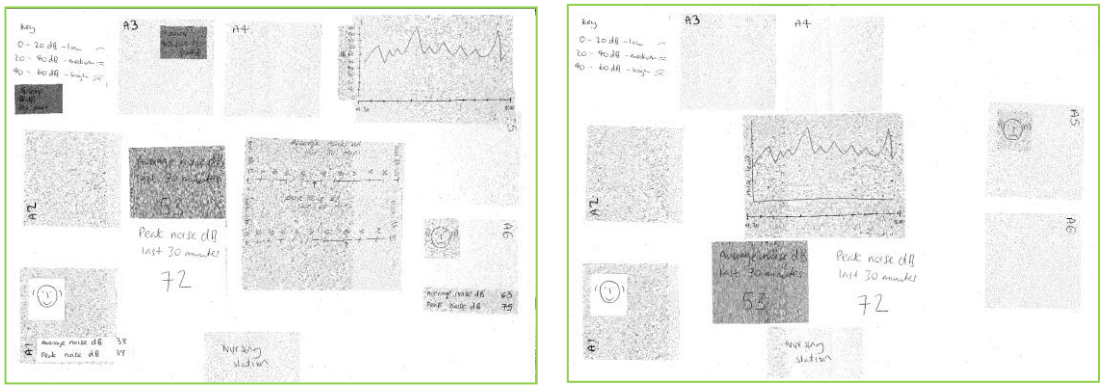


Figure 7-13: Iteration 2a (left) showing the complex design schematic and Iteration 2b (right) showing the simple design schematic

These schematics were translated into non-functional prototypes (Figure 7-14). One version was given a dark background to explore concerns regarding light pollution that might be generated by the display. The 'complex' version incorporated all features suggested by >1 individual during initial user testing.

Despite its popularity (n=6), the happy-face/sad-face icon requested was not adopted due to potential for misinterpretation by relatives or patients.

These prototypes were presented to a user panel for think-aloud review.

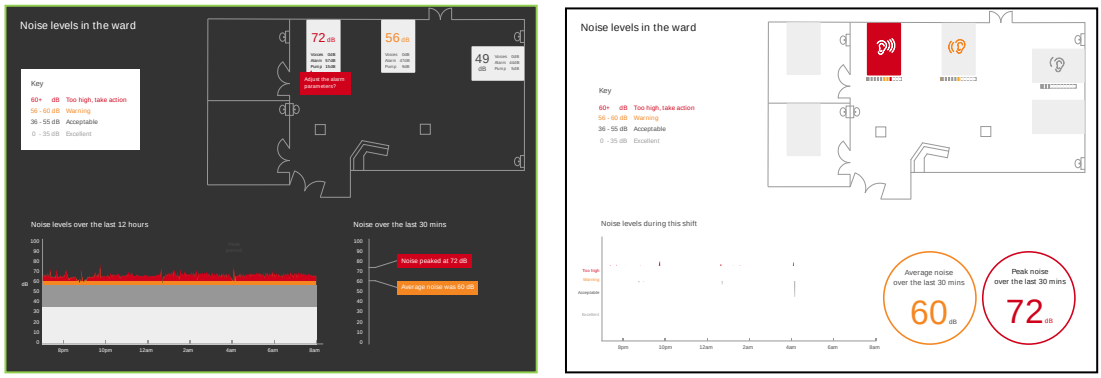


Figure 7-14: Iteration 2a (complex design prototype) and Iteration 2b (simple design prototype)

- **Format:** Paper
- **Functionality**: None
- **Priority:** Mental model testing & user understanding
- **Testing group:** 8 AICU nurses, 1 AICU registrar

Review of these second iterations led to a formal specification (appendix E). This was supplied to Oxford Computing Consultants, Oxford, UK (OCC) who created a functional electronic version used for subsequent iteration.

Summary of feedback

- Users expressed a strong preference for numeric values over icons indicating volume.
- Users were divided between wanting patient specific values and not.
    - Some were concerned the information was confusing / data overload
    - Some felt this detracted from the team environment
    - Some thought this indicated the importance of the patients in the environment
- Most (but not all) liked the key.
- The dark background was felt to be less obtrusive and more suited to the clinical environment.
- There was some confusion between individual bed space values and overall unit measures.

A hybrid version incorporating comments from both phases of testing was taken forward to allow the development of interactive elements.

Iteration 3

Specifically for iteration 3 (Figure 7-15), display elements were split into separate screens allowing for progressive disclosure of information. This simplified the display and allowed for distinction between data on real-time sound localisation and overall environmental trend values. An icon (miniature floorplan) controlled switching between the map screen (displaying source location of sounds) and overall sound levels. Historical timelines were accessed by tapping relevant circles.

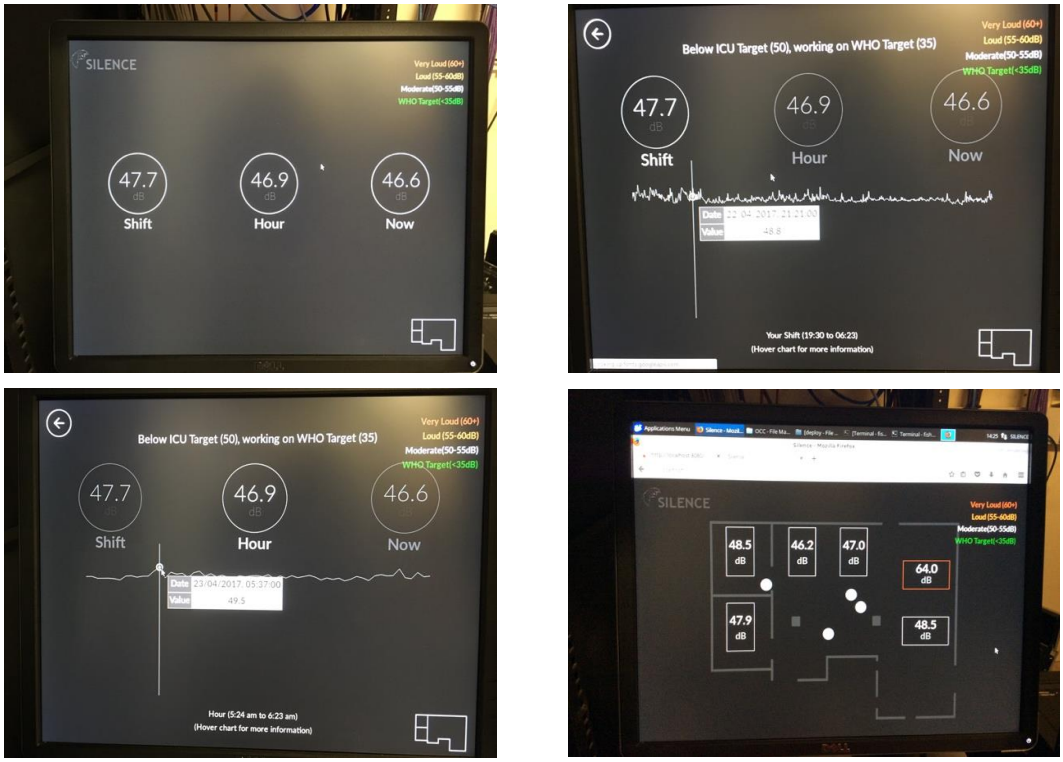


Figure 7-15: Iteration 3 included an overall sound level display (top left), an overall display with trendlines for the last shift (top right) and hour (bottom left), along with a unit map displaying localised sound levels (bottom right). This iteration was interactive and allowed screens to be encountered progressively.

- **Format:** Electronic
- **Functionality**: Interactive
- **Priority:** Refining data presentation
- **Testing group:** 6 AICU nurses, 3 AICU registrars, 1 physiotherapist, 1 pharmacist

This was the first functional version. Tapping circles called up timeline trend graphs. Tapping the floorplan icon (bottom right) switched mode to show sound localisation. General comments were that the timescale visuals indicating peaks were understandable and useful, but labels were needed on graphs. It was clear from observing interactions with the prototype there was an implicit understanding that the display was capturing real time data but the 'refresh' rate (about every two seconds for the prototype) was too frequent and overwhelming ("the rate of change is difficult to follow…it's all over the place"). It also became clear that the most recent values (displayed as now) were a snapshot time delayed by ~30 seconds. These values were not credible as current.

The system was designed to present contemporaneous sound levels and historical values. There was little consensus over what periods these data should average. Anything from thirty seconds through to a full shift was suggested. With no unanimity from the testing, three timeframes were chosen: average sound levels for the current shift, the last hour, and "now" (in fact averaged over the previous fifteen minutes, smoothing overly frequent updates).

The system made use of progressive data disclosure. Circles on the primary (landing) screen were also 'buttons' that displayed more information when activated. As well as being a pleasing shape, the circles mimic the traditional shape of a physical button. The intent was that they did not need further indication that this was an affordance [316] of the interface that would access additional information. Tapping on these accessed trendline graphs showing historical data plotted against time.

The heuristics of the system were based on spatial and temporal understanding of the ICU environment. The icon used to signify access to the spatial noise locator was a miniature map of the ICU bay. This was recognised by everyone and required no explanation. Tapping to access a map denoting the current sound conditions in the bay was intuitive to the team.

The think-aloud process demonstrated that users were successfully able to navigate the hierarchical display, correctly interpreting the meaning of icons used to transit between screens. The only difficulty identified was that it was not intuitive to access trendlines by tapping the values (circles).

New functionalities suggested at this stage included presenting individual bed space values on the floorplan to provide nurses with motivation to reduce sound levels ("It would be great to put this on a big screen and turn it into a competition of who has the quietest bed"), the ability to acknowledge alerts ("if it was flashing but I couldn't physically resolve the sound issue I would ignore the interface…it would be good if I could click to stop or snooze it"), and some clarity on the presentation of spatial representation of sound sources ("I'm unsure where the centre of the sound is coming from in a big circle"). Senior members of the team wanted to export reports from the system. There was a particular interest in comparing daytime with overnight and the possibility of being able to associate these data with patient experiences collated from feedback questionnaires. An unexpected use suggested for the real-time display was the proposal to identify a "quiet bed" when another nurse required assistance. Nurses speculated this could be a useful means of balancing workload across the AICU. Nurses were also keen to be able to use the display and reporting feature to identify persistently loud areas that would enable them to relocate patients they felt would benefit from "silent side room" care.

A key theme identified from this phase was that nurses wanted more (rather than less) information to be displayed. In particular there was a consistent request for a 'target' or 'comparison' value, against which they could monitor real-time values. They were also keen to see specific information about the type of sound that was dominant at any given time ("I want to find out why this bed is loudest as we have patients to recover and need to resolve noises").

Users were asked what type of feedback would be helpful. Non-specific language from the system such as "there is a sound disturbance" was considered by users bland and unhelpful ("A context around the sound location here would be useful"). The most popular statement from testing was "sound levels are louder than average". This was viewed as informative enough to encourage action without sounding patronising. Competitive suggestions comparing shifts (for example "this shift is currently <n>dB louder/quieter than yesterday/last <comparative day of the week>") were also popular.

The spots on the floor plan (Figure 7-15) representing sound localisation were generally understood and popular, but there was concern the screen became overly cluttered at busy times.

Iteration 3.1 (source mapping screen only)

Following further user tests, the programming team at OCC were instructed to refine the localisation display to illustrate recency of sound sources. This was achieved by way of a fading icon at the point of origin, the brightest colour suggesting most recent detection.

Static screenshots of two variants (Figure 7-16 and Figure 7-17) were circulated to members of the University of Oxford Critical Care Research Group, most of whom were familiar with the ICU. One version was more highly coloured than the other, the intention being that colour could indicate sound intensity. The purpose of this feedback was to collate general opinions and

understanding of the display. Recipients of the email were asked to offer comparative comments between the two options.

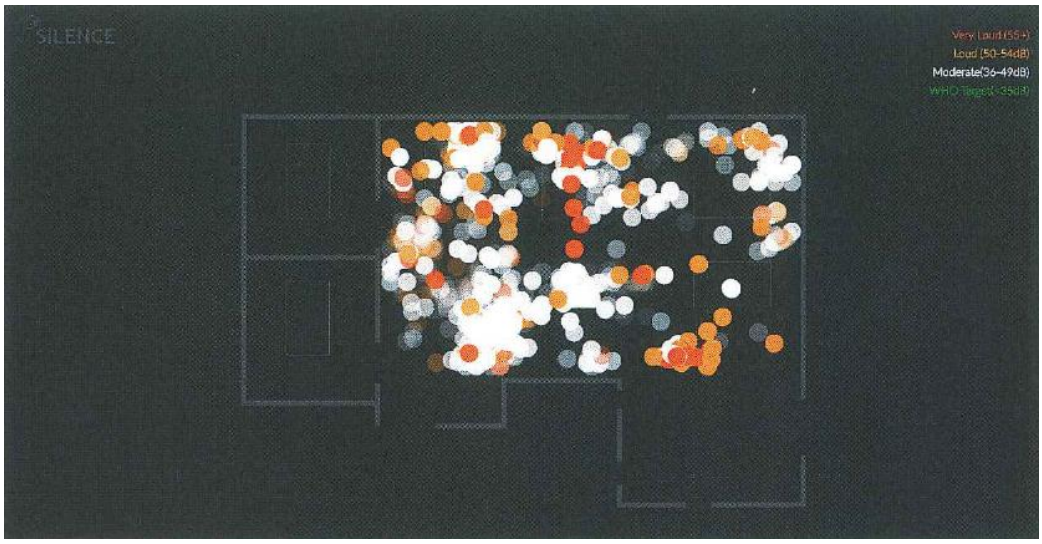


Figure 7-16: Early version (3.1a) of sound localisation map, which included mid-range sounds (marked in white) as well as high intensity sound sources (orange and red)

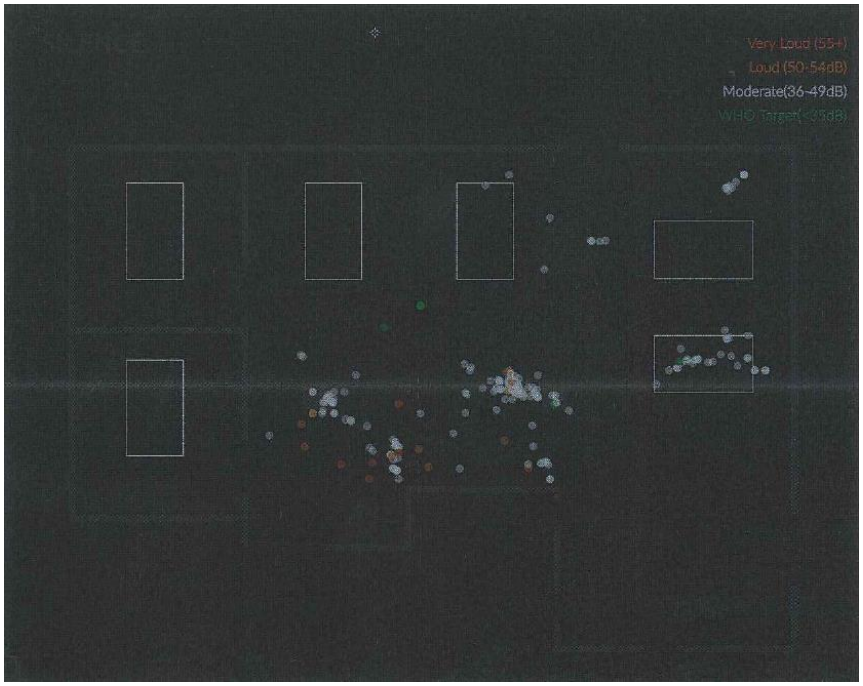


Figure 7-17: Alternative version (3.1b) of the sound localisation display

Responses were collated in the form of an OSOP (one sheet of paper) [164] that enabled significant themes to be identified. These comments led to constructive feedback for the design team. Summary 'OSOPs' are in appendix D.

The colour scheme was universally disliked ("currently looks like a bad 1970s dress"). Although it was supposed to reflect the 'traffic light' scale of red – amber – green, the muted hue combined with the built-in fade over time (which was intended to represent how recently the sound had occurred) was non-intuitive when realised in the display. The mid-range values (36-49dB, displayed in white) were visually dominant, obscuring the more important localisation of high-intensity sounds.

Feedback from this version testing directed final specification for the fully-featured working prototype. Specifically, comments led to a more vivid colour scale and removal of mid-level sounds from the display. Eliminating mid-range sounds from the display increased focus on the most important high-intensity sounds. Sounds <35dB were also retained, displayed in green. The intent behind keeping low values on the display was to provide motivation to encourage proactive behavioural change [362]. As one respondent commented: "makes me want to experiment with everyone being as quite as possible to see if we can get it to go green".

Iteration 4

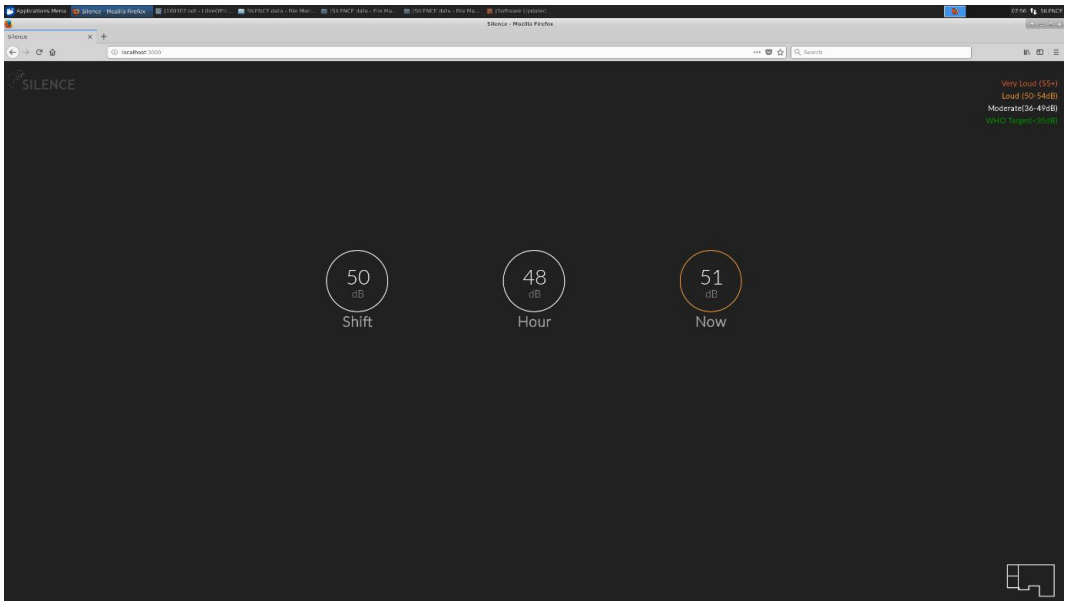


Figure 7-18: Primary sound display screen, showing sound values by shift, hour, and current levels

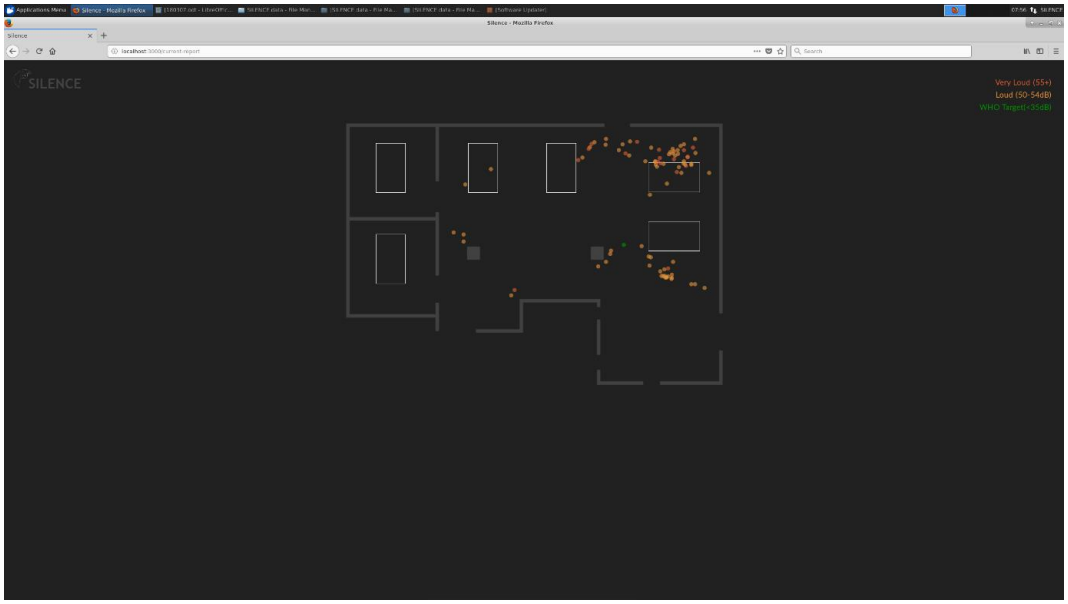


Figure 7-19: Sound localisation display featuring updated localiser icons

- **Format:** Electronic
- **Functionality:** Fully-functional
- **Priority:** Beta-testing
- **Testing group:** Full staff group

The primary display, comprising three circles displaying sound levels across different timescales, are ordered progressively from left to right ('shift', 'hour', 'now'). Use of colour is limited to presenting information about sound levels and consistently applied to the red-amber-green scale. The cognitive load required to interpret the limited information displayed is low, since visual clutter is kept to a minimum (see section 7.5.4). Information search is therefore efficient.

Ethnography was conducted to evaluate this working prototype. In software terms this stage is 'beta testing', where a near-final, fully-featured version is presented to allow detailed study of the system prior to installation. On a technical level this also enabled confirmation of mapping orientation to display sound-source localisations correctly. Specific attention was also paid to how staff interacted with the live display in the AICU and how the presence of a working display influenced behaviour. As with the original baseline observation sessions (chapter three), the primary researcher (JD) aimed to be unobtrusive in the environment to avoid influencing behaviour as far as possible.

Comments and feedback were summarised:

- The screen was out of plain sight from most positions in the bay. No-one ever spontaneously registered the display screen was 'on' during any of the sessions.
- When prompted to comment, several people thought the "subtle, understated" look was important. The predominantly dark background was particularly liked.
- Several people suggested that 'now' values should be more dynamic. This idea was corroborated by field note comments that current sound level was not visibly altered with sudden loud sounds. To consider reporting current 'peak' sounds here rather than LAeq(15mins)
- The ability to review sound levels retrospectively over the shift was unanimously liked. However, when selecting the graph screen it was universally requested that the screen shouldn't automatically 'time-out'. De-selection of the graph should be user-directed to allow time to review information and reflect on changes over time.
- Live sound levels were consistently much lower than during baseline ethnography sessions
- Field notes report evidence of increased speech volume following an increased sound level (for example as a result of ward round having started or a trolley being pulled across the unit) This is consistent with previous observations during the earlier phase ethnography.
- Field notes report a noticeable subjective difference between 50dB and 47dB
- Orientation of mapping overlay incorrect
- Several members of staff volunteered they thought the ICU was "quieter these days" and that they were more aware of obtrusive noises.

7.5.4. Visual Clutter

Examples of each iteration were evaluated for Feature Congestion (Table 7-2 and Figure 7-20) and Sub-band Entropy (Table 7-2 and Figure 7-21). Both Feature Congestion and Sub-band Entropy are measures of visual information. Feature Congestion indicates how effectively an additional item would be noticed and includes assessment of colour usage. Lower scores in all cases indicate simpler views which are easier to scan for information.

	Feature Congestion	Sub-band Entropy
Cerner Millennium®	6.43	3.98
ICU patient monitor	3.94	2.72
Iteration 1	2.34	1.09
Iteration 2a	3.44	2.45
Iteration 2b	3.83	2.49
Iteration 3a (splash screen)	3.05	1.75
Iteration 3d (floor plan)	1.99	3.21
Iteration 3.1a (large spots)	1.96	3.37
Iteration 4 (small spots)	1.81	1.09

Table 7-2: Feature congestion and sub-band entropy scores for each iteration and a standard patient monitor

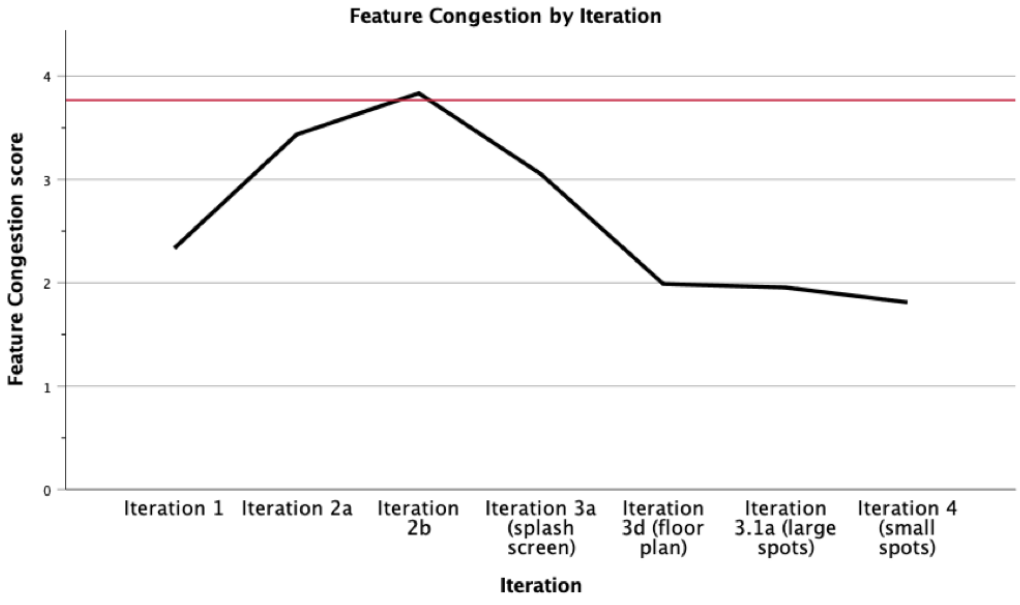


Figure 7-20: Feature congestion scores for each iteration of display. The red line indicates the feature congestion score of a standard patient monitor.

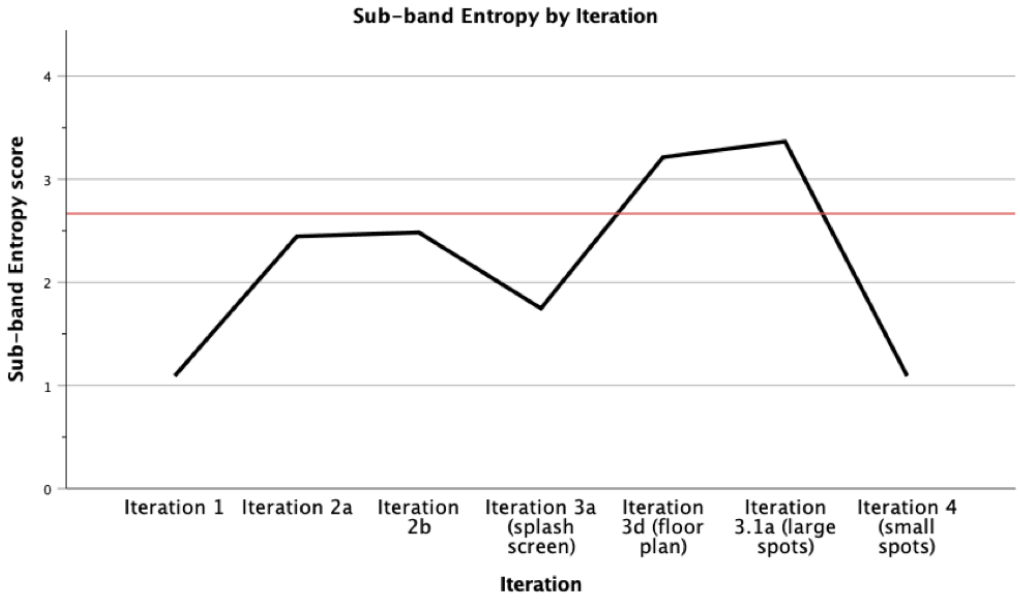


Figure 7-21: Sub-band entropy scores for each iteration of display. The red line indicates the sub-band entropy score of a standard patient monitor.

All versions were visually simpler than both Cerner Millennium® and the patient monitoring used by ICU staff for routine care.

7.5.5. Patient involvement

Feedback from the patient group was positive. The main concern voiced by non-staff members was that visibility of individual bed spaces should be restricted to staff only. They were worried about visitors monitoring noise levels of neighbouring spaces and requesting a change of location to a quieter space. They felt this would be inappropriate. Staff members of the group agreed. This led to a reversal of screen priority with the floorplan being the secondary screen, activated from the new primary screen showing overall average values.

A live demonstration of the final system was presented. The group were able to 'see' the sound levels in the ICU in real time, and this proved a highly popular demonstration of the working product.

7.6. Discussion

Sound monitoring systems are commercially available, but for various reasons these are not suitable for use in an ICU. Industrial monitoring systems report daily average values in retrospect, providing no real-time data or feedback to enable reflective behavioural change. 'Sound Ear' (Figure 6-1) and similar systems are commonly used in the clinical environment. They have an icon of an ear composed of many LEDs, the number of lights, colours, and icon size varying with sound levels. They are widely considered too sensitive, as they are generally continuously 'lit'. Staff then perceive they are being constantly 'punished', as they cannot see any effect from modifying their actions. This is demotivating. The AEBCD group felt a system able to report differently would be more effective at helping staff manage sound levels in the AICU (chapter four).

The iterative design process is a powerful means of developing a system that is strongly focussed on end-user needs. Unlike linear product development processes, the 'agile' system of rapid prototyping allows for fast paced change. Each test stage is evaluated quickly, allowing features to be introduced, tested, and discarded if not appropriate.

Early exemplar designs for this project were developed on paper. This low-fidelity approach is a cost-effective and rapid method to generate early concepts and ideas. Later electronic iterations were presented for user testing with limited functionality. Concurrent software programming enabled final designs to be fully operational within a reasonable timeframe, while the interactivity of the think-aloud technique "invites the user to become a participant in the analysis of his or her own cognitive processes"[363]. This technique kept the design process centred on the users, which is crucial because new devices tend to succeed or fail not because of their technical merits or failings, but as a result of the socio-cultural context into which they are introduced [308]. Products with a higher chance of long-term success are those that include implementation and evaluation strategies by design, and are created with an understanding of their setting, purpose, and use.

The purpose of this system is embodied by theories of adult learning as outlined in chapter five. By providing staff with objective data on which they can reflect, it was intended they would experiment with ways to modify their behaviour to achieve better sound hygiene.

7.6.1. Principles of design in practice

> *"A good user interface is like a joke. If you have to explain it, it's not that good" (Stuart Weinberg, Vanderbilt University Department of Biomedical Informatics, Research Colloquium 4th April 2019, via Twitter) [364].*

Users' heuristics and convergence

A system of this type has never before been designed for the ICU workplace, so there were limited data available to determine how best to present the data. As Henry Ford reportedly said "If I had asked people what they wanted, they would have asked for faster horses"[48]. This reflects the problem that users may not be able to accurately articulate their needs, or realise that a particular solution is possible. Part of the designer role is to "identify the real problem" [316]. The first iteration of the interface was intended to establish what users expected, what features they required, how a soundscape might be used in the ICU, and how well this aligned with recommendations from the AEBCD panel.

[48] The quotation may be apocryphal; the earliest written account doesn't appear until 2002.

Staff who work in an ICU are familiar with a wide range of systems. Nurses in particular spend much of their working day interacting with monitoring systems interfaces. It would have been foolish in the design of this new system to ignore how nurses might expect the system to behave, and to conform to those expectations where possible.

Wayfinding, Typography, and iconography

In keeping with other medical device interfaces common in an ICU (for example the patient monitor, Figure 7-2), the sans serif typeface is intended to be clear when viewed from a distance. The primary screen is dark with high contrast, large size, minimal text. These specifications were perhaps so obvious that no one commented on these features during user testing unless prompted. There are clear similarities to the patient monitoring display with which the ICU team is familiar. In contrast, the Cerner Millennium® display (Figure 7-1) is clearly quite poor in this regard.

The typeface (Helvetica Neue) used throughout the system is consistent, aiding wayfinding. It is distinct from the typeface used in other clinical applications such as the patient monitor (Arial Narrow), and users can be confident they are still interacting with the sound monitoring system at each stage of navigation. This is especially important for future deployment when the interface may be viewed from the same hardware as other clinical interfaces.

There was a strong preference from the design team to present noise levels using icons. This was to keep the display simple and visually appealing, capitalising on knowledge that the majority of ICU staff have relatively limited understanding of what decibel values actually mean. There was a concern that numerically presented values might be prone to misinterpretation. Despite this intention, when discussed with staff they were unanimous in their preference for a numerical display. This perhaps reflects their experience of clinical monitoring systems leading them to a strong expectation that measurements are presented numerically. This preference was too strong to be overridden, and the design group responded with a numerical display, but with features, for example markers on trendline graphs, to aid interpretation.

Colour

Whilst mindful of difficulties with the Red-Amber-Green colour scale, this emerged as a very strong preference from user testing. There were problems realising colour representation on screen. The colours were initially muted which was widely disliked. This was a design solution to the request for the GUI to be unobtrusive in the environment, and the specification for a dark screen. Feedback during the design process identified that hues needed to be brightened between iteration three and four.

The on-screen sound markers needed to represent three dimensions of data. The first, the spatial location of the sound source was easily indicated (and interpreted) with circular markers (spots) centred on co-ordinates of the originating source. The other two dimensions were more difficult to accommodate. The same spot needed to indicate both noise intensity and the recency of the sound event.

Intensity was indicated by colour, and time as gradually reducing opacity. Users found this somewhat more difficult to interpret, possibly because once the time-fade was applied colours no longer mapped to a recognised hierarchy, particularly noticeable as the white spots became more transparent. Against the black background they merely looked grey, leading to confusion over how this fitted with the colour chart. User feedback led to a simplification of data displayed by removing mid-range (36-49dBA) sounds.

The advantage of eliminating mid-range sounds was two-fold. The first-generation was overwhelmed by a large number of white/grey spots as the majority of sounds detected were in

this mid-range. With these removed the display became clearer immediately. The high-level sounds remaining in the display were also theoretically the sounds most amenable to change. The display of low-level sounds (<35dBA) was also retained. These presented an opportunity for positive re-enforcement, since staff would recognise the system was acknowledging their efforts to maintain a quiet workspace. This was considered especially important when viewed in light of comments criticising the perceived negativity of commercial systems.

7.6.2. Visual Clutter

The iteration process identified quickly that a single screen would require too much information to be assimilated. This was evident in the comparably high feature congestion scores. High scores predict inefficient visual search. This validated the decision to move towards progressive disclosure, in which individual screens can be simplified by prioritising data displayed. It is reassuring that when this change was implemented there was a corresponding fall in complexity scores.

7.6.3. Assessment of final prototype

The original planned assessment of the display was to deploy the prototype interface and leave it running with no external intervention for an extended period of time (up to six months). A reduction in sound levels over time would have demonstrated proof of concept. Unfortunately, the prototype system was not sufficiently robust to run for prolonged periods of time. The system depended on a wireless network connection between the recording hardware and display. This connection was disappointingly prone to random and unpredictable failure. The final assessment was instead completed via in-situ ethnography sessions.

Two main points emerged from this final ethnographic evaluation that are relevant for future development of the system. Firstly, when staff were motivated to engage in discussion about the interface, their comments were positive and their suggestions for improvements were sensible. This confirms there is a cohort of staff interested in addressing the problem of sound levels in the unit. Identifying a larger number of ICU staff to support the integration of the interface into routine clinical care might have minimised some of the local engagement problems experienced during this project. Any future development should perhaps be better embedded within the standard clinical care team.

Secondly, the display screen was quite obviously installed in the wrong location. This meant that no-one spontaneously looked at it. Practical considerations constrained system installation and these influenced the user experience. The display was mounted on a wall behind two bed spaces. This was the only position where it was within reach of a power socket and also out of immediate view of patients. This position meant the display was not in easy sight of staff at any point, and completely hidden from general view when privacy curtains were drawn round adjacent bed spaces.

Although no-one mentioned this, it is possible that because the screen was physically in the bed spaces for A5 and A6, staff looking after patients in A1 – A4 may have felt the screen was not relevant to them. The ICU is organised by bed space. Everything around an individual bed is necessary for that patient, but not relevant to patients elsewhere. Nurses are not therefore conditioned to look into another bed space for information about their patient, so the positioning of the system meant it was difficult to incorporate into the workflow of most staff.

Better positioning might have been in a ‘common’ space, but the only truly shared spaces are the nursing station and staff common room. Early in the project it was suggested that the display could be installed in the common room. The intent behind this was to encourage peer support to achieve lower sound levels. Feedback from staff (almost universally) was that they did not

want to feel they should monitor the ICU environment or their patients when they were taking a break.

It was not practical for hospital estates to wire in a new power point to site the display at the nursing station, and experience of environmental monitoring in the very early phases of the project suggested that staff were prone to unplugging devices not directly relevant for immediate patient clinical need. Placing the system here would not therefore have guaranteed that the system would have been successful. In retrospect, it might have been better to connect the interface to the NHS Trust intranet. This might have reduced the recurring connectivity problems, but may have delayed development due to NHS IT security and testing requirements.

If the system's data feed had been routed through the Trust intranet, the interface could have been displayed on a dedicated 'computer on wheels', or a handheld device carried by a senior member of staff each shift. This would have moved the system out from individual bed spaces, making it potentially more visible, but still dependent on the integrity of the wifi network. If the display had been mobile this may also have made it difficult for staff to develop a routine for checking and updating their noise-related situational awareness. The potential for a computer on wheels to be 'parked' and forgotten about would have been high, and there would have been a major hazard that the system would not have been kept charged.

It is worth mentioning that shift handovers now occur outside the main unit bays. Installing a display in the service corridor, with the senior nurse being able to monitor sound levels in real time via a hand-held device might now be a potential solution to consider. The system was designed to be independent of device constraints and robust to change. As a web-based system it can be accessed from any hardware device within the local network.

7.6.4. Local engagement

Despite clear support from high level senior staff, there were variable levels of engagement from those present in the ICU on a daily basis. Some individuals were interested and keen to participate in the user testing. Others obviously struggled to understand the relevance of the project, or how their input could be helpful. Whilst there was enthusiastic support from some key members of middle management, this was not universal. Anecdotal reporting suggests this may be related to historical limited interaction and support between research and clinical teams. This variability of support made it difficult to maintain consistent interest across teams and over time. Coupled with technical issues and poor system reliability there was no unifying message of support communicated throughout the workforce.

This has previously been identified as a reason for non-adoption of new technology [118,308,315,365]. Whilst we recognised that diffusion was likely to be better supported and influenced through informal interaction rather than formal 'opinion leaders' [366], and this project made every effort to include clinical staff in the development and implementation phases, the scale of this need may be wider than predicted. We failed to induce a sense of ownership within the clinical team.

7.7. Strengths and Limitations

Strengths

- User-centred development ensured the design delivered was consistent with what was requested
- Principles of good design fed into an attractive and easy to use interface
- Some members of clinical staff were particular champions for the system

Limitations

- The clinical duties of the few interested champions meant that they were not available continuously which meant that information sharing about the project was not consistent
- The programmers were not able to accommodate every request, so for instance the final system does not support interactive reporting
- The limited involvement of patients and their families in the interface design might be viewed as a weakness, however patients are not the intended users of the system (the end users are staff) therefore the impact of late consultation is likely to be minor

7.8. Conclusions

The final version is visually simple, includes most of the features requested by the AEBCD panel and subsequently by ICU staff[49] and successfully incorporated good design. The overall style of the interface is visually appealing, easy to search, and similar to other monitoring displays with which the ICU clinical team are familiar. The user experience methodology imposed a focus on the needs and preferences of the end user. This allowed exploration of typical use-cases through scenario and real-time in-situ assessment. This process led to a highly acceptable display that is both functional and aesthetically pleasing for the key user demographic. Whilst some system features are likely to need adjustment before deployment as part of a cluster randomised controlled trial, the system as a whole has clear benefits.

Future work

Real-time identification of sound sources[50] is unlikely to be included in near-future system iterations due to the complexity of isolating individual sound signatures from general background sounds. It also seems likely that the microphone array system is too complex for widespread use. However, displaying sound levels of individual bed spaces is relatively simple to achieve. The advantages to this more simplified system include ease of set up, low computational resources, and simplified reporting. We know from the source location work (chapter six) that the majority of loud sounds occur in around patients' heads and that focussing on the individual patient area in the ICU matches the mental model of how ICU staff (especially nurses) view their workspace.

Some refinement of system features is needed. The senior staff had a consistent request to export reports and it was specified that the timeline graphs have an average or 'previous shift' indicator

[49] Indication of specific origin of sound (eg one of the alarms associated with patient monitoring, conversation, or infrastructure disturbances such as doors slamming) remain missing from the display. Some accommodation for the level of annoyance likely has been achieved through presentation of loudness levels rather than standard LAeq values.

[50] The system being able to recognise noise source by type as well as by location

line as well as the WHO recommendation. It was speculated that staff would aim to beat their colleagues, thus driving sound levels down through natural competition [367,368]. A commercial collaboration with a software design company is the next sensible step.

7.9. Dissemination and impact

7.9.1. University of Oxford

The SILENCE project was selected as part of the "make: " series of talks hosted by the University of Oxford IT Services team to showcase the range of interesting ways technology is used by people from around the University. Julie Darbyshire presented "SILENCE is golden: mapping noise levels in intensive care" in May 2018.

7.9.2. OCC Company profile

The pilot prototype interface created as part of the SILENCE project features as an exemplar health project on the OCC website:

https://www.oxfordcc.co.uk/custom-software/noise-levels-attract-intensive-care/

8. Chapter Eight: Discussion and conclusions

8.1. Chapter summary

The first part of this chapter highlights the key points from earlier chapters, and reflects on the benefits (and limitations) of mixed methods.

The second part considers the social context of introducing change, exploring insights from ethnography (chapter three) and display development (chapter seven).

The chapter concludes with a focus on future developments.

8.2. Summary of thesis and evaluation of methods

8.2.1. Summary of thesis

Chapter One reviews sound levels in ICUs, looking at studies published since the WHO Guidelines for Community Noise were released in 1999. The WHO recommended that sound levels be limited to a daily average of 35dBA, with peaks no higher than 40dB overnight. The review demonstrates that despite these targets, almost no ICU achieves compliance. While some interventions show short-term improvements, no study was designed to test for sustained change. Heterogeneity of process and outcomes makes synthesis of evidence difficult, and the field would benefit from better standardisation of research methods.

Chapter Two outlines the rationale for using the mixed methods approach and describes when and how the different types of data interact over the course of the project. With equal weighting attributed to both qualitative and quantitative datasets, the overall study design is an exploratory sequential design whereby the initial qualitative analysis (secondary analysis of patient and relative interview transcripts) builds into an embedded convergent parallel design with concurrent data collection and analysis incorporating quantitative results from sound level measures and sleep and disturbances questionnaires and qualitative results from ethnography and focus group interactions. This exploratory study in turn builds into an explanatory sequential design whereby the sound level measures are explained by ethnography and discussion with staff working in the ICU.

Chapter Three introduces the AEBCD method for quality improvement and explains the initial mixed methods approaches to characterise noise in the ICU. The starting point for this was an exploration of patient experiences. Secondary analysis of interview transcripts[51] highlighted that patients were disturbed by noise during ICU admissions. This was confirmed during follow up ethnographic observation in local Units, which highlighted that much of what patients had described ten years earlier were still current problems. This limited change in the patient experience over ten years indicated that, despite sound level guidelines existing for nearly 20 years, the output of this project would still be relevant. Discussion with staff (ad-hoc and structured focus group) confirmed that they were aware of the problems associated with high sound levels and disturbances but highlighted they had limited empowerment to effect change.

Sleep assessment data[52] were incorporated into the AEBCD process and were presented to the mixed patient and staff group as additional evidence along with sound level measures taken throughout the observation period. Patient sleep whilst on the ICU is both limited in quality and

[51] Transcripts were from an earlier qualitative study completed in 2005/6

[52] The NIHR funded SILENCE project included EEG monitoring and sleep assessment questionnaires

quantity and highly fragmented. Patients in the ICU can expect only a fraction of the REM and slow-wave sleep of a healthy adult. The median duration of individual bouts of sleep for patients in the ICU was just one minute. The sleep assessment phase has been explored in more detail and is published elsewhere [52].

Consolidation of the qualitative data generated from interview analyses, ethnography, and focus group led to a coding frame that highlighted the key aspects of noise and disturbance in the ICU. These were *alarms*, *lights*, *being disturbed by people*, *being disturbed by equipment*, and *feeling overwhelmed*, and these themes were carried forward throughout the AEBCD process forming the basis for group discussion and intervention development.

Chapter Four describes the practical aspects of the AEBCD process. The method was modified slightly to accommodate the restricted availability of frontline clinical staff (both before and after the AEBCD group meeting) and patient representatives. Briefly the modifications were: only one focus group was held (attended by nurses only); the trigger film[53] was shown in five short segments (arranged according to themes outlined above) to allow focussed discussion; follow up development and delivery of interventions was led by the research team rather than through sub-groups of those who attended the AEBCD meeting (in July 2015).

Four interventions were proposed by the AEBCD group. All interventions were based on the need to improve patient sleep whilst in the ICU.

- The first change made following the AEBCD group meeting was that new bins with working soft-close mechanisms were introduced just before Christmas 2015. These had an almost immediate effect on reducing the peak sounds in the ICU.
- Alarm management guidelines included recommendations for best practice (for example lowering volume overnight and adjusting alert limits as appropriate for individual patients) as well as environmental suggestions to control lighting levels overnight.
- A dual-module teaching programme was request, the creation of which is explored in more detail in chapter five.
- The final intervention proposed was that sound levels needed to be measured, but it was clear that industrial methods of single daily-averaged values were unsuitable for this purpose. Alternative methods of monitoring were required, and it would be desirable to have a visualisation of live sound levels. These are explored in more detail in chapter six and seven.

Chapter Five describes how a focus on adult education theory enhanced fidelity and quality of the training programme. The clinical workforce is a particularly diverse group of individuals from various professional and cultural backgrounds. To meet their educational needs it is essential to cater for a broad range of learning styles, and provide materials that allow learners to engage in different ways. These theories are captured by Honey and Mumford's learning styles and Fleming's VARK preferences, and both were considered when creating content for this course.

Although available to all staff groups in the participating units, the package was predominantly accessed by nurses. Post-course evaluation confirmed the materials were well-received and popular. It was decided that a formative assessment was appropriate to motivate engagement with the materials, and a proportionate validation process was undertaken to prove its value.

[53] Trigger films are an effective mechanism through which discussion of often difficult topics can be approached using excerpts from interviews (known as touch points) to stimulate discussion

Comparison of pre- and post-course test scores demonstrated the success of the module in improving staff knowledge around ICU noise.

Engagement with the package was positive and, more importantly, evaluation of the teaching programme included direct measurement of sound levels in parallel with the deployment of the teaching package. This was consistent with the underlying assumption that improving knowledge would translate into reduced sound levels.

The bespoke sound measuring system[54] used to explore sound levels in the ICU was designed by acousticians from the University of Southampton. Chapter Six uses data exported from this microphone array system to describe the ICU acoustic environment in more detail than would be feasible using the single daily average (LAeq24) that is more commonly used for environmental monitoring. A key finding was that the majority of loud sounds are generated near patients' heads, suggesting alarms and other monitoring equipment contribute significantly to the overall ambient sound level experienced by the patient. The detailed sound level review also identified a circadian rhythm to the ICU which did not change significantly at the weekend. This is somewhat surprising given that staffing levels are different, and some routine weekday activities do not take place at weekends. The initial sound reduction identified using the single-point commercial sound level monitor was not replicated when the multi-point microphone array data were analysed. This is a valuable finding in two ways; obviously knowledge of the sound environment is critical to acoustic hygiene, but it also highlights the inadequacy of single-point averaged values in this context.

The microphone array recorded a number of values relating to sound measures. These comprised raw volume and processed values including A-weighting, peaks, and Zwicker calculated 'loudness'. The Zwicker loudness calculation represents perception of sound and incorporates quality and duration of sound as well as frequency and volume. Although A-weighted values account for the frequency differentiation in human hearing, the 'loudness' calculation may be a more representative value for how humans perceive sounds in their environment, thus is more relevant to patient experience.

Chapter Seven explains how the data from the microphone array system was used to design and develop a visual display for live monitoring of sound levels[55]. This chapter highlights the importance of good design (and how this is often lacking for healthcare interfaces) and the importance of including the target user group in the design process. Following industry practice methods, the interface was designed around the needs of the user persona 'Suzanne' and her expectations. These initial designs were then tested with ICU staff which led to a series of iterative changes before a final prototype was installed and tested in-situ.

This in-situ testing was more limited than originally planned due to timing and technological restrictions. Findings from this in-situ testing were still valuable, and included: confirmation that the general 'look' of the interface was good; a new understanding that physical location of the screen was more important than previously thought, and that it would be useful if some features were altered to better inform behaviour change in real time.

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[54] 72 individual microphones were installed. This included an 'array' of 64 microphones which identified significant locations of high level sounds. The remaining eight were single source, placed above individual patient bed spaces, the nursing station, and outside the sluice room. Due to technical failure, analysis was limited to the 64 microphone array.

[55] The technical aspects of re-coding the exported data to create the visualisation were carried out by Oxford Computer Consultants

8.2.2. Strengths

This thesis presents an in-depth mixed-methods investigation of sound levels in the Intensive Care Unit (ICU), including exploration of patient and staff experiences of the environment (chapter three), a review of sound levels in ICUs (chapter one), and development of a complex intervention designed to mitigate effects of noise on patients and staff. The intervention involved some simple environmental changes to the ICU (chapter four), a teaching package (chapter five), and noise monitoring display for the ICU (chapter seven). Project results are underpinned by high-fidelity sound levels (chapter six). The strength of the mixed methods approach is that it allows conclusions to be based on broad spectrum data. Through these it is possible to develop insights which can lead to a more complete understanding of the problem.

Noise in the ICU is well-documented and frequently mentioned by patients and their relatives. Excessive exposure to noise is a known contributor to adverse physical and mental health effects but hospital sound levels still regularly exceed WHO recommendations. Over time ICUs are becoming louder, and the recent increase in publications on this topic suggests motivation for change. However, to maximise staff engagement there need to be evidence-based interventions they can control that have direct benefits for "their" patients. Given the lack of progress to date, this is a problem that needs to be understood better, and new approaches may be beneficial.

Healing and recovery benefits of sleep are well-known, and the importance of a good night's sleep can be understood easily. During this project it has become clear that sleep is inadequately monitored for patients admitted to ICU. Better, simpler methods are needed [78].

Exploration of patient and staff experiences, combined with objective measures of sound, has highlighted key factors associated with noise and disturbance in the AICU. A mismatch was identified between factors staff predicted would be disturbing and the reality of the patient experience of noise (chapter three). In contrast to nurse prediction, patients were seldom troubled by conversation or movement; they were more concerned by machine noises and alarms. This was perhaps unsurprising as sound level analyses (chapter six) confirmed the majority of loud sounds converge around patients' heads.

These new insights guided development of a complex intervention focused on improving the ICU environment. Primarily this was to create better conditions to facilitate patient rest and sleep. Secondary benefits of a less frenetic environment may also reduce errors, improving patient safety. It is possible that a calmer workplace might also reduce incidence of staff burnout and fatigue.

8.2.3. Limitations

Joint coding and analysis is unusual in qualitative approaches but this brought additional opportunities to minimise potential for bias. It is recognised that workers can become blind to hazards in their workplace[56]. It was therefore important to ensure that fresh eyes were brought to the problem that would be able to question aspects of the clinical environment.

There is risk of bias when two views are reconciled. To reduce this risk, the two researchers met frequently to compare and contrast their notes. There were surprisingly few points of conflict and both observers reached agreement very easily about conclusions to be drawn from the data.

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[56] Normalised deviance occurs when work-arounds are so common that they become routine practice and are not questioned

As reported earlier in this thesis, the AEBCD method was modified to accommodate restricted resources (time and personnel) during both the discovery phase and intervention development/delivery. There is a risk that this may have limited staff engagement but was a pragmatic decision forced by circumstances. The ideal AEBCD method [153] is often led by a nurse known to the clinical team. Despite significant efforts to include the clinical teams in both the discovery phase and in the development and delivery of the interventions, it is likely that perceived socio-cultural factors (see sections 8.4.2 and 8.4.3) were more influential than expected.

It is important to acknowledge that some nursing staff were interested in the project, and were keen to help if they could. Despite enthusiasm for the project from the senior management team, staffing restrictions meant formal rota time was not allocated to allow nursing staff to assist with the research project. This meant that despite vocal support, it was difficult to realise the full potential of the work because clinical duties took priority over the research components of this project. As discussed in more detail in sections 8.4.2 and 8.4.3, it can be difficult to step outside expected roles, particularly when managerial support is perceived to be limited.

Outside of this project the University of Oxford Critical Care Research Group (CCRG) has recognised that whilst research skills are an integral part of medical training, the nursing community is less well-served. The CCRG has worked hard to integrate research into the clinical team by offering secondments to nursing and allied health professionals (AHPs) who would otherwise not have this opportunity. These secondments mirror the short-term research placements offered to academic clinical training posts. As a new initiative, the success of these nursing and AHP placements has been variable, and this is to be expected. What has been a surprise however is that over time, these secondments have moved away from the nursing team as the local physiotherapy team has consistently put forward candidates better suited to the role[57]. Many nurses seem to be entering research roles to further their careers within healthcare [369] rather than having an inherent interest in the academic role. The physiotherapists seem to have a primary interest in research and developing research skills, and this is reflected in the degree of engagement between the professional groups.

The effect of this evolution of the secondment role may be increasing the perception that 'research' is a separate activity from 'patient care/nursing'. This is perhaps a research question in its own right and not for detailed exploration here, but may go some way to explain the apparent lack of engagement seen from the local nursing team.

Embedding the project within the clinical team, with a number of highly visible project champions drawn from different areas of the multi-discipinary team, *may* have yielded better engagement. This increased interaction would have significant resource implications.

8.3. The Complex Intervention

The benefits of ensuring well-maintained and appropriately positioned equipment cannot be over-estimated. Although simple, environmental changes were effective almost instantaneously. Replacing metal bins with new versions with soft-close plastic lids, combined with repositioning to ensure lids and foot pedals were free to move unimpeded, immediately reduced a significant source of sudden loud noises. These changes that followed the AEBCD event (chapter four) required input from the multidisciplinary team. Including the AICU housekeeper in procurement ensured the wider facilities team were aware of the project and supported its goals.

[57] Partly, this may be a result of the AICU Physiotherapy team leader having a strong interest in research

The AICU environment is understandably arranged for the convenience of staff. Most equipment is placed around patients' heads. This makes devices and displays easy to see from the foot of the bed in a single glance, also enabling sight of the patient. This positioning also ensures cables and ventilator tubing are close to where they are needed, but at a cost of being close to patients' ears. The frequent alarms, most of which were observed to be 'false positives' (chapter three), confirmed more needs to be done to manage alarms in the AICU. The development of an alarm-management policy (chapter four) supported adjustment of thresholds to reflect individual patient needs rather than pre-programmed default values. Raising awareness of how alarms can affect patients and how continuous alarm sounds can lead to inattentional deafness and alarm fatigue is a priority for ongoing professional development, and provides reassurance that reducing alarm volume can increase safety. The sound location analysis that was completed after the post-AEBCD interventions had been implemented identified that the alarms and other monitoring equipment were the source of the majority of loud noises in the AICU.

The teaching programme (chapter five) encouraged staff to consider effects of high noise levels in the AICU and confirmed that knowledge increased following completion of the package. It was popular with staff and fulfilled its goal of facilitating reflection on working practices and their impact on patients. Successful rollout to an independent site was encouraging, particularly since it resulted in lower peak sounds. This demonstrates the intervention is both effective and transferrable and also how adult learning theory supports design and development of new training programmes. Whilst the hardware systems developed later in this project are more difficult to install elsewhere, the educational package is simple to train teams to deliver locally. It can be used immediately in other institutions with few additional resources required.

The teaching has been adopted by the Oxford University Hospitals NHS Foundation Trust neuro-intensive care team but despite evidence of success neither the e-learning module nor the experiential session has yet been incorporated into routine education sessions for the general AICU. There was strong support from senior clinical staff, but the nursing faculty found it difficult to find resources to deliver the sessions. This was disappointing as in the development process many traditional barriers to innovation [370] (such as including the target audience in the development process and ensuring broad appeal in materials) had been addressed.

This teaching package was developed to be meaningful for staff. Using recognisable situations drawn from patient experiences and ethnography (chapter three) ensured it provoked the reflection required to effect behavioural change. The AEBCD group considered quantitative measurement essential (chapter four) but it became clear quickly that current methods of environmental sound monitoring are inadequate for the purposes of patient welfare. Standard reporting (chapter six) using the A-weighted scale imperfectly addresses the human experience of sound. This is better captured by 'loudness', and it is logical to use an experiential measure where disturbance is a higher concern than physical damage to hearing, such as in hospital environments.

Mindful of these requirements, a sound monitoring system was developed to present live data to staff. This necessitated significant design effort to ensure data captured were presented to clinical teams to enable interpretation (chapter seven). The resulting system fulfilled its design intent and reflected the brief from the AEBCD process well. Unfortunately the system is not suitable for widespread deployment in its current form. The technological infrastructure was unreliable and prone to unpredictable outages. The system needs to be simplified and made more robust before commercialisation, but future research use of the system is feasible with modification.

8.4. Key messages

The core of this project addresses introducing change into the ICU. In healthcare environments, introducing change successfully requires staff support. Support can be encouraged by building plans for sustainable change into the project from the beginning, and by recognising key drivers for motivation.

8.4.1. Introducing change into the healthcare environment

Initiating sustainable change is not straightforward. It requires recognition of cultural practices within teams, departments, professions, organisations, and strategies to maximise staff engagement [114,118].

Traditionally healthcare has been strictly hierarchical with strong separation of roles and responsibilities between professions and departments. This results in barriers to systems change, particularly when introducing complex interventions requiring involvement from multiple teams, especially where teams straddle organisations. This project required input from two Universities, the local research team, clinicians, and IT services from both University and NHS.

There is evidence that tribalism and stereotyping dissolves when clinical teams are in a neutral environment [371]. This suggests these are learned characteristics rather than intrinsic to staff identity. Interprofessional relationships are relaxing as NHS Trusts begin to adopt the mindset of High Reliability Organisations (HRO). Flatter hierarchies can improve communication within and between teams, and encourages shared priorities and mental models [372]. Mutual understanding, alongside conscious and continuous reflection on working practices [373], can improve both patient safety and efficiencies in care [374].

This project brought the full multi-disciplinary team together to plan and deliver the sound reduction intervention. In this respect the project was successful and benefitted from a co-design approach [153] that ensured relevance and significance.

Unfortunately there remains a hidden curriculum [375] through which senior staff (sometimes unconsciously) communicate unspoken messages about risks and priorities. These non-transparent communications, or '[mis]leading by example', are at the core of how healthcare trainees develop professional identity and attitudes [376]. Clinical teams can be so frequently exposed to a hazard, in this case noise, that it becomes accepted as a normal, even essential, feature of the workplace. NASA refers to this as the normalisation of deviance [377]. This project has generated new knowledge to address this. New perspectives from the research team, coupled with objective measurement and meaningful data, has demonstrated to staff the problem that exists, and more importantly, that meaningful steps can be taken to initiate change.

Technological problems experienced in this project mirror those described by Johannson et al [58]. In particular, protocols, procedures, and policies that do not explicitly permit co-operation across multiple departments or organisations can limit staff action. Success then depends on identifying individuals with the authority and motivation to work flexibly and independently. Individual willingness to support change will be subject to social theories of behaviour [378,379]. These explain how people are influenced by perception of likely success, peer (or normative) pressure, and control (ability to perform supportive tasks) [380]. Success in a (perceived) restrictive environment only seems possible if individuals are willing to take responsibility for working outside routine processes [381]. To do this they need to be sufficiently motivated, convinced that their actions will result in success, and believe that what is being asked of them is morally and socially acceptable [382]. They also have to be empowered to act and confident of management support.

8.4.2. Inciting motivation

The 'hook' model for behavioural change [362] (chapter seven) exploits three core motivators [383]. These are that humans are motivated to seek pleasure and avoid pain; to seek hope and avoid fear; and to seek social acceptance and avoid rejection. For 'Suzanne' (the primary user of the interface, see chapter seven) the key driver is socially determined. She is, first and foremost, part of her nursing team. The communal 'want' of her team is to improve the health of the critically ill patient they are collectively caring for in the ICU. She knows this is best achieved when the team works together toward the common goal and she self-defines as the integral pivot in this process, referring to herself as a 'multitasker', 'patient advocate', and 'efficient administrator' [384].

For 'Suzanne', her lived experience of being a nurse is fundamental to her own personal identity [385]. This identity is developed through on-going interaction with her peers [386]. As such, her social allegiance to her team and her sense of belonging will be an integral part of her sense of self [387,388]. Such is the strength of this interaction between professional and personal identity that even if the professional role ends (if she stops working clinically), her professional identity and self-image will continue to include the role of nurse [386].

Humanity is collective, inclusive, and socially reinforcing. Tribe culture is how humans interact and connect with others, and how they form communities with like-minded individuals. Social gratification comes through acceptance, recognition, and approval from peers. This possibly reflects an underlying mental model that the role of a nurse is to be seen to be caring, so *not to be seen to do something* is a problem [389]. This hints at a wider issue at the heart of identity shaping, particularly in the nursing profession where professional and personal identities are so firmly interconnected. Social deviance, real or perceived, in a tightly interwoven community such as the ICU can lead to disruptive practices and social isolation [390,391]. In this context normative pressure of the team will dominate. Being seen to be busy, providing evidence of having taken action (for example completing checklists), and (in the ICU environment) a focus on physiological data from the patient are all factors that impact how nursing identity is shaped [392,393]. There is an often encountered opinion that the ICU is noisy, that is a natural feature of caring for critically ill patients, and that it is not possible to change [95]. In this context, a noisy environment may be perceived evidence of busyness.

Although the ICU nursing team were unanimous in their definition of their role within the wider ICU team, it was clear they also took personal responsibility for their individual patients. During the user-testing this manifested in a desire to apply game theory to changing the environment ("makes me want to experiment with everyone being as quite as possible to see if we can get it to go green"; "It would be great to put this on a big screen and turn it into a competition of who has the quietest bed"). There is a well-known social facilitation effect by which individual performance improves through the presence of others [394]. Recent work suggests that performance is further improved in the presence of rivals [368]. The hypothesis behind an interface displaying individual bed space sound levels exploits this recognition of competition within the nursing workforce. Theories of behavioural change suggest that normative pressure acts as a natural social intervention, with the display serving as an objective arbiter, and anchor to best practice.

8.4.3. Sound source localisation

The microphone array demonstrated the majority of loud sounds originated from the relatively small space around patients' heads (chapter six). This suggests strongly that major contributors to high sound levels in the ICU are the various pieces of monitoring equipment located at the top of each bed space. The qualities of sounds generated by this equipment are consistent with

those that humans find most disturbing and, although it is good practice to adjust alert thresholds and alarm volume according to individual patient requirements and wider environmental conditions, ethnography (chapter three) identified that settings were rarely changed. It was also noticed during these observation sessions that alarms not immediately clinically relevant were not silenced quickly.

Whilst not a direct patient safety issue, this practice can (and does) lead to inattentional deafness and alarm fatigue. Each alarm that is allowed to sound increases the background sound levels, leading to general disturbances for patients and contributing to staff mental workload. In an environment where there is almost always an alarm sounding, it is easy to mentally 'tune out' and miss important clinical events.

8.4.4. Creating sustainable change

It was suggested during planning and evaluation (chapters four and seven) that the interface could be a focus during the 'group hug'. This is how the multi-disciplinary team refers to the discussion of patients' care plans. This would focus attention on the problem and raise the importance of 'environment' in the mental model of critical care by including sound levels in the same conversation as clinical needs. This addresses the normalisation of deviance by normalising conversations about the environment in a manner analogous to how pre-operative WHO briefings break down team barriers in operating theatres.

The 'hook' model is, at its most basic, a method to engineer a product to make it easy for people to do something that they already want to do but which (prior to the new product) they found difficult. In this specific instance of an interface displaying live sound levels in the ICU, we know that staff want to reduce sound levels and we know that they know high noise levels create a poor restorative environment for their patients. Specifically, we know from the user persona work (chapter three) that 'Suzanne' is keen to minimise disturbance to her patient as much as possible. We also know that 'Suzanne' does not recognise when she is the cause of significant disturbance and we know from repeated interaction with healthcare staff that they do not have a clear idea of which sounds cause most disturbance, or which are modifiable. For this new interface to entice interaction then, it needs to indicate in real time and be appropriately reactive to allow reflexive behavioural modification that leads to visible change, thus triggering a sense of reward.

8.5. Clinical and policy implications of sound level results

The quantitative data reported in chapter one demonstrates that although it is likely that most ICUs could reduce their average sound levels somewhat, achieving the WHO suggested limit is unlikely to be possible in the majority of units. Consistent failure to achieve is demoralising and there is value in recognising that these targets may be unattainable. The WHO may wish to consider revising their guideline so that it remains aspirational but within reach.

Qualitative assessment of peoples' experiences of the environment suggests a higher WHO target may be acceptable, particularly if peak sounds could be reduced and/or the sources of high sound levels that occur around patients' ears could be moved elsewhere (see for example Luetz et al [66]). This understanding of how sound levels are distributed around the ICU and

how different sounds are perceived has implications for both sound level generation[58] and sound level monitoring[59] in the clinical environment.

The particular strength of this project is the use of mixed methods. Using experience to interpret numbers is essential as the true objective underlying sound reduction interventions is to improve the experience of the people (both patients and staff) who occupy the AICU environment.

This project has highlighted the complexities surrounding the experience of noise are not represented well by the LAeq24. Current environmental methods are unsuitable for the clinical environment where the predominant problem is frequent startle rather than risk of hearing damage. Other groups working in this field should be aware that simple measures are not sufficient to fully understand these hazards. The HSE and NHS England should consider mandating noise monitoring using methods identified in this project, which include the appreciation of loudness values, reflecting that hospitals should be hospitable.

The foundations of design outlined in chapter seven demonstrate that good ergonomics are often lacking in clinical informatics. Clinicians and commissioners are rarely familiar with these principles and therefore high-level centralised guidelines and quality metrics for information presentation are required.

8.6. Future Work

The SILENCE project (of which this thesis is part) demonstrated that lower sound levels are possible in the AICU. To test the interventions thoroughly (separately or as a combined package) would require a cluster randomised trial. Feedback on the study report from the Research for Patient Benefit secretariat was positive. A follow-up funding application to the NIHR is likely.

Some refinement of teaching materials (chapter five) would facilitate formal launch of the education package. These changes would largely focus on professional presentation of materials and discussions are ongoing with Oxford University Innovations to provide materials to the wider health service.

A simpler version of the sound levels interface (chapter seven) is another obvious development. Minor changes to data collection would simplify physical installation. The sound location software (chapter six) demonstrated the majority of loud sounds in the ICU are generated near patient heads. Specific bed space microphones (replacing the array) would illustrate individual patient experiences of sound. This would make the system more generalisable, negating the need for specialised acoustic engineering involvement in the installation and environment calibration. The ability to export data from the system would widen scope of use, allowing retrospective analysis of known disturbance (unusually busy shifts for instance) and routine fluctuations in sound levels. This feature was requested during development, but was not feasible within the timeframe. Linking with a partner software development company would be a practical development plan.

Sleep is inadequately measured and monitored for patients admitted to intensive care. New methods of sleep detection might include wireless monitoring techniques. Camera-derived measures of heart rate, respiratory rate, temperature, oxygen saturation, and blood pressure

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[58] The University of Plymouth are currently investigating the specifics of alarm sounds in the clinical space and how different sounds might affect both their audibility and effect on the surrounding environment (https://www.plymouth.ac.uk/staff/judy-edworthy).

[59] The finding that single-point microphone measures of A-weighted values may not be the most appropriate method for monitoring sound levels in patient areas needs further investigation.

surrogates are feasible, although not yet suitable for routine clinical use [395]. Full sleep staging is perhaps an unrealistic aim for the near future but algorithms combining physiological variables with additional data on movement offers something of interest to the clinical community.

8.7. Dissemination and impact

8.7.1. ICU Management & Practice

Following the poster presentation at ISICEM (Brussels, March 2019), Julie Darbyshire was asked to write an article for the online journal ICU Management & Practice: Darbyshire JL, Noise in the intensive care unit: where does it come from and what can you do about it?, *ICU Management & Practice 2019*; 19(2): https://bit.ly/2m1myoU

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Sleep in the Intensive Care Unit: Limiting Elements of Noise in the Critical Care Environment (SILENCE)

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Appendix A: Acknowledgements

DPhil supervised by:

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Project delivery

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NIHR SILENCE Project Steering Committee

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Data collection, extraction, and data entry

I am grateful to the Health Experiences Research Group, Department of Primary Care Health Sciences, the University of Oxford for permission to conduct a secondary analysis of interviews collected for their study of experiences of intensive care, which was funded by ICNARC. Summarised findings from their study are also available on the www.healthtalkonline.org website run by the DIPEx Charity.

The following people assisted with patient recruitment, data collection, and data entry for the sleep assessment phase of the NIHR funded project: Laura Beck, Clare Hird, Emma Jeffs, Charlotte Robbins, Dhaneesha Senaratne, and Anne-Marie Sly.

Emma Jeffs collected some of the observation data for the in-situ ethnography.

Markus Müller-Trapet, supervised by Filippo Fazi and Jordan Cheer from the Institute of Sound and Vibration Research at the University of Southampton, designed and built the microphone array system, including the automated calculation of sound level values which were exported for analysis and enabled visualisation of environmental noise.

Andrew Wilson from Oxford Computer Consultants assisted with user testing of the display and translation of feedback into features of design.

Teaching package development and delivery

Paul Greig provided general advice for curriculum purpose and development, Nadeem Khan and Lyn Bennett facilitated the in-situ training sessions and Ellie Peters made the e-learning module available to staff via the local intranet.

Paul Greig, Russell Sinclair, and Verity Westgate assisted in the making of the ICU soundtrack used for the experiential simulation.

Laura Beck, Clare Hird, Emma Jeffs, Breda Lynch, Charlotte Robbins and Anne-Marie Sly assisted with the delivery of in-situ experiential training sessions.

Sound monitoring system implementation

The facilities team at Oxford University Hospitals NHS Foundation Trust, led by Kevin Selwood, installed the microphones and associated connective wiring into the adult intensive care unit.

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Data Manipulation and Analysis

Emma Henderson (secondary analysis) and Emma Jeffs (ethnography) assisted with qualitative analyses. Lisa Hinton reviewed and commented on coding frames and assisted with identification of themes for the qualitative analyses.

Paul Greig and Robert Hatch created the underlying systems that transformed unworkably large datasets into smaller, more manageable units to enable quantitative analysis of sound levels.

Duncan Young processed spatial data for the results published in the British Journal of Anaesthesia (doi:10.1111/anae.14690).

Jonathan Bedford, Robert Hatch, and Oliver Redfern offered guidance with data manipulation and processing in R.

Data presentation

Markus Müller-Trapet translated microphone array data to the initial visual display (iteration 1a).

Paul Greig translated live sound level data feeds from the Casella monitoring system to a prototype visual display for demonstration purposes (iteration 1b).

Duncan Young manipulated data from the microphone array system to create a visual display of sound density that was published in the British Journal of Anaesthesia (doi:10.1111/anae.14690).

Matthew Gallagher, Reynold Greenlaw, James Greig, Mariana Morris, Beverley Newing, Rob Pym, Ekta Rathi, Matthew Standage, Andrew Wilson, and Andrew Wroe from Oxford Computer Consultants ensured that the prototype display was programmed in line with staff and patient feedback.

Appendix B: AEBCD materials

Sleep and disturbances questionnaire

Sleep Assessment Part 1

Patient Completed Richards-Campbell Sleep Questionnaire

Sleep in the ICU: Limiting Elements of Noise in the Critical Care Environment

The SILENCE Study

Phase 1: Sleep Assessment in the ICU

Study ID:_____ **Date:** ____/____/_____

Each of these questions is answered by placing an "X" on the answer line. Place your "X" anywhere on the line that you feel best describes your sleep during the Sleep Monitor recording period.

			Office use only:
1.	My sleep last night was:		
Deep Sleep	_____	Light Sleep	
2.	Last night, the first time I got to sleep, I:		
Fell asleep almost immediately	_____	Just never could fall asleep	
3.	Last night, I was:		
Awake very little	_____	Awake all night long	
4.	Last night, when I woke up or was awakened, I:		
Got back to sleep immediately	_____	Couldn't get back to sleep	
5.	I would describe my sleep last night as:		
A good night's sleep	_____	A bad night's sleep	
6.	I would describe the noise level last night as:		
Very quiet	_____	Very noisy	
7.	Last night, the light levels:		
Didn't affect me at all	_____	Kept me awake all night	

Each question is scored using a 100mm visual analogue scale in which a higher score is better.

SILENCE

Oxford University Hospitals NHS NHS Trust

UNIVERSITY OF OXFORD

SILENCE1: Sleep Assessment: 08 May 2014: Version 1.1

Sleep Assessment Part 2

Patient Completed Significant Disturbances Questionnaire

Sleep in the ICU: Limiting Elements of Noise in the Critical Care Environment

The SILENCE Study

Phase 1: Sleep Assessment in the ICU

Please indicate (by placing an "X" at the best point on the answer line) how often you felt the following noises disrupted your sleep during the Sleep Monitor recording period.

	Not at all — ***All the time***	Office use only:
Handover/s at Bedside		
Care given by Nurse or Doctor		
Equipment Alarms		
Visitors		
Cleaning Staff		
Telephone/s ringing		
Bleeps going off		
Music/Radio/TV		
General Chatter		
Footsteps		

Were there any other significant disturbances? *(please specify)*

Many thanks for your help!

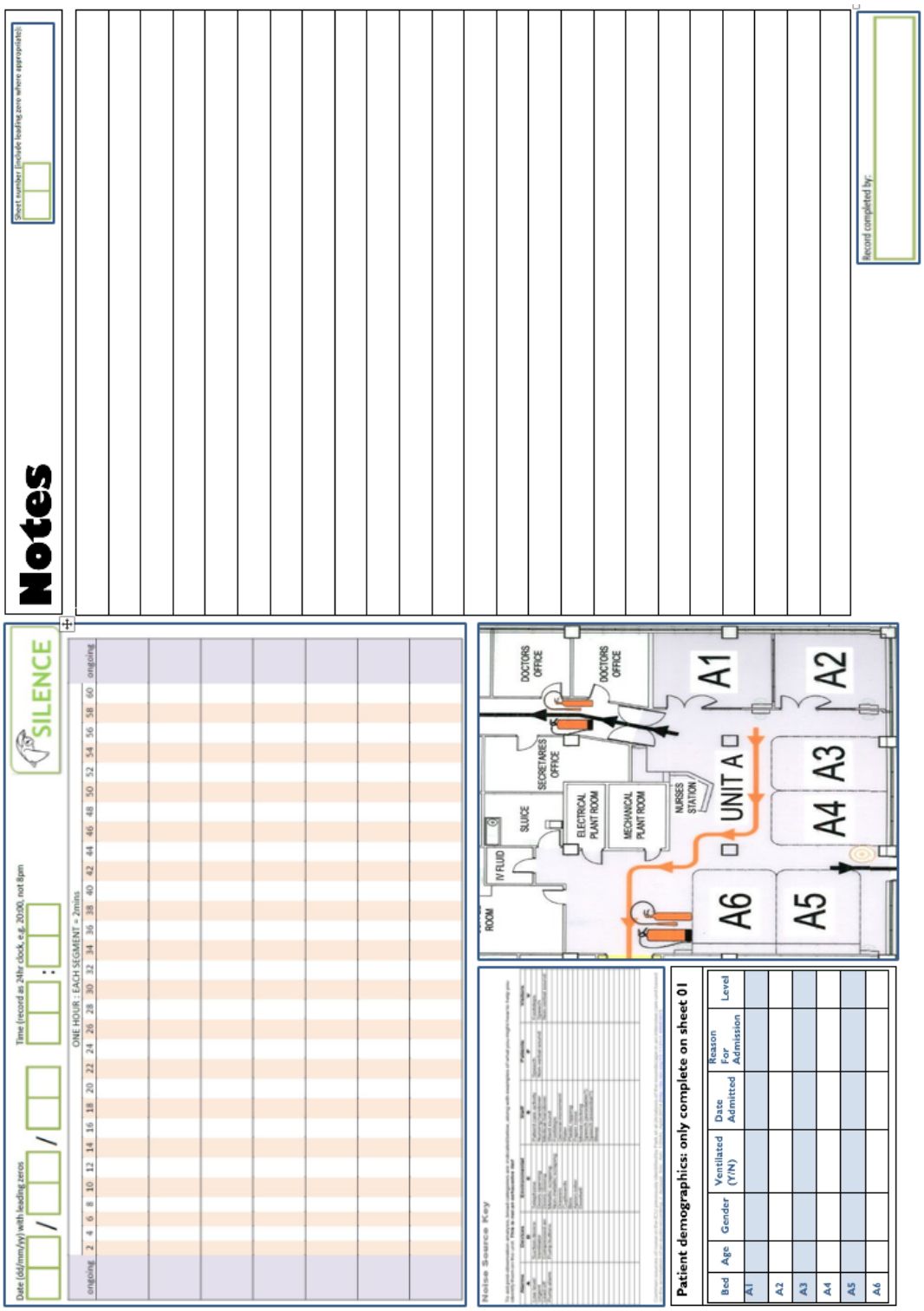
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Field notes data collection form



Focus Group agenda & topic guide

- Welcome
- Confirm timings
- Introductions to research team
- Confirm filming

Summarise results of pre-SILENCE noise monitoring study, reasons for applying for RfPB grant and outline results of ongoing sleep study.

Next steps are to bring together staff and patients in a joint exercise to develop plans to lower noise levels, improve patient sleep and reduce delirium. Already large patient-focussed body of evidence so today want to explore noise on the ICU from a staff perspective.

- Sources of noise:
- Reasons
- Effects
- Possible solutions to put forward to staff/patient group

Trigger Film transcript

The following is the text transcript to accompany the film clips. The background colour refers to the source of the quotation being from a patient (green), relative (purple) or staff member (pink).

Key

Patient
Relative
Staff from focus group

Section: Being disturbed by equipment
The sound of the ventilator I think is a sound that'll never go out of my head. I think now having, because he was on that for over two weeks, and when they initially tried to take him off it he couldn't breathe for himself and they had to put it back on. And that sucking and blowing, oh my goodness that sound lives with you, I think, forever.
And also I could hear, I thought it was a plane, it was like a whoosh, whoosh, whoosh sound and apparently that was the ventilator.
They told me everything. I knew everything from every bleep because he was wired up. At one point I think he had nine or ten drips in and his heart monitor and the ventilator, which is very scary anyway. Because the best way I can describe it is sounding Darth Vader.
I do think they need to know about the environment and we used to do it so this is the ventilator, you hear that noise that's what the noise is, don't worry about it
To start with when I first came round, I was on a special bed, one that tipped. It used to sound like an aeroplane taking off because it would go up and down and whatever. When I went into the room and I was on a Pegasus mattress, as I say, I just found it, and that's what it was, and I had a hard job getting them to prescribe me sleeping tablets. But there was ones that were understanding, and they said, because I was just, I wasn't sleeping and the nights seemed to go on forever.
I've spoken to a majority of people, one patient I know in particular was moved into a side room because of the apron rollers
[...] the lids on the bins, the lids, you could hear the lids on the bins. Well when I was sedated I could hear these big bangs and it made me jump and it made me frightened

[…]

when people put their foot on the pedal of the bin and the bin crashes down and you're just dropping off to sleep and, you know, you already think you're in a strange environment, that you've been abducted like by aliens and then this thing comes crashing down.

[…] when I woke up I thought, because I was so frightened, I thought they were like champagne corks popping and that wasn't because I thought people were having champagne, I thought I hope the doctors and nurses aren't drinking, I've nearly died.

Section: Alarms

I found myself looking at the monitor all the time, every time an alarm went off I'd try to fathom if anything, I think you get to the stage then where you're waiting for something else to go wrong.

I wouldn't let my alarms go off and off and off not where we are but it's probably different on a ward but if I'm looking after a patient then I should know that my insulin's going to run out so …..

And one of my friends said oh it was really frightening, she said it was like spaghetti junction, she said you were frightened to approach the bed, you didn't know which side to go. She said there were wires and beeps and you know and everyone was listening, if your machines weren't beeping somebody else's were. And because it was in intensive care they said they knew the beeping was quite serious so people were really frightened.

Don't worry about noises, don't worry about things going off because they're all looking after you. They're all there for a purpose and they're gonna do, they're all doing a job and it's wonderful, you know. If something does go beep and it shouldn't go beep they'll straightaway come over and say, "What's up here?" They used to do it all the time with me, you know, if something didn't look quite right, straightaway over, adjust it. They're listening for those beeps, don't worry.

It might just sound nothing to you, that beep means something. Very often they can be going for a little while and somebody will say, "What's that?" "No it's nothing, don't worry". Then all of a sudden another beep would go off, zoom they're there, you know, sort of on it straight away, so it all means things to them 'cause they're trained that way.

[…] there was one particular one that goes into your arm, or your finger, or your wrist and if your arm is lying in a certain way it blocks it. And then it sets off the, ding dong, ding dong, ding dong, and these kept on going off. And every time I went to sleep I moved and of course I moved in such a way that it set it off and woke me up.

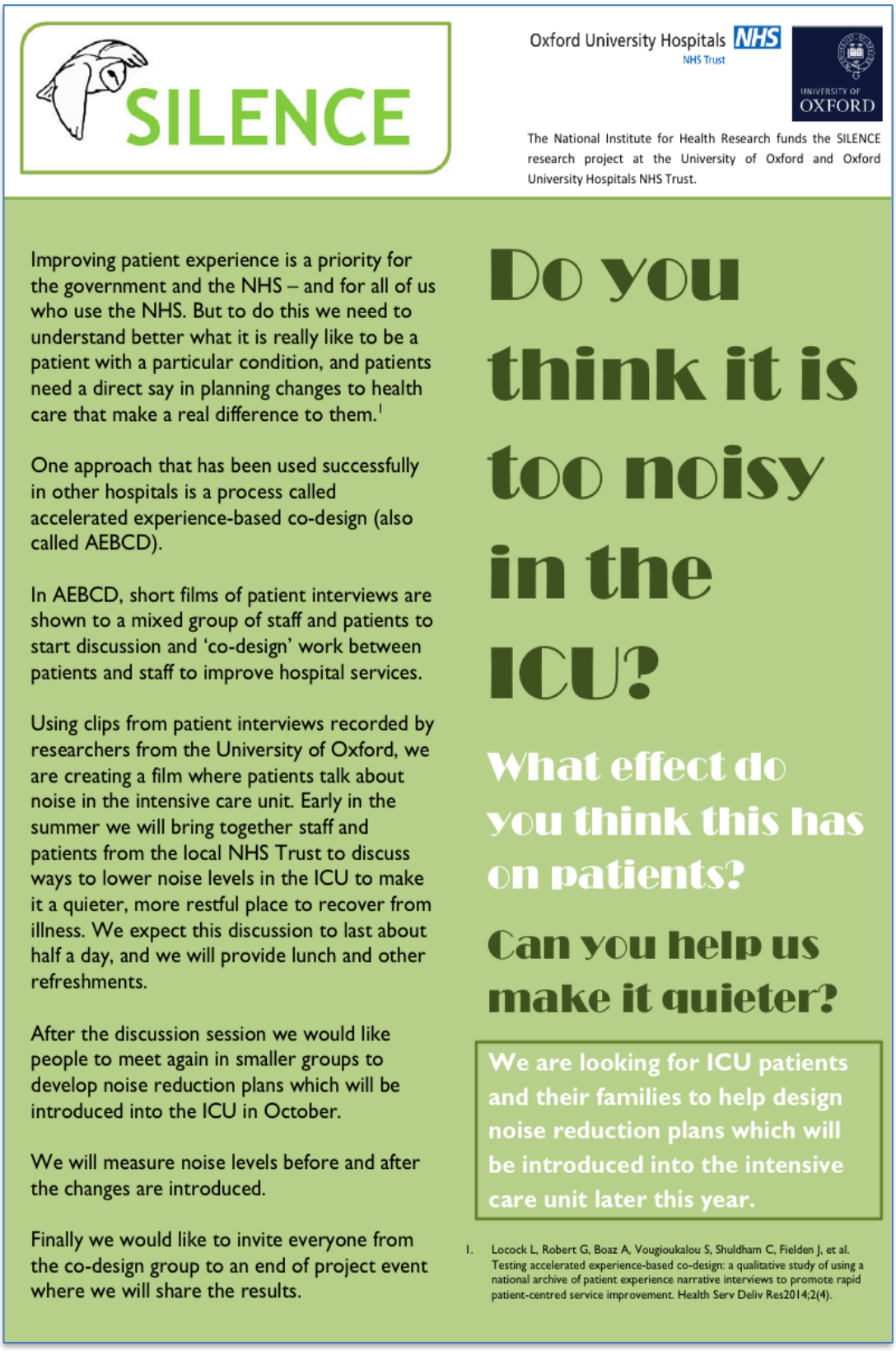
[…] as she began to, to lighten the sedation she was obviously finding things quite irritating and she would often pull the SATs clip off and of course it would then start to bleep. So that was when we started putting it on our finger. Just to stop the monitors from bleeping.

Section: Being disturbed by people
But the worst part of it was, is when people got loud, they got loud, noisy. I think there must have been an awful lot of people in Intensive Care who were out of it, so didn't know what was going on. So therefore it didn't matter, or I think people had got used to it not mattering if they made a lot of noise. But I could be sort of dozy, and I'd be startled because [laughing noise] someone's having a big laugh or whatever. And that kind of start, it makes you feel very anxious, and it increases your anxiety.
The problem is trying to get a fine balance. You don't want to be too dictatorial because the team work in an ethos and working together and communication they've got to be able to talk and its not just about work its go to be because that's how you build up relationships
sometimes it kind of passes you by but to be honest you're so busy you don't realise how much you're clattering around I don't think. Its more noticeable at night time when you're being noisy but actually sometimes making noise is the last thing you're thinking about.
I mean the only instance where I had slight misgivings in ICU was a particular nurse, excellent lady, I'm sure, [Laughs] who had the worrying habit of whispering. I mean, all the care that she gave me was fantastic, and they worked. But she was on night shift and whether for her own benefit or what I don't know, going through procedures, she looked as if she'd been in the business for a long time, and to be in ICU she must have been. But she whispered while she was doing things. So she would have, I remember specifically, two antibiotics one evening, that she had to mix and she was going [Whispering] "This is the one, yes this is the one and that's the other one ...." And then you wouldn't hear any more, you would just hear this, this low whispering.
[...] I got tired very quickly, I kept dozing off. And I can't go to sleep when I've got visitors, not really, so it's not a good idea really for visitors to stay too long and they knew that. [...}if the visitors see that the patient is drowsy to the extent of dropping off to sleep, best that they leave for a little while and perhaps come back later. Because you have the feeling that you ought to try to stay awake for them. It doesn't matter if they say oh you go and have a little rest, go to sleep, we won't mind. It doesn't work that like that somehow.
High-intensive, that I was in, had 6 beds and there was one particular patient who hallucinated and shouted through the night. Eventually they got members of the family to come and sit by the bed to try and sort of calm him down. But it did make sleep extremely difficult and I spent several nights without any sleep at all.
And I got to the point where tablets were no longer required in the evening. But I was still wakened at quarter to twelve to see if I was sleeping all right. And did I need any painkillers, anything to help me to sleep? I was so obviously in dreamland. Why don't they leave me? But, you know, the system requires that you are wakened to see if you're all right.
[...] I want to be discharged today. I'm really, I don't want to spend another night in this place because I'm not getting any sleep cos I'm, so many people are walking in and out of this room. I'm getting given so many informations, I'm still not well.

Section: Lights
[…] Lights play tricks on the mind, so that in the middle of the night when the lights are on in the ward, lights suddenly become faces, which are quite scary.
[…] I was in ITU on the Wednesday when I just come round I didn't get any sleep at all because of, I don't know why, because the light was on I just didn't get any sleep. The Thursday I didn't get any sleep when I came, when they took me into that room because the fluorescent light was on ahead, on top of me, adjacent to me where the sluice room was, a fluorescent light was on. On the left hand side of me there was a door with a light shining right through
What sort of noises are acceptable because obviously there's nothing we can do about some of the noise as much as we might want to because it is always going to be there because people are going to get really, really sick and we are going to be being noisy and have the lights on at two o'clock in the morning? There is some of the noise that we can definitely do nothing about
And the way that the lights sort of went across the ceiling made it look like some kind of lit grid. And for a long time I thought that there was some kind of laser grid thing for this high-tech place.
you don't have any conception of time. It could be day, it could be night, it could be the middle of the afternoon, as a patient you don't know, because the lights are on all night, the lights are on all day, there's activity all night and there's activity all day. So I didn't, half the time I didn't know what time it was

Section: Feeling overwhelmed
[…] I might have found it a bit alarming actually because, as I say, there are all these machines, a very, very high population of machines and bells and lights and drips and drains and people in there of course, not at their best.
The environment was quite difficult because people were coming and going, there's other patients that died during that time and of course you're in a quite a small environment and you know everything that is going on and that's quite upsetting. And again [my husband] couldn't respond to it, he couldn't say what he was thinking and his worries, he couldn't communicate his worries and in the Intensive Care, he was quite frightened that he was going to die. But it's just that environment that, you can't escape it.
sleep deprivation is a massive issue isn't it? I spoke to somebody yesterday and she was on ITU for three days and didn't sleep a wink and I said why was that and she said it was just so noisy, it was constant all the time and again I think she was next to, she was a level two patient, a level three patient with every piece of equipment possible so the patient was just busy constantly so she ….. a paper curtain's not going to keep any noise out is it really?
And it's a very, very noisy place. And so it is quite hard to kind of switch off in that respect. And also there's the whole discomfort of kind of you know. You are lying on your back. I mean when you can't go to sleep at home in normal life, you just kind of turn over and pump your pillows up and kind of get into a different position. There was no scope for doing that because I was wired up to, you know, I had a drip in each hand and a central line in my neck and stuff in my, you know in the side of my neck. I had a tracheostomy in the front of my neck and, quite apart from that, I was paralysed because I had a very severe intensive care neuropathy.
I used to make [my partner] wait till I did drift off to sleep. I mean I'd only go to sleep for a couple of hours but I used to say don't leave me, didn't I, don't leave me. Because the other thing that was quite frightening was because I couldn't move, the hospital of a night was really quite frightening and dark and all the noises.

AEBCD group invitation poster



Appendix C: Teaching package

Post-experience feedback questionnaire



Oxford University Hospitals NHS
NHS Foundation Trust



After the immersive experience please complete the following questions. They are designed to promote critical reflection of the experience and your practice. We would like this experience to be useful and relevant; your feedback on improvements is greatly appreciated.

1. Interviews were conducted with patients after their stay in the intensive care unit (ICU). The following words were frequently used to describe their experience. Please circle any words which come to mind after your completion of the immersive experience:

Worrying	Watched	Confused
Intensive	Frustrated	Excellent
Difficult	Poorly	Uncomfortable
Concerning	Pressured	Scarred
Manageable	Brilliant	Trusting
Hopeful	Rested	Exhausted
Awareness	Sick	Distressed
Emotional	Drained	Terrified
Upsetting	Stronger	Stupid
Shocking	Attacked	Mad
Frightening	Enjoyable	Settled
Worse	Horrible	Determined
Awful	Angry	Relaxed
Tired	Reassured	Scared
Weak	Fortunate	Alone
Amazed	Silly	Perspective
Small	Encouraged	Afraid
Stressed	Surprised	

2. Please record any other words which describe your feelings about the immersive experience:

4. Please tick one response to the following questions:

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
I feel I will change my practice after undergoing the immersive experience	☐	☐	☐	☐	☐
I found the immersive experience useful	☐	☐	☐	☐	☐
I feel that the immersive experience recreated the patient experience well	☐	☐	☐	☐	☐
I feel that patients in ICU undergo significant stress	☐	☐	☐	☐	☐
Staff in ICU can do more to create a less stressful environment for patients	☐	☐	☐	☐	☐

5. If you feel you will change your practice after completing this experience, please write how:

6. Please write here any suggestions you have for improving this experience:

Immersive experience guidelines



Scope

This document is intended to guide facilitators through the steps for setting up and performing the immersive simulation experience for staff nurses on Intensive care units.

The aim of the immersive experience is to heighten the idea of what it can be like for a patient staying in an intensive care unit (ICU). The SILENCE project (NIHR ref: PB-PG-0614-31034) is particularly focussed on noise levels, but this experience also highlights how disorientating and frightening unfamiliar clinical sounds can be.

The simulation will involve the member of staff participant placed in a hospital bed and attached to monitoring equipment and (with tapes!) lines. Their vison will be altered with glasses. A clinical scenario has been recorded for this experience and will be played to the staff participant through earphones (some SILENCE earphones are provided, staff may use their own). This is what is known as a binaural recording. This means that the sounds will be heard by the participant in stereo and it will seem like noises are happening all around them.

In addition, live action will be performed around the bed space, including interaction with the staff member.

After the simulation the participant should be asked to give feedback on the experience using a simple questionnaire. This invites reflection on the experience. Reflection is a vital part of adult learning and will help to reinforce the learning points.

The participant simulation lasts around six minutes but we recommend that each member of staff allows about 15 minutes in total to be set up in the simulation and to answer the short post simulation questionnaire.

Venue

The simulation works best in a live, working intensive care unit. It can be delivered in a simulation suite as long as there is a bed and monitoring equipment that would be found in the ICU.

Equipment (examples, not exhaustive list)

- Tape (eg micropore or similar)
- 1 x sheet (this can be used multiple times)
- 1 x pillow and pillow case
- Flowtron boots
- Distortion glasses
- Pegs (for pegging uniforms to sheets)
- IV lines (no IV access required!)
- Neck collar
- Questionnaire Sheets & pens

Setting up the participant

- 2 – 3 members are needed to deliver this experience to one staff participant at a time
- Attach blood pressure cuff, oxygen saturation probe and ECG monitoring to the participant. Set limits to alert for normal values (to guarantee they will sound during the experience).
- Apply glasses and stick lines to arms/legs.
- Peg uniform to the bed (simulates immobility of patients)
- Turn lights off in the room
- The audio recording will be played to the participant through headphones.
- Tasks around the bed space can cause extra, unexpected, sounds and unexpected "patient" interaction.

Examples of actions for the immersive experience (not an exhaustive list):

- Turn on ventilator
- Turn on Alaris pumps to activate warning alerts
- Wash hands in sink
- Put paper in the bin
- Move trolleys around
- Use the apron roll
- Place BP cuff on patient and start
- Pull on sheets
- Fit boots/neck collar
- Rustle packets by ear
- Open/close drawers/cupboards
- Turn on/off mattress.
- Undo the brakes and push bed backwards
- Change positon setting of bed
- Knock (gently!) into bed
- Perform patient roll (with/without explanation)
- Use torch to examine patient (inc passing light over face)

Questionnaire

After the immersive experience debrief the participant and ask them to fill out a questionnaire on the experience

Make sure everything is wiped down at the end of the sessions and that the bed space/room is left the way it was found.

Assessment Validation

As described in chapter 5, the validation of a testing regimen requires consolidation of multiple sources of evidence. Classically these were subdivided into items such as 'face' and 'construct' validity, but a more modern approach is to consider this body of evidence in a manner analogous to a research hypothesis, interpreting data with reference to context.

For this project a number of sources of evidence (table 5-2) were available to support a valid formative assessment at the conclusion of the teaching programme. Confidence in the content of the course was established through a robust process of content development, supported by educational experts and patient representative. The blueprinting exercise (tables C-1 and C-2) confirmed that the assessment content mapped well to the course materials, and pilot testing was conducted prior to roll out.

The internal structure of the assessment was tested by a measure of internal consistency (Cronbach Alpha value 0.72). Although not 'excellent' (which would require an alpha value >0.90), this was adequate for a formative assessment such as this. Further evaluation might be feasible through factor analysis or calculation of test-item statistics, but this would require a larger sample of responses, and would probably be disproportionate given the formative decisions this test is designed to enable.

Establishing the relationship of this test to other variables available was perhaps the most challenging point on which to gather evidence. As a novel assessment, no existing tools were available for comparison, and it was difficult to identify a suitable population for expert-novice comparisons. Although not ideal, the pre- and post- test comparisons revealed a significant improvement after learners engaged with the teaching materials, indicating higher assessment results with greater levels of knowledge.

The response process was largely evaluated through participant feedback which was overwhelmingly positive. The teaching package was delivered as a mixture of online content and face-to-face simulation. Candidate assessment supplemented the e-learning module. This offered convenience and accessibility to learners, whilst also being an economic and easily scalable means of assessment. The assessment therefore had to be in a suitable digital format. This indicated short-answer and multiple-choice questions.

This format shares a commonality with other professional and (post)graduate examinations, including those used by most Trusts' e-learning packages. Users will be familiar and comfortable with this style of assessment.

The consequences of the test were assessed through participant feedback. It was clear the test had the desired emotional impact on participants (based on the post-course word-cloud), and the positive responses received from the course evaluation suggested no-one experienced any adverse impacts from their assessment. The fall in sound pressure level recorded at YDH demonstrates a positive behavioural impact. An assumption remains that this translates into improved patient outcomes, but evidence supports the use of assessment in this context.

Question title	Domains explored
What is the WHO guideline limit for ICUs	EM2
What is local LAeq?	LNP1
What is LCpk?	EM1
In normal healthy sleep what proportion of time is spent in the deepest stages of sleep?	SA1
How long does an average sleep cycle last in normal healthy sleep?	SA1
Main feature of sleep for patients in the ICU?	SA1
Measures of ICU sleep	SA3
ICU sleep risks in ICU	SA1
Sleep disturbances in ICU	EM2, LNP3, SA2
Interventions proven to improve sleep	EM2, LNP3, SA2
What have been shown to be a source of intrusive noise?	LNP3
Which interventions have been demonstrated to reduce patient disturbance?	SA2
Monitor: Which icon number activates the volume control	LNP2

Table C-1: Assessment question mapping to curriculum domains

By checking the number of questions mapped to each content area (Table C-2), it is clear that prevalence of content is appropriate to the weight they were given in the curriculum (Table 5-2). This suggests the assessment tool possesses both sampling and content validity.

Content Area	Number of domains explored	% of curriculum
Environmental Monitoring (EM)	3	20
Local Noise Patterns (LNP)	4	27
Sleep Architecture (SA)	8	53

Table C-2: Breadth of curriculum explored by assessment

Appendix D: Interface development

Example user-testing topic guide



I am going to show some proposed interface designs for the SILENCE project.

It is important to note that these set of designs have been designed with no user input. We will be doing further testing with designs that have been designed with user input.

We are interested in getting your feedback – positive and negative – regarding these.

Please feel free to make any suggestions you have for improving the design.

Do you have any questions?

Interface specific questions:

Interface 1

What are your first impressions of this proposed design?

What do you think each of the following are/ represent?

- Rectangular box with markers and yellow level
- Blue rectangles
- Red circles
- Green circles

Ask further probing questions as applicable

What do you like about this proposed design?

What do you not like about this proposed design?

What would your suggestions be to improve this proposed design?

Is there anything you would add to this proposed design?

Interface 2

What are your first impressions of this proposed design?

What do you think each of the following are/ represent?

- Main graph at top of the page
  - Orange 85dB line in the graph
- Time under target:
  - Circle with grey border 35dB
  - Circle with grey border 50dB
  - Circle with orange border 85dB
- Trend average:
  - Circle with black border 52.3dB
- Day average:
  - Circle with yellow border 53.3dB
- Night average:
  - Circle with dark blue border 51.5dB
- Graph at bottom of the page
  - Columns of data in the graph
  - Different colours of data in the graph

Ask further probing questions as applicable

What do you like about this proposed design?

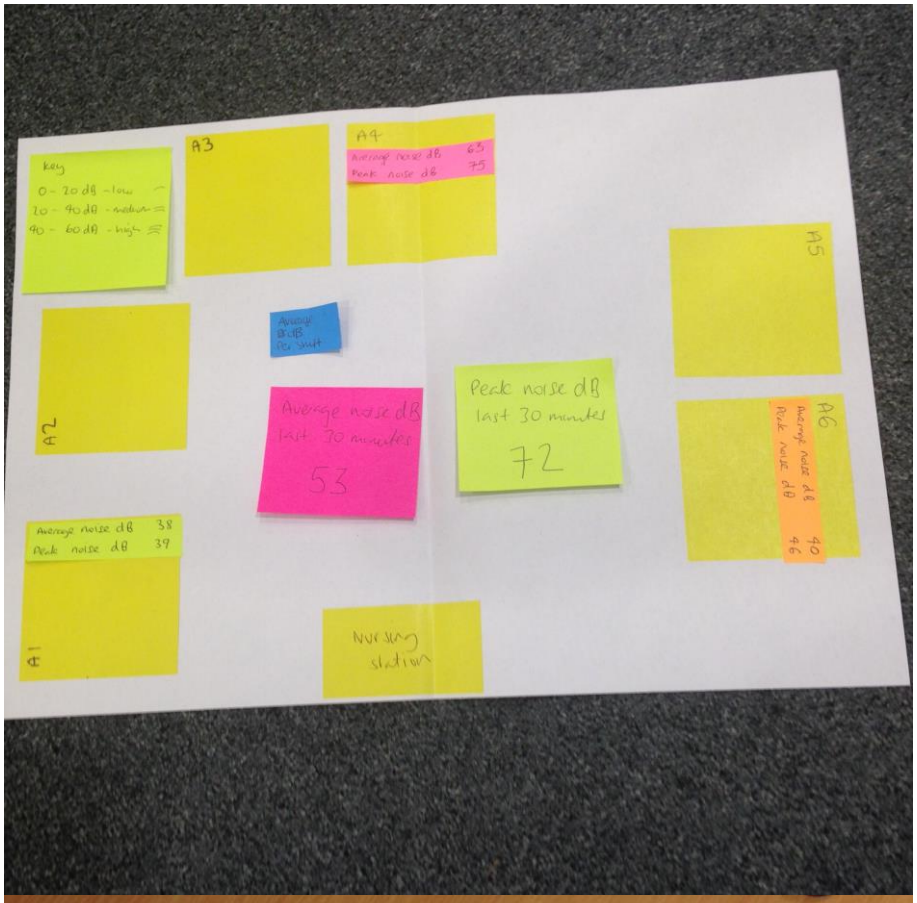
What do you not like about this proposed design?

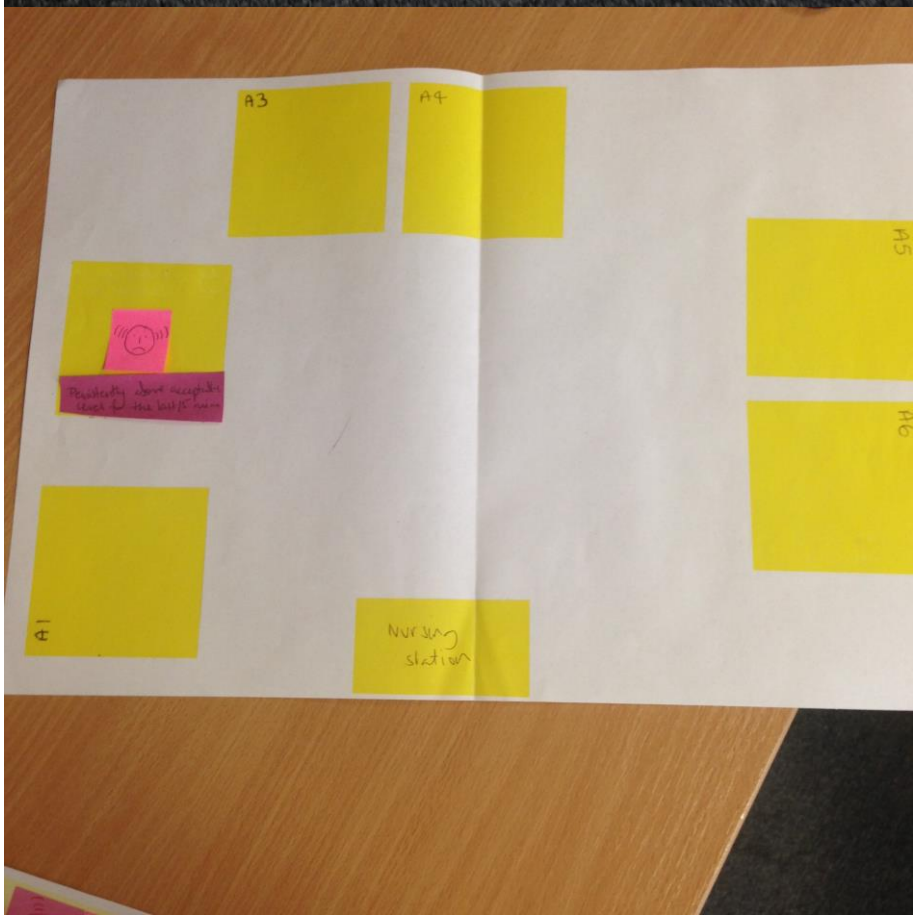
What would your suggestions be to improve this proposed design?

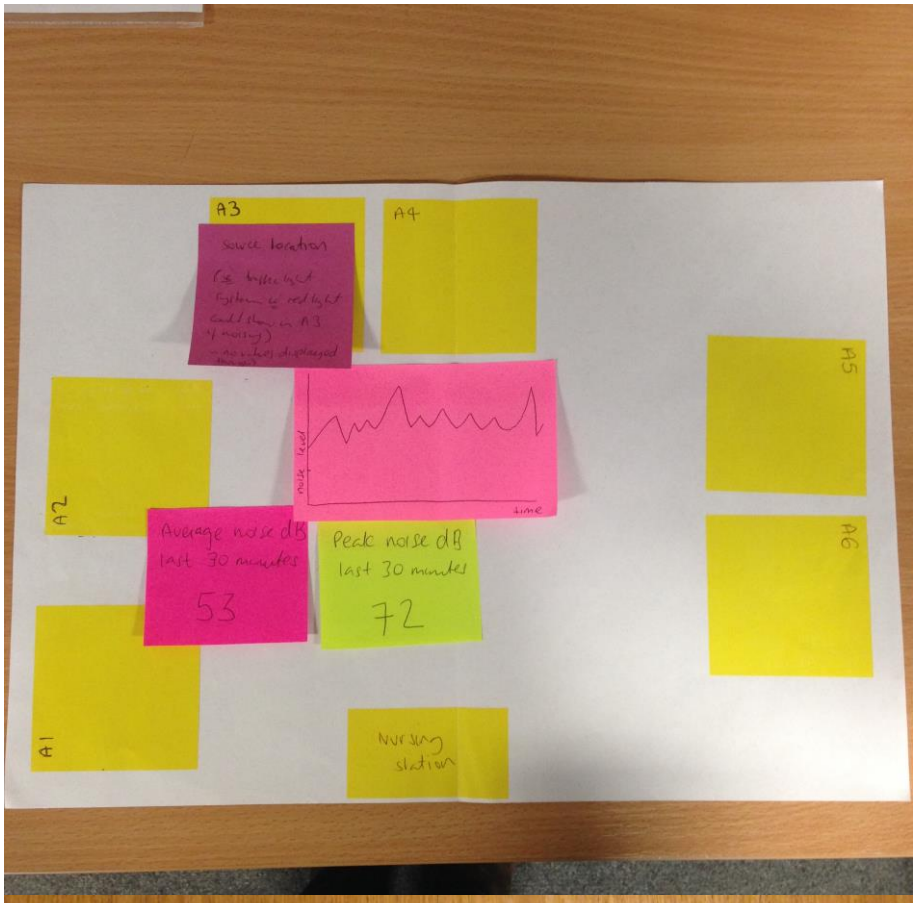
Is there anything you would add to this proposed design?

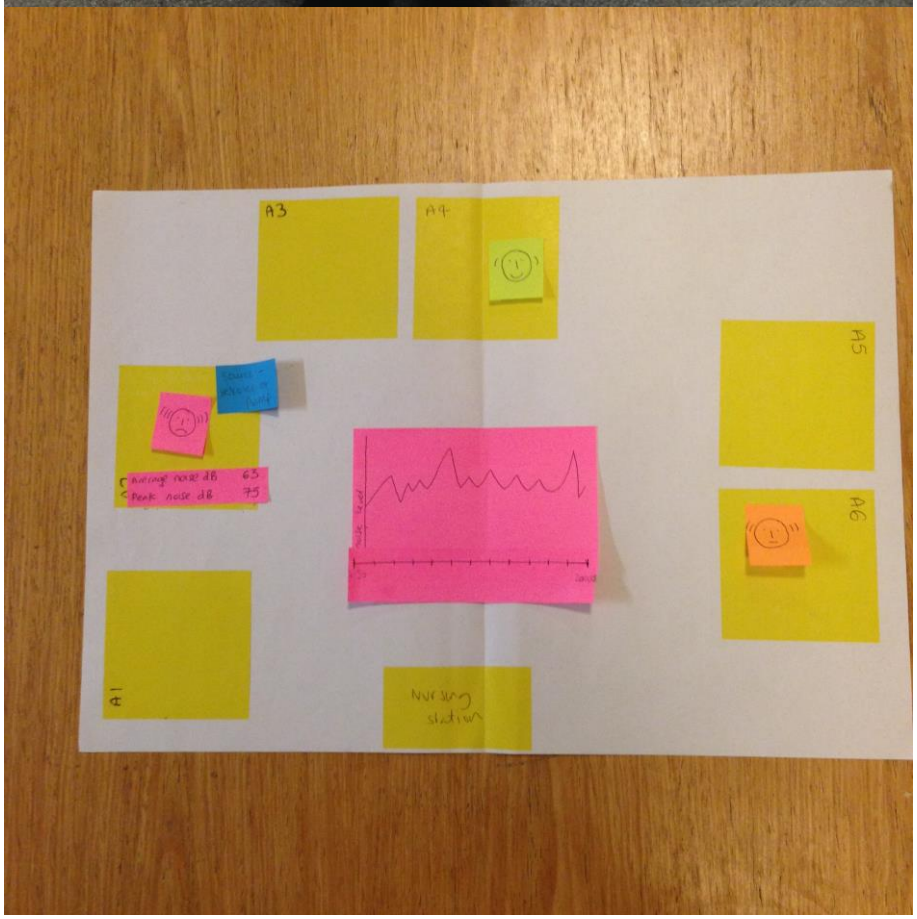
User designed interfaces

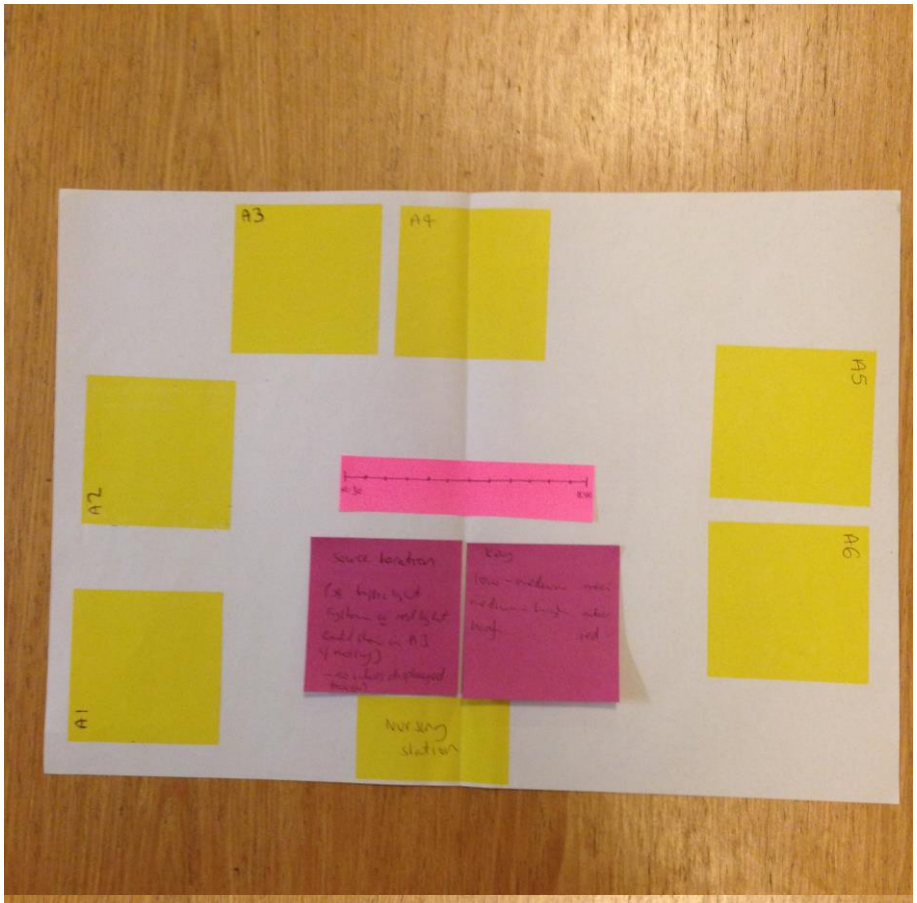


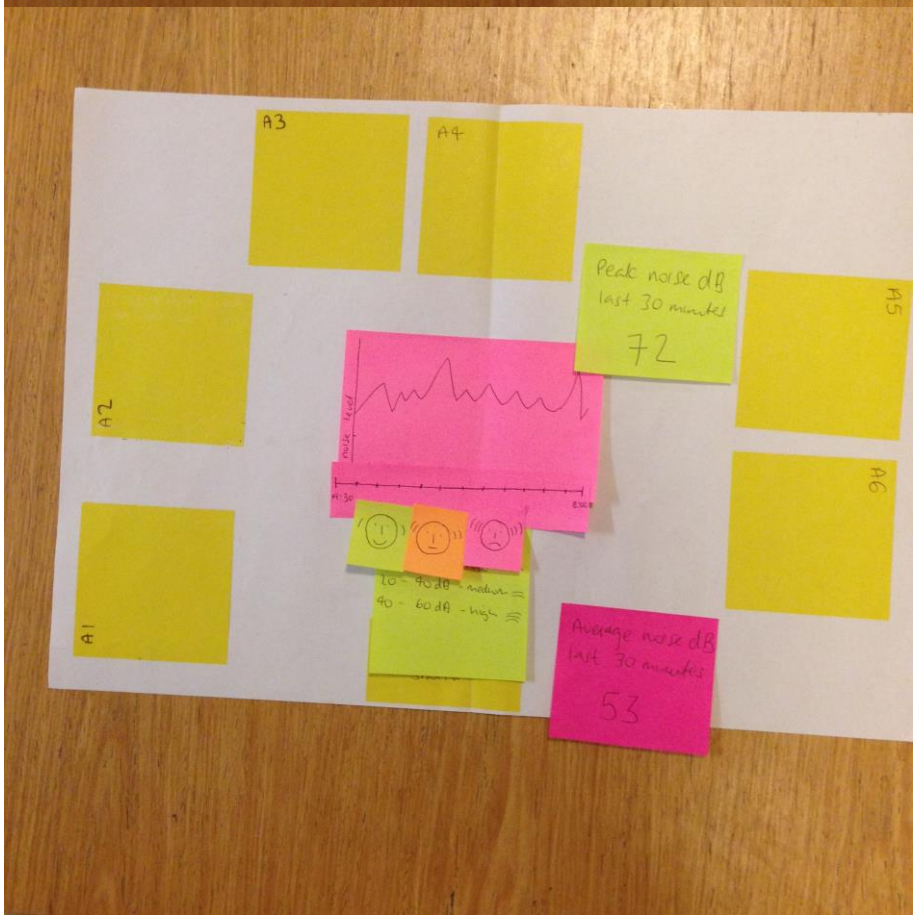

key
0 - 20 dB - low
20 - 40 dB - medium
40 - 60 dB - high
A3
A4
Average noise dB 63
Peak noise dB 75
A5
A2
Average noise dB
last 30 minutes
53
Peak noise dB
last 30 minutes
72
A6
Average noise dB 40
Peak noise dB 46
Average noise dB 38
Peak noise dB 39
A1
Nursing station

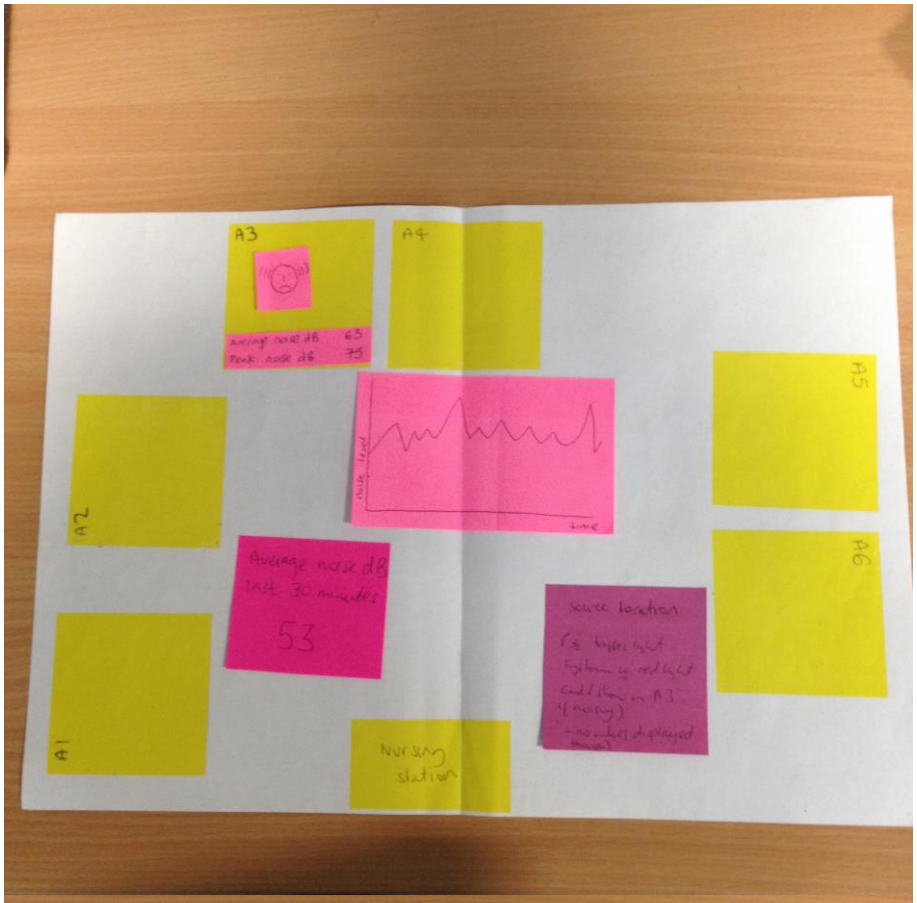

A3
A4
A5
A6
A1
Nursing station

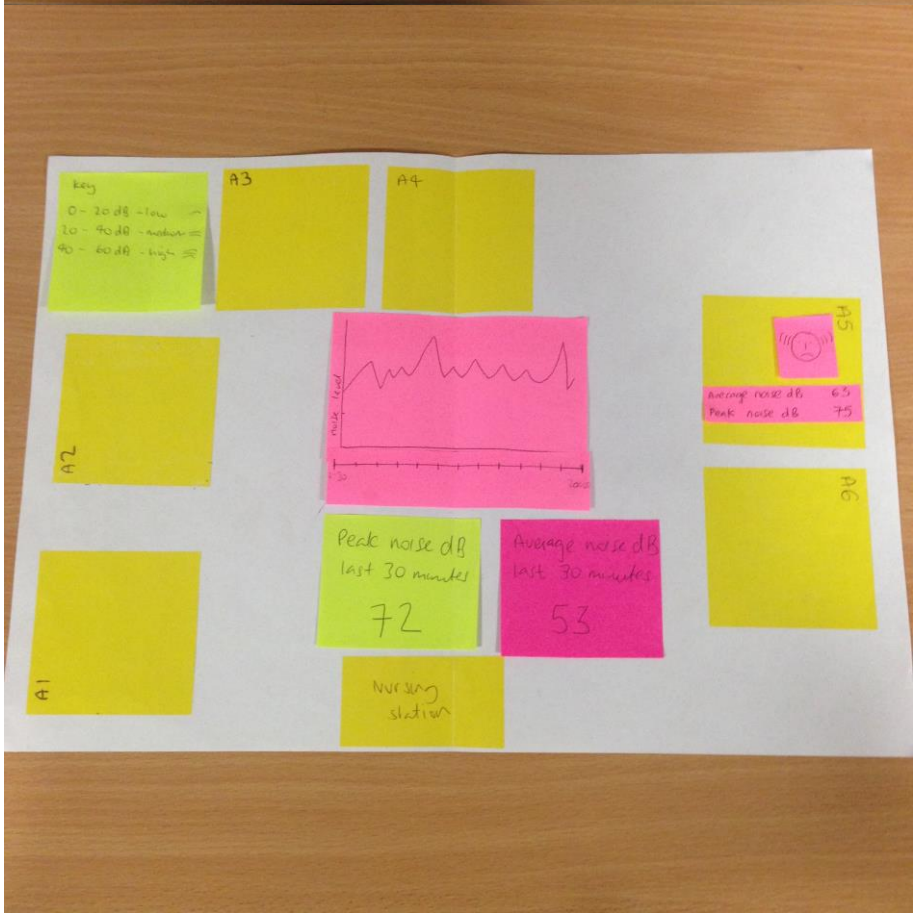

A3
A4
A5
A6
A2
A1
Average noise dB
last 30 minutes
53
Peak noise dB
last 30 minutes
72
Nursing station


A3
A4
A5
A6
A1
Nursing station

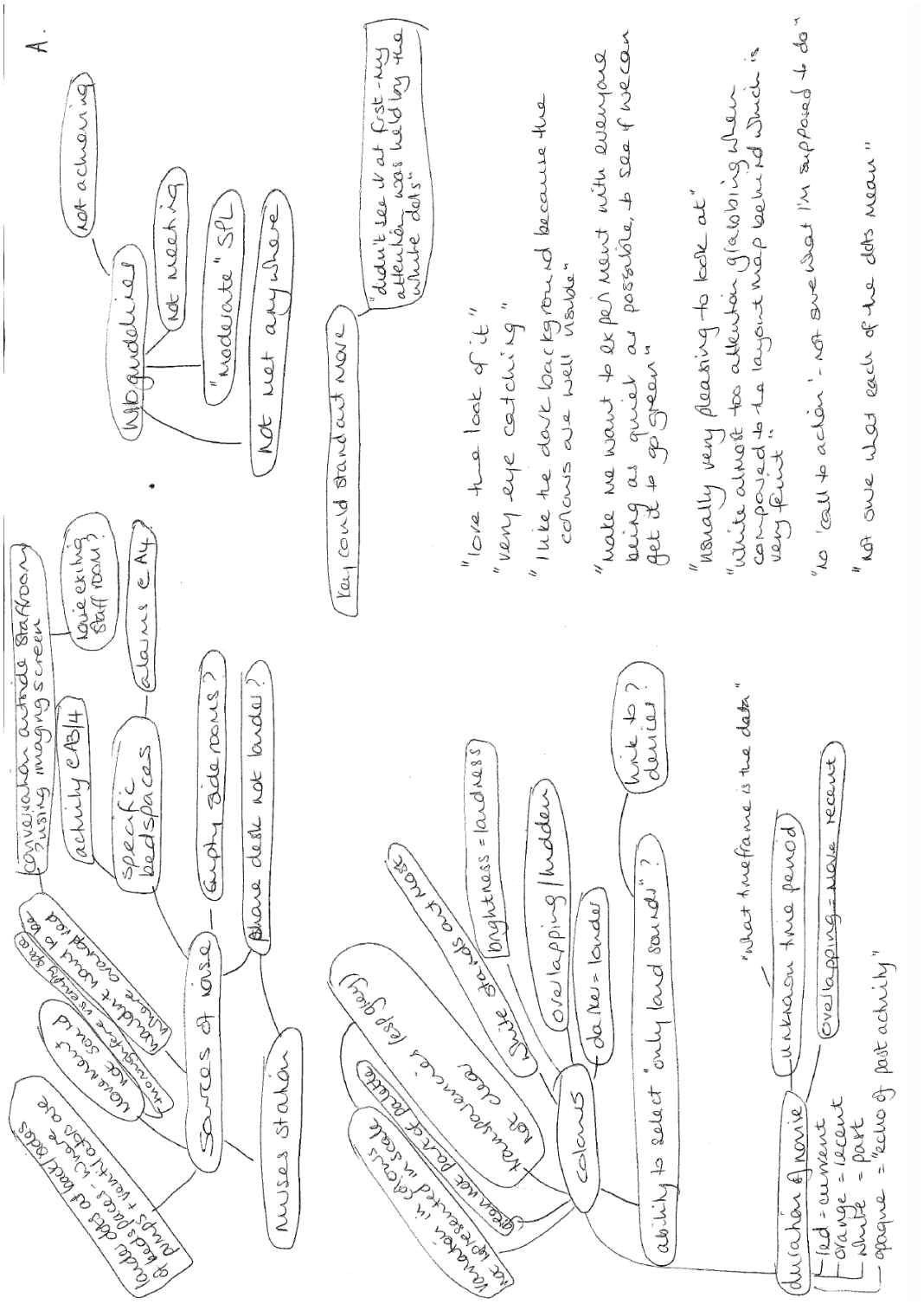

A3
A4
A5
A2
A6
A1
Nursing station


A3
A4
Peak noise dB last 30 minutes
72
A5
A2
A6
A1
Average noise dB last 30 minutes
53


A3
A4
A5
A2
A6
A1
Average noise dB
last 30 minutes
53
Source location
Nursing
station


key
A3
A4
A5
A2
A6
A1
Peak noise dB
last 30 minutes
72
Average noise dB
last 30 minutes
53
Nursing
station

Feedback summary for iteration 3b designs


A.
not a learning
not reading
"moderate" SPL
Not met anywhere
Key could standout more
"didn't see it at first - my attention was held by the white dots"
"love the look of it"
"very eye catching"
"like the dark background because the colours are well visible"
"make me want to OK pen want with everyone being as quick as possible, to see if we can get it to go green"
"visually very pleasing to look at"
"white almost too attention grabbing when compared to the layout map behind which is very faint"
"no 'call to action' - not sure what I'm supposed to do"
"not sure what each of the dots mean"
conversation outside staffroom
using imaging screen
activity cABJ4
leave existing staff room?
specific bedspaces
rooms c A4?
Sources of noise
Empty side rooms?
Phone desk not loaded?
Nurses station
Would days of week/dates be helpful + visually clear
Would want to be able to customise what is displayed
Would want to see all
Make sure
Would want to be able to customise what is displayed
Visually separated in groups
Use different font/size
Use different font/size
Use different font/size



"aesthetically better and less cluttered"

"second version is better but the colours that stand out most are white and green which are the lower dB"

"its much clearer as the colours don't obscure the floor layout so much"

Appendix E: Publications

The following pages are copies of publications, posters, and reports arising from this thesis at the time of submission.

CRITICAL CARE

RESEARCH Open Access

An investigation of sound levels on intensive care units with reference to the WHO guidelines

Julie L Darbyshire[1*†] and J Duncan Young[1,2†]

Abstract

Introduction: Patients in intensive care units (ICUs) suffer from sleep deprivation arising from nursing interventions and ambient noise. This may exacerbate confusion and ICU-related delirium. The World Health Organization (WHO) suggests that average hospital sound levels should not exceed 35 dB with a maximum of 40 dB overnight. We monitored five ICUs to check compliance with these guidelines.

Methods: Sound levels were recorded in five adult ICUs in the UK. Two sound level monitors recorded concurrently for 24 hours at the ICU central stations and adjacent to patients. Sample values to determine levels generated by equipment and external noise were also recorded in an empty ICU side room.

Results: Average sound levels always exceeded 45 dBA and for 50% of the time exceeded between 52 and 59 dBA in individual ICUs. There was diurnal variation with values decreasing after evening handovers to an overnight average minimum of 51 dBA at 4 AM. Peaks above 85 dBA occurred at all sites, up to 16 times per hour overnight and more frequently during the day. WHO guidelines on sound levels could be only achieved in a side room by switching all equipment off.

Conclusion: All ICUs had sound levels greater than WHO recommendations, but the WHO recommended levels are so low they are not achievable in an ICU. Levels adjacent to patients are higher than those recorded at central stations. Unit-wide noise reduction programmes or mechanical means of isolating patients from ambient noise, such as earplugs, should be considered.

Introduction

Over 30% of patients treated in ICUs become confused or develop delirium. These patients have longer hospital stays and higher mortality and morbidity [1]. Risk factors for the development of ICU-related delirium are sedation use and invasive procedures, but there also is a link with environmental factors, including noise-induced sleep disturbance [2].

Although there is wide variation due to individual sensitivity to noise and tendency to aggravation [3], the normal healthy adult can tolerate an A-weighted sound level in decibels (dBA) of about 50 to 55 dBA relatively well during the day and 40 to 45 dBA overnight [4]. At these levels, most individuals would not experience annoyance, sleep disturbance or any detrimental health effects. However, quantifiable effects from sleep disturbance can be seen at time-averaged sound levels (L_{Aeq}) as low as 30 dBA and corresponding peak noise levels (L_{Amax}) of 45 dBA or less [4].

The World Health Organisation (WHO) *Guidelines for Community Noise* includes advice on noise levels in hospitals and suggests that, because patients are less able to cope with the increased stress levels generated by excess environmental noise, the sound level in hospitals should not exceed 35 dBA L_{Aeq} for areas where patients are treated or observed, with a corresponding L_{Amax} of 40 dBA [4].

We decided to assess the sound levels in the ICUs in our hospital group and adjacent hospitals to see how they compared with these standards.

Methods

This study was undertaken over two weeks in June 2012. Daytime and night-time sound levels were monitored

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during the week and at the weekend in five ICUs in the Thames Valley region of England (John Radcliffe Hospital, Oxford, Adult ICU and Neurosciences ICU; Churchill Hospital, Oxford, Adult ICU; Royal Berkshire Hospital, Reading, Adult ICU; and Wycombe General Hospital, High Wycombe, Adult ICU). These units were chosen for both their proximity and their heterogeneity because they are examples of different physical ward layouts, patient populations and building designs. This exercise did not involve patient recruitment or the use of any identifiable information. Our local ethics policy states that studies based on fully anonymised data which the study team cannot trace back to individuals does not constitute 'research involving human participants', and therefore this study was not subject to ethical review. The lead physician at each unit gave written permission for the sound levels to be measured, and staff members working on the units were aware of the monitoring.

Sound levels were collected using a pair of CEL-630 portable sound level monitors with integral recording fitted with a CEL-495 preamplifier and a CEL-251 microphone (Casella Measurement, Kempston, UK). In each ICU, the two monitors ran concurrently for 24 hours for each period of recording, one placed centrally in the unit on or adjacent to the central station and one placed adjacent to a patient's head. Where possible, patients centrally located within their section of the unit were chosen. The devices were calibrated using an acoustic calibrator (CEL-120/1; Casella Measurement) and set to record continuously for 24 hours. Every minute, the devices recorded peak noise levels (L_{Apeak}) and an averaged sound level (L_{Aeq}) from the preceding 60 seconds. The reference level (0 dB) was the limit of human hearing at a frequency of 1 kHz.

Short-duration sample recordings were also taken in an unoccupied ICU side room in the John Radcliffe Hospital Adult Intensive Care Unit with the monitors and other device alarms sequentially activated. These included examples of the most common alarm signals (Philips IntelliVue MP70 patient monitor, Philips Healthcare, Best, The Netherlands; Puritan Bennett 840 ventilator, Covidien, Dublin, Ireland; and Alaris Asena infusion pump, CareFusion UK 306 Ltd, Basingstoke, UK) as well as ambient noise only with all equipment in the room powered down.

The monitor data were downloaded to custom software (Casella Insight version 005-5 data management software; Casella Measurement) and exported to Microsoft Excel (2010 version; Microsoft Corp, Redmond, WA, USA) for analysis. The final graphs were drawn using SigmaPlot version 11 software (Systat Software, Chicago, IL, USA) and Microsoft Excel. Because of their similarity, time and $L_{Aeq,}$ data from all units were combined and are presented as averaged L_{Aeq} values with confidence limits expressed as ±1.96 SEM.

Results

Table 1 gives details of the results from the ICUs in the study. The John Radcliffe Hospital Adult ICU is a general adult ICU admitting secondary and tertiary referrals, and the Neurosciences ICU admits patients with neurological or neurosurgical problems and patients after head and neck surgery. The Churchill Hospital Adult ICU is in a hospital without an Emergency Department and admits patients after elective surgery as well as patients from specialist medical and surgical wards. The Royal Berkshire and Wycombe General Hospital ICUs are large-district general hospital ICUs.

Table 2 gives the sound levels averaged for each site over the whole 24-hour period recorded both at the central station and adjacent to the patient. The averaged time × sound-level plots for all ICUs for both recording positions are shown in Figures 1 and 2. All ICUs recorded L_{Aeq} levels above 45 dBA at all times and between 52 and 59 dBA for more than 50% of the time.

Figure 3 gives the cumulative frequency plot of the L_{Apeak} recorded minute-by-minute in each ICU adjacent

Table 1 ICU details

Details	John Radcliffe Hospital Adult ICU	Churchill Hospital Adult ICU	John Radcliffe Hospital Neurosciences ICU	Royal Berkshire Hospital ICU	Wycombe General Hospital ICU
Number of beds	12 in 3 bays plus 4 side rooms	6 plus 2 side rooms	12	9 plus 2 side rooms	7 plus 2 side rooms
Nursing handovers	7:30 AM and 7:30 PM	7:30 AM and 7:30 PM	7:30 AM and 7:30 PM	7:30 AM and 7:30 PM	7:30 AM, 1:00 PM and 8:00 PM
Medical handovers	8:30 AM and 8:30 PM	8:30 AM and 8:30 PM	8:30 AM and 8:30 PM	8:00 AM and 8:00 PM	8:00 AM and 8:00 PM
Visiting times	No restrictions	No restrictions	No restrictions	No restrictions (with a quiet period from 3:00 PM to 4:30 PM)	Open visiting except from 1:00 PM to 3:00 PM

Table 2 Sound levels averaged over 24 hours[a]

Location and day	Central station	Adjacent to patient
John Radcliffe Hospital Adult ICU weekday	58.4 dB	59.7 dB
John Radcliffe Hospital Adult ICU weekend	59.1 dB	59.5 dB
Royal Berkshire Hospital ICU weekday	58.7 dB	59.9 dB
Royal Berkshire Hospital ICU weekend	57.7 dB	58.5 dB
Wycombe General Hospital ICU weekday	52.4 dB	55.4 dB
Wycombe General Hospital ICU weekend	51.3 dB	54.1 dB
John Radcliffe Neurosciences ICU weekday	58.0 dB	58.8 dB
Churchill Hospital Adult ICU weekend	55.7 dB	55.4 dB

[a]dB, decibel. Sound levels averaged over 24 hours for each site. At the John Radcliffe Hospital, the Royal Berkshire Hospital and Wycombe General Hospital, two recordings were measured: on a weekday day and night and on a weekend day and night. Only one recording was taken at the Neurosciences ICU and the Churchill Hospital ICU in Oxford.

to the patient. In more than 50% of the minutes sampled, L_{Apeak} occurred between 79.0 dBA and 84.6 dBA. During every minute sampled, there was a L_{Apeak} in excess of 60 dBA. The highest L_{Apeak} recorded was 127.9 dBA.

Figure 4 shows the average number of minutes per hour across all sites when L_{Apeak} above both 85 dBA and 100 dBA were recorded next to the patient. There is a clear diurnal variation that correlates with the L_{Aeq} plots of Figures 1 and 2.

Figure 5 shows the frequency components of the noise recorded adjacent to a patient in the adult ICU at the John Radcliffe Hospital averaged for an hour at the quietest time (4:00 AM to 5:00 AM) and during working hours (4:00 PM to 5:00 PM). The frequency scale is logarithmic in third-octave frequency bands.

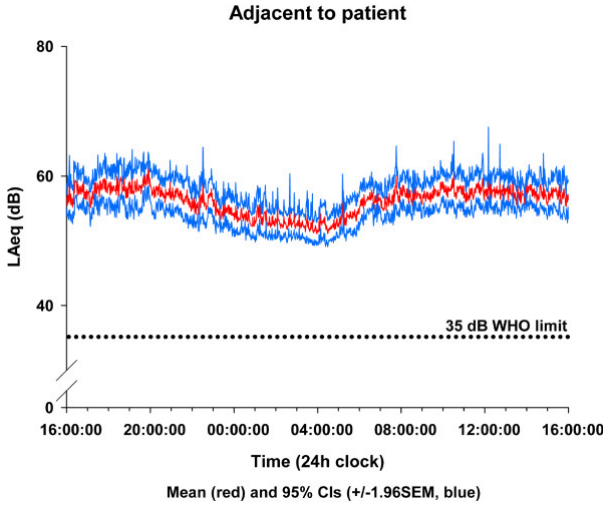


Figure 1 Average sound levels for patient sited recording device. Average sound levels at one-minute intervals (L_{Aeq}) throughout the day with recording device positioned adjacent to the patient. dB, decibel; WHO, World Health Organisation.

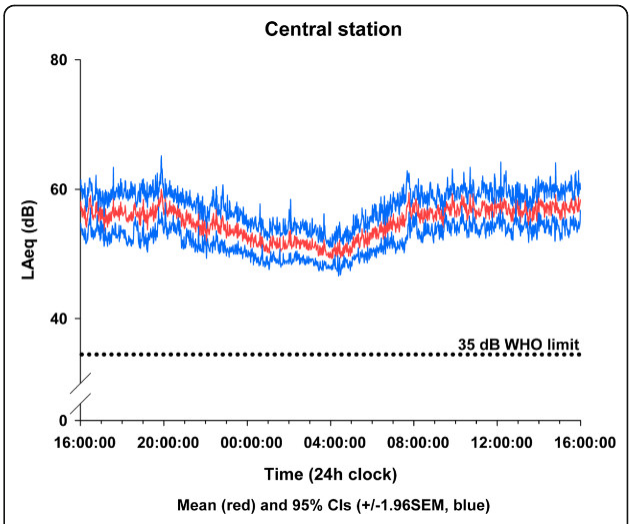


Figure 2 Average sound levels for centrally sited recording device. Average sound levels at one-minute intervals (L_{Aeq}) throughout the day measured by a recording device on a central station in the ICU. dB, decibel; WHO, World Health Organisation.

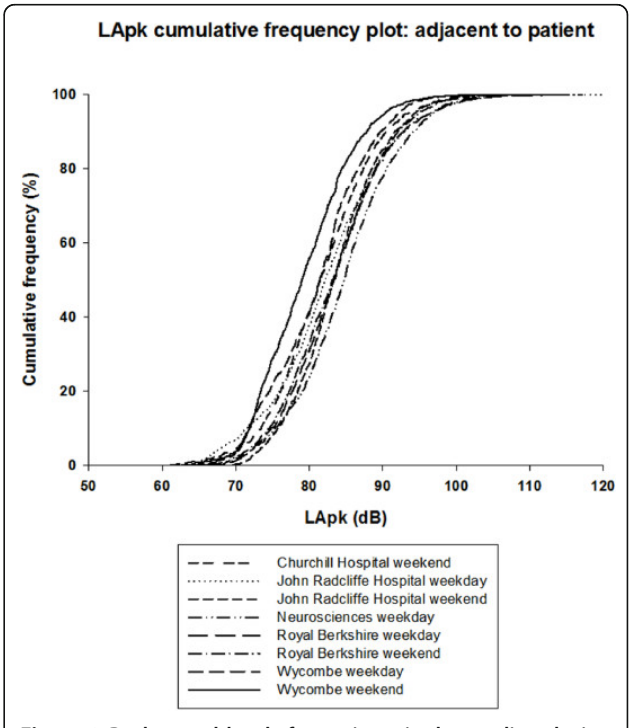


Figure 3 Peak sound levels for patient-sited recording device. Peak sound levels (LApk) measured at one-minute intervals throughout the day by a recording device positioned adjacent to the patient. dB, decibel.

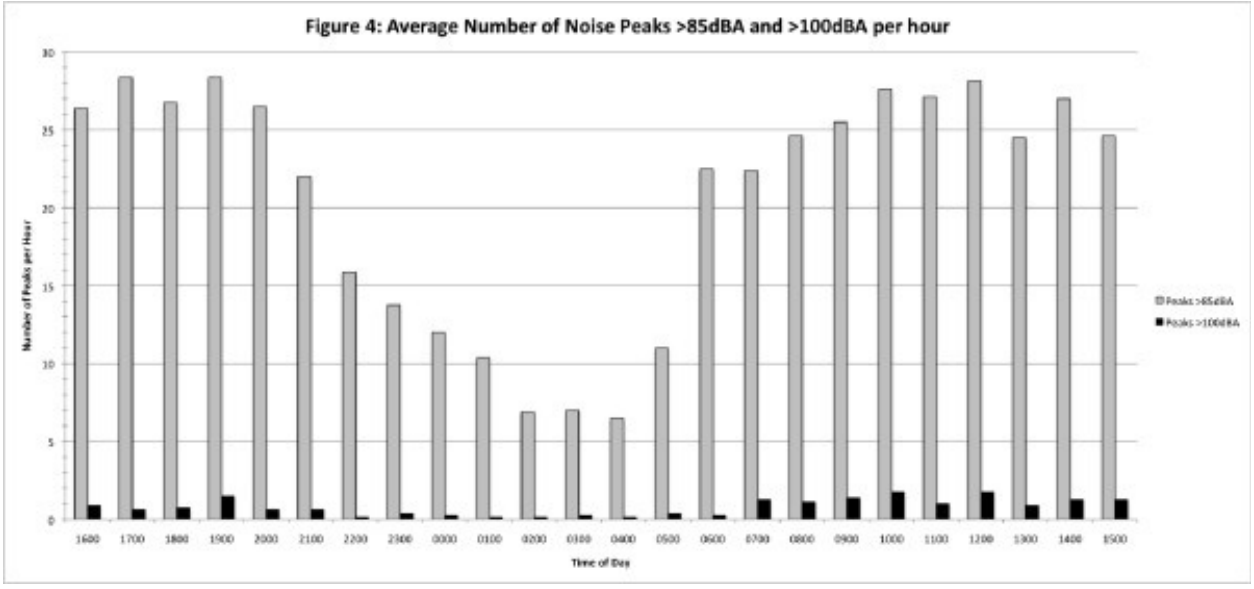


Figure 4 Average number of peak values per hour for patient-sited recording device. Average number of minutes per hour when peak values above 85 A-weighted decibels (dBA) and above 100 dBA were recorded with the recording device positioned adjacent to the patient.

Recordings were also taken at midmorning in an empty side room at the John Radcliffe Hospital Adult ICU with the door closed and the recording equipment placed where the patient's head would normally be situated. With all equipment in the room switched off, the L_{Aeq} was 34.1 dBA, with increases (1) to 43.5 dBA when the ventilator was running with a test lung; (2) to 47.2 or 51.2 dBA when the ventilator sounded a low- or high-level alert, respectively; (3) to 53.0 dBA with the suction unit turned on; (4) to 59.2 dBA when the monitor sounded a high-level alert; and (5) to 63.3 dBA when the syringe pumps were alerted.

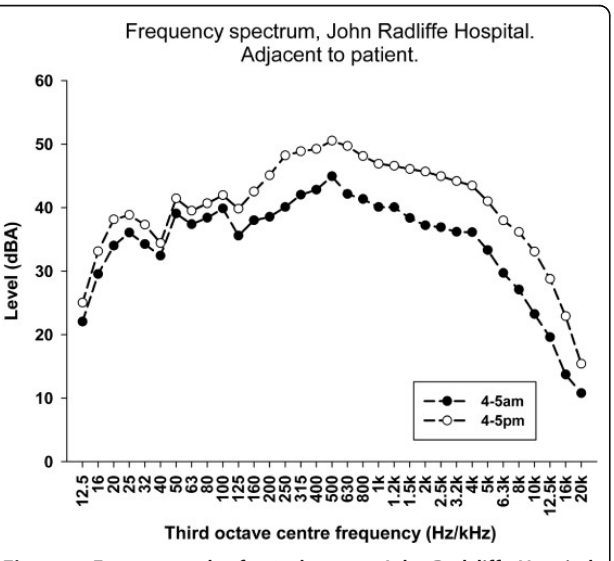


Figure 5 Frequency plot for 24 hours at John Radcliffe Hospital ICU. Frequency components of the noise adjacent to a patient at the John Radcliffe Hospital Adult ICU on a weekday at the quietest period (4:00 AM to 5:00 AM) and during working hours (4:00 PM to 5:00 PM).

Some frequency components of the alarm noise were identified using one-third octave frequency plots. The physiological monitors showed frequency peaks in the 1.6- to 3.15-kHz bands for the first-level alarm and 2.5- to 3.15-kHz peaks for the second-level (more urgent) alarm. The infusion pump alarms registered frequency peaks in the 800-Hz to 1-kHz range. The ventilator alarms contained a broad spread of frequencies and could not easily be distinguished from other sounds.

Discussion

Noise is measured using a logarithmic scale of dB. The threshold for normal human hearing is 0 dBA, a quiet room or a whisper is about 30 dBA, normal conversation is about 55 dBA, a television generates about 60 dBA, heavy traffic at 10-m distance is about 80 dBA and a pneumatic drill is about 100 dBA. A 3-dB change in noise level is considered just discernible; a 5-dB change is clearly discernible; and a 10-dB change louder or softer is perceived as a doubling or halving of volume, respectively. For speech to be easily intelligible, it needs to be 15 dB above background noise levels. Thus the recommended WHO average levels for hospital wards are the equivalent of a very quiet room with transient peaks at night well below conversation level.

Although it has been reported that there is no significant reduction in overnight activity in the ICU [5], the

link between sleep deprivation and poor outcome has been well-reported in recent years [6-8], and all five units in our present study routinely decrease overnight activity and lower the unit lighting to encourage natural sleeping patterns. The noise levels certainly drop by about 5 dB in the early hours of the morning, but only to the level of continuous conversation. The beginning and end of the night are characterised by obvious increases in noise levels at handover time (see Figures 1 and 2). On average, there were approximately 25 minutes of every hour during the day when peak levels above 85 dBA occurred. Peak levels above 85 dBA occurred less frequently overnight, but a patient can still expect to be disturbed at least once every 7 to 16 minutes of every hour between 10:00 PM and 7:00 AM (Figure 4). At these dB levels, it is highly likely that this is alarm activity, and, as has been reported elsewhere [9], electronic sounds are more arousing than human voices, so they are very likely to continually disturb patients' sleep. Frequent and persistent arousal has been shown to have negative effects for both healthy volunteers and patients [10,11].

Hospitals generally appear to be getting noisier over time. A review of published data over the past 50 years [12] suggests an average increase of 15 dB since the 1960s, more than a doubling of the perceived noise. The same study looked at noise in multiple hospital locations in an American teaching hospital and demonstrated the highest levels in the paediatric ICU, although there were no recordings from the adult ICUs.

It is immediately obvious that sound levels in the Thames Valley Intensive Care Units are considerably higher than the WHO guidelines recommend. The patients are subjected to a continuous level of sound which, at best, is only a little below conversation level and during the day equates to a nearby television or dishwasher. At no point during any of the measurement sessions did the L_{Aeq} near the patient fall below 50 dBA. Peak levels (measured as L_{Apeak}) were always above 60 dBA and at worst were almost 128 dBA. In previous studies conducted in specialist ICUs, average levels were about 10 dB higher in a Turkish cardiac surgical ICU with a similar time profile [13], similar to our results in a two-bed Swedish neurosurgical ICU with a comparable frequency distribution of peaks [14], and 5 to 10 dB higher in an American paediatric ICU with no diurnal variation [12].

Given the physical and environmental differences in the selected units, it was perhaps surprising that the data generated were so alike. It might be expected that the single-room ICUs would be louder than the three-room John Radcliffe Hospital Adult ICU, but this proved not to be the case. The quietest unit was also not the unit with the lowest number of patients during the recording period. This suggests that noise level is associated with more than simple acoustics and occupancy.

L_{Aeq} values were between 51.3 and 59.1 dBA at the central station and 54.1 to 59.9dBA at the patient location. The sound level adjacent to the patient's head was almost always greater than that at the central station. This is probably due to the way equipment is positioned. All the units use pendant or rail systems to suspend the equipment adjacent to the patient's head on each side of the bed, allowing unhindered access to the back of the patient's bed. Whilst this is both convenient and conventional, it does put noise sources close to patients' ears. In all the units studied, the ventilator was positioned at one side of the head of the bed and the monitor was placed on the other side, so these two sources of noise often were 50 cm or less from patients' ears and a similar distance from the recording devices. The noise generated by functioning equipment and alarms seems to be considerable, as evidenced by the levels recorded when the equipment or alarms were recorded in isolation. All units provide patient entertainment (television and/or radio), and it is possible that their use contributed to the slightly higher values recorded at the patient location; however, we did not record television and radio use during the assessment period. We also did not record patient intervention activity, which may have increased noise levels in the bed space.

The frequency components recorded during the day and at the quietest period show a different pattern from that reported in an adult ICU [14] and a paediatric ICU [12] in that there was much less noise below 400 Hz. This is probably simply an effect of the weighting used. We used A-weighting, which is less sensitive to lower frequencies to approximate human perception, which reduces the level at both ends of the frequency spectrum, whereas previously reported results were based on unweighted (absolute sound level) measurements. If the A-weighting is removed, the results more closely resemble the earlier adult ICU results [14]. The change previously noted during the quietest part of the day, with a reduction in sound levels predominantly above 400 Hz [14], was also seen in this study. This may be because much of the lower-frequency sound may be caused by hospital plant and other factors that do not show diurnal variation. By contrast, the higher frequencies, where conversation, alarm sounds and the like are found, do decrease at night. It would be interesting to repeat this exercise at a time of year when the day-night light durations are different to compare seasonal diurnal effects.

A comparable study recorded sound levels in an outpatient chemotherapy clinic [15] and found similar, constant, average (55 to 60 dB) and peak (>90 dB every minute) sound pressure levels during the day.

Concurrent questionnaires completed by patients, visitors and staff revealed that, whilst staff felt that the noise was disruptive, in particular causing difficulties with communication, neither patients nor visitors were concerned. Although this suggests that levels seen in the ICU may be acceptable, the authors of that study found a correlation between the time an individual spent at the clinic and the level of irritation expressed. Thus the levels measured in our investigation are likely to affect both staff and patients in the ICU, and attempts should be made to lower noise levels.

The frequency spectra of the alarm sounds were recorded in an attempt to distinguish alarm sounds from background noise, but the acoustic 'signature' of the alarms was difficult to distinguish from the broadband background noise. As a result, we could not consistently measure alarm and non-alarm sounds separately. However, these sounds have been reported elsewhere [5], and it is clear that a significant proportion of the background noise is probably generated from modifiable behaviour such as conversation, operating and moving equipment, telephone use and allowing doors and container lids to close freely. A number of studies have reduced L_{Aeq} levels in the adult ICU, at least for a limited period of time, by introducing noise awareness initiatives and unit-level behavioural changes [16-18]. Introducing 'quiet times' has also been shown to improve general well-being [19] and sleep patterns when synchronised with natural circadian rhythms [18].

Three previously reported studies [20-22] used continuous polysomnography alongside environmental noise measurements to determine whether noise could be the reason for irregular sleep patterns in ICU patients and reported that environmental noise caused between 11% and 17% of arousals and awakenings. In interviews after ICU discharge, patients regularly reported disturbed sleep, attributing this to noise, light and frequent nursing interventions [23-28]. Sleep disruption in the ICU is also associated with increased requirements for anxiety and depression treatments [28]. Volunteers exposed to a simulated ICU environment show disturbed sleep and biochemical markers of stress [29], and two studies [25,30] used the ICU Environmental Stressor Scale to assess patient experiences in the ICU. Both studies reported that patients identified alarms as a source of stress. The problem of environmental noise is not limited just to patients; high levels of noise on an ICU have been associated with increased levels of stress for staff [14,31,32]. Studies outside the hospital environment have demonstrated that noise has a negative impact on physiology [33,34], motivation and general health [35].

Mechanical measures to reduce perceived sound levels, such as earplugs or ear defenders, which each reduce perceived noise by 15 to 30 dB, have also been shown to be effective. A recent 136 patient, randomised controlled study in a large Dutch mixed-use ICU showed a dramatic reduction in delirium and an improvement in sleep with this simple intervention [36]. An earlier, smaller US study in a general ICU and a cardiac ICU showed subjectively reported sleep quality was improved with the use of earplugs [37].

Discussions with ICU staff during our data collection period revealed that many we spoke to considered some patient monitor alerts to be disproportionate to their urgency, which led to louder sounds being prolonged while more immediate needs were treated. This inappropriateness in the alarm 'urgency mapping' [38] may quickly lead to desensitisation [39] and a corresponding reduction in alarm response. Alarm fatigue has been cited in a recent report as the leading hazard faced by hospitals in the United States [40]. Visual correlation of the data recorder real-time screens with alarm sounds confirmed that equipment alarms were the likely source of at least some of the peak values. It has been shown that active alarm management can reduce the total number of alarms. A study in the United States [41] introduced a programme by which staff were encouraged to modify machine default limits in line with their patients' individual physiology, thus reducing the opportunity for alarm fatigue to become established. Additionally, the development of smart alarms has been advocated [42-44]. In 2009, Gorges *et al.* [45] reported that only 23% of the alarms in the ICU were 'effective', specifically suggesting that introducing a 19-second delay would eliminate 67% of the ignored and ineffective alarms.

Research is ongoing to improve the system by which patients whose condition is deteriorating are identified [44,46-48], and, although not in widespread use in the United Kingdom, there are alarm management systems which can transfer the audible alert from the patient bedside to a centralised control room or to the care provider. There may therefore be technological solutions that could be used alongside awareness programmes to lower sound levels by more than that which can be achieved by behavioural interventions alone.

We could achieve sound levels within the WHO guidelines only in a closed side room with all patient monitoring equipment switched off. Although some studies have found that it is possible to lower noise levels, at least temporarily, none achieved levels below the WHO guideline limit. Our findings suggest that, with the current equipment required for patient care, the WHO guidelines are not achievable in ICUs in the United Kingdom.

Limitations

Our study was limited to one day of recording at each site. One full week at each site would have provided more robust data less susceptible to short-term events, which

might have affected the sound levels recorded on any given day. We did not collect information on patient sleep assessment or document activity around the patient bed space (for example, treatment and interventions or visitor and/or patient use of television and/or radio), which may have contributed to the noise levels in the patient's vicinity. A more accurate description of the sources of the noise may have been possible with more frequently sampled data, combined with greater frequency discrimination. This would have enabled us to run more detailed analysis of noise levels, particularly with regard to the number of peak levels and their duration.

Conclusion

The ICUs studied were very noisy places, with a constant level of noise equivalent to that of a lively restaurant. One noise source is obviously staff activity, but ambient noise levels adjacent to the patients are still high, even when this is at a nadir in the early morning, probably due to hospital plant, equipment noise and alarms. Various programmes of staff education, task scheduling, equipment repositioning and alarm threshold review have not lowered sound levels to within WHO-recommended levels. The practical solution within the National Health Service at present seems to be earplugs or other ear defender devices for patients, although there may be opportunities in the future to modulate alerts through the use of smart alarm systems.

Key messages

- Sound levels in ICUs in the United Kingdom are consistently above WHO-recommended limits.
- L_{Apeak} above 60 dBA occurred every minute.
- Earplugs or other ear defender devices can reduce the impact of noise on the patient.
- Environmental changes and/or technological solutions should be investigated as alternatives to noise awareness interventions.

Abbreviations

dB: decibel; dBA: A-weighted sound level in decibels; L_{Aeq}: A-weighted steady noise level containing the same amount of noise energy as in the actual noise, effectively giving an average level over the measurement period (for example, $L_{Aeq(24\ hours)}$, $L_{Aeq(8\ hours)}$ or $L_{Aeq(day)}$ and $L_{Aeq(night)}$, where (*n*) refers to the number of hours in the measurement period and (day) and (night) are traditionally understood to be 8:00 AM to 4:00 PM and 4:01 PM to 7:59 PM, respectively); L_{Apeak}: maximum level in A-weighted decibels reached by sound pressure at any instant during measurement period (peak is the true peak of the pressure wave, which should not be confused with the highest sound pressure level (L_{Amax}); WHO: World Health Organisation.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Both authors devised the study and collected the data, which were analysed by JDY. JLD wrote the first draft of the manuscript, and JDY made revisions. Both authors read and approved the final version of the manuscript and take equal responsibility for its accuracy.

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Both authors are senior researchers at the Kadoorie Centre Research Group, which is based at the John Radcliffe Hospital in Oxford, UK. JDY is an anaesthetics/intensive care consultant for the Oxford University Hospitals NHS Trust and a Senior Clinical Lecturer at the University of Oxford. JLD is the Critical Care Research Programme Manager for the University of Oxford and has a background in public understanding of science, with a particular interest in the dissemination of research results and the impact research projects have on the patient experience.

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EDITORIALS

Excessive noise in intensive care units

Bad for staff and very bad for patients

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Noise levels in the intensive care unit are known to be high. World Health Organization (WHO) guidelines suggest hospital noise levels should average 35 dBA during the day and 30 dBA at night.[1] Research conducted by our group in five local units recorded levels just under 60 dBA during the day (equivalent to a busy restaurant) with peaks above 100 dBA 22-28 times every hour. Although it was quieter at night, we still identified peak sounds above 85 dBA up to 16 times an hour.[2] These data are consistent with those of other studies. No study in a 2012 review recorded sound levels within WHO recommendations, although some interventions achieved significant reductions in sound levels.[3] Staff activities and alarms are primary sources of disturbance in intensive care units,[4] but noises from other patients and infrastructure also contribute.

Staff and patients may be in a chronic state of alertness when alarms are constantly sounding. Alarms share characteristics with the human scream and tend to activate areas of the brain that recognise danger. Raised sound levels have been associated with increased stress for staff,[5-7] and non-clinical studies show that noise adversely affects physiology, motivation,[8 9] and general health.[10]

The brain has a limited resource for processing information, and sensory overload caused by high noise levels and complex patient needs can lead to fixation bias and loss of situational awareness among staff.[4 11] The cognitive cost associated with the subconscious processing of distractor noises limits the brain's ability to process auditory and visual information.[12] Desensitisation to background noise may reduce staff alertness. Up to 75% of alarms are false alerts, require no immediate action, or are simply ignored.[13] It is also difficult to distinguish serious problems from minor ones as all machine alerts sound urgent to the untrained ear. Alarm fatigue has been cited as a leading hazard faced by hospitals in the United States,[14] and the Royal College of Anaesthetists' safe anaesthesia liaison group has prioritised this as an area for improvement in the United Kingdom.

Volunteers exposed to a simulated intensive care environment show disturbed sleep and biochemical markers of stress,[15] and patients attribute difficulties with sleep to disturbances around them.

Typical sleep in intensive care units has been reasonably well characterised even though it is difficult to measure accurately. Patient sleep is fragmented and brief. A review of intensive care and postoperative sleep studies found that patient sleep in intensive care is highly variable,[16] and in two observational studies in Australia and the UK patients had three to five hours sleep in any 24 hours, with a median duration of unbroken sleep of just three minutes or less.[17 18] Most patients in general intensive care units are not heavily sedated for long periods and would be expected to have near normal sleep patterns if they were not in hospital.

Disrupted sleep could be a trigger for intensive care unit delirium. Links between psychological disturbances and poor sleep are recognised, and paranoia symptoms can be reduced in psychiatric patients simply by improving sleep.[19] Descriptions of patient experiences in intensive care make harrowing reading.[20 21] Between 30% and 75% of patients experience at least one delirious episode while in intensive care. These patients tend to have longer hospital stays and long term health problems after they have been discharged home.[22] There are clear benefits to preventing delirium when possible and to minimising the duration and adverse effects when it occurs.

A recent meta-analysis confirms the link between patient exposure to high noise levels and delirium.[23] Ear plugs may be a simple solution. However, ear protection is not suitable for all patients and does not tackle problems of staff communication, staff wellbeing, or potential for clinical error. Side rooms offer some protection from disturbances caused by other patients, but patients remain at risk of noise from their own physiological monitoring.

Lowering environmental noise levels, even modestly, may help patients sleep, improve staff concentration, and result in fewer episodes of delirium. Building design and materials can reduce noise, and various quiet periods have been trialled with mixed results.[24 25] Staff education can be effective, as can individualising alarm thresholds and volumes, and use of visual alerting. Anecdotally, changing culture has been one of the hardest barriers to overcome. More and better trials of interventions designed in partnership with patients and families are urgently required, along with newer approaches such as

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"experience based codesign" (www.kingsfund.org.uk/projects/ebcd).

Smarter alarm algorithms are also promising, offering opportunities to deliver intuitive alerting without increasing overall noise levels. Frequency and tone affect the visceral response to noise perhaps more than overall decibel levels.

It seems unlikely that WHO limits can ever be achieved in full, and they should perhaps be revised. Changing monitoring standards to take account of psychological effects of noise would be a welcome shift in attitudes to the problem. But moving away from a single 24 hour average sound target to include measures of frequency may be a better way of describing acceptable sound levels for hospital environments. Defining an achievable and evidence based target specific to intensive care units would also be helpful. Technological advances should also help us design environments that are more conducive to patient recovery and efficient working practices.

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PLOS ONE

RESEARCH ARTICLE

"I Can Remember Sort of Vivid People. . .but to Me They Were Plasticine." Delusions on the Intensive Care Unit: What Do Patients Think Is Going On?

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Data Availability Statement: The original dataset of interview transcripts is held by the Health Experiences Research Group (HERG), University of Oxford. There are legal and ethical restrictions on how the data may be shared, in order to protect interview participants and ensure their interviews are used only in accordance with the conditions set out in the attached copyright agreement between the University of Oxford and participants. Transcripts and supporting documents are therefore retained in the HERG archive; they are available under licence to other researchers for secondary analysis, subject to

Abstract

Introduction

Patients who develop intensive care unit (ICU) acquired delirium stay longer in the ICU, and hospital, and are at risk of long-term mental and physical health problems. Despite guidelines for patient assessment, risk limitation, and treatment in the ICU population, delirium and associated delusions remain a relatively common occurrence on the ICU. There is considerable information in the literature describing the incidence, suspected causes of, and discussion of the benefits and side-effects of the various treatments for delirium in the ICU. But peer-reviewed patient-focused research is almost non-existent. There is therefore a very limited understanding of the reality of delusions in the intensive care unit from the patient's point of view.

Method

A secondary analysis of the original interviews conducted by the University of Oxford Health Experiences Research Group was undertaken to explore themes relating specifically to sleep and delirium.

Results

Patients describe a liminal existence on the ICU. On the threshold of consciousness their reality is uncertain and their sense of self is exposed. Lack of autonomy in an unfamiliar environment prompts patients to develop explanations and understandings for themselves with no foothold in fact.

approval and administrative costs. Many extracts from the interviews are publicly available, with summarised findings, on the DIPEx Charity website (www.healthtalk.org).

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Conclusion

Patients on the ICU are perhaps more disoriented than they appear and early psychological intervention in the form of repeated orientation whilst in the ICU might improve the patient experience and defend against development of side-effects.

Introduction

Delirium in patients on the intensive care unit is recognised as an unwelcome consequence of the experience and environment. Patients who become delirious stay longer in the intensive care unit (ICU) and hospital [1], and are at risk of long-term mental and physical health problems including debilitative cognitive degradation [2–4]. In addition to being an independent risk factor for more serious physical morbidities and mortality [5–7], this represents an ongoing burden to the patients, their carers, and to the National Health Service [8, 9].

Although the pathophysiology of ICU-acquired delirium is poorly understood, it is commonly considered to be related to disturbances in neurotransmission, either due to a natural response to severe illness, or as a result of drug induced changes [10–17]. Delirium may manifest in increased agitation or activity, paranoid thoughts, hallucinations, or the patient may become withdrawn and disinterested in communication. It can be hard to identify these hypodelirious individuals in the ICU because many patients are partially sedated and/or can find it difficult or impossible to speak. In all cases patients are at risk of self-injury as a result of dislodging equipment or falling out of bed in an attempt to escape. There are clear benefits to recognising delirium early, reducing its duration, and limiting its enduring effects [18].

Delirium is characterised by a rapid change in mental state, detectable through validated screening tools such as the Confusion Assessment Method for the ICU (CAM-ICU). Current guidelines recommend screening all patients at least daily [19] but there are obvious limitations for sedated/ventilated patients and the tool may be less sensitive for those patients with hypoactive delirium [20–22].

Estimates suggest between 30–75% of all patients experience at least one delirious episode whilst they are in the ICU [1, 23–25] and there is evidence that it is often not recognised [2]. In the UK, the first line of treatment for hyperactive delirium is haloperidol [26]. Other pharmacological treatments include benzodiazepines, propofol and atypical antipsychotics. Some of these agents are themselves potentially deliriogenic [27–30].

There is a large body of medical literature that describes the incidence [1, 23–25] and suspected causes of delirium in the ICU [10–17, 31, 32], along with discussion of the benefits and side-effects of treatment. There is however limited understanding of the reality of the delusions that can occur in the context of delirium as experienced by the patient in the ICU. Descriptors of psychosis are largely limited to the psychiatric patient population [33, 34], and drug induced symptoms for agents including ketamine [35], cannabis [36], cocaine [37–41], and LSD [42, 43]. Psychotic features of Parkinson's disease have also been described [44]. There are detailed descriptions of the nature of ICU-delirium and associated delusionary thoughts and hallucinations within the realms of public and social media [45–49], but published, peer-reviewed research is rare.

This paper sets out to describe the patients' experiences in their own words, based on a qualitative secondary analysis of narrative interviews with patients treated on UK ICUs in 2005–6. The interview data presented here are patients' own reflections and recollections of their experiences and there is no clinical link made to their intensive care diagnoses or treatments. While there are obvious limitations to this, the patients' descriptions of their intensive care

experiences are rarely reported and remain a valid and useful insight into their understanding of the intensive care environment.

Methods

Setting

The original study collected patient and relatives' experiences of treatment on intensive care. Participants' experiences of the ICU are from between 1994 and 2005. A maximum variation sample was recruited and included both men and women who had been admitted to the ICU as emergency and elective cases, as well as those who were cared for on units for different durations. See Table 1. Participants were approached to take part through health professionals, charities, and support groups. In-depth interviews were recorded in 2005–6 around the UK, and results of the original analysis were published on the Healthtalk website in 2006 and in the scientific press [50, 51]. The original study was granted ethical approval from the Eastern MREC (ref: 03/5/016) and all patients consented to take part in the 'personal experiences of health and illness project'. Where patients consent to future use of their interviews for education and research, Healthtalk project interviews are copyrighted and archived at the University of Oxford. For this study, access to the archived interviews was granted by the Health Experiences Research Group (HERG), the custodians of the archive, to allow a secondary analysis of anonymised transcripts exploring themes relating to sleep and delirium.

Design

The purpose of the original interviews was to develop a broad overview of patients' experiences of treatment on an ICU. Secondary analysis allows exploration of a new conceptual focus using existing data [52].

The rich data source included in the database [53] enables detailed review of specific themes, and transcripts of all 77 interviews (40 patients, 37 relatives) were made available for the secondary analysis. Two researchers reviewed the text with a specific focus on sleep and delirium, and constructed a coding framework as outlined by Ziebland and McPherson [54] which was adapted as new themes emerged. We then undertook at thematic analysis of these extracts using constant comparison, seeking to define and interpret the concepts within the data [55]. During this process the richness of the data provided by patients describing their delirious experiences became apparent. In this re-contextualisation of the data [56], the core message, or the 'body' [57], in the results was discovered.

It is not the intent of qualitative research to offer statistically irrefutable results and, as such, does not attempt to define itself numerically. In keeping with the accepted reporting of qualitative studies this analysis makes no attempt to present numerical results as these are likely to mislead [58, 59]. Including numbers and proportions suggests representativeness, which is not the case for qualitative work. The strength of qualitative work is that it can offer rich sources of information and insight into the lived patient experience, in this case of being critically ill and treated in an ICU, which can offer a better understanding of a topic. We do not attempt to generalise, because we acknowledge we cannot do that. However, through this presentation of patient voices and perspectives we can raise awareness in the clinical community of some of the concepts that may underlie their patients' apparent disinterest, or overt delirious or delusional actions.

Results

We anticipated themes that would include descriptions of dreams, nightmares, and hallucinations. Themes that emerged from our secondary analysis included noise on the ICU, particularly

Table 1. Patient demographics.

Patient ID	Age at interview	Sex	Admission	Year of ICU admission	Length of ICU stay	Length of HDU stay	Length of post-ICU ward stay	ICU follow up
1	41	F	Emergency	1998	11 day	None or unknown	2 weeks	Regular appointments with clinical psychologist
2	60	M	Emergency	2004	about 1 month	None or unknown	4 days	Attended initial appointments, declined future appointments
3	66	M	Emergency	2002	5 weeks	None or unknown	5 weeks	1 appointment
4	46	F	Emergency	Not reported	about 5 weeks	1 week	Discharged after 1 week in HDU	2 appointments
5	40	F	Emergency	Not reported	22 days	10 days	Just over a week	1 appointment
6	35	F	Emergency	2003	3 weeks	36 hours	5 weeks	2 appointments and private counselling
7	60	M	Emergency	2004	7 months	None or unknown	1 month	None at time of interview
8	50	M	Emergency	2004	10 days	None or unknown	Readmitted in 2006 and died	Not reported
9	60	M	Emergency	2004	3 days	None or unknown	10 days	No ICU follow-up
10	76	F	Emergency	2004	about 1 week	None or unknown	1 week	1 appointment
11	37	F	Emergency	2002	Unknown duration	None or unknown	Not reported	Not reported
12	23	F	Emergency	2005	21 days	2 weeks	2 weeks	Had been invited to attend 1st appointment
13	42	F	Elective Surgery	1998	Not reported	None or unknown	Not reported	Not reported
14	35	F	Emergency	2005	2 days	None or unknown	2 days, discharged herself	Declined appointment
15	38	F	Emergency	2004	1 month, admitted three times in 2004	None or unknown	Several months on and off	No ICU follow-up
16	67	M	Emergency	1994	8 weeks	None or unknown	3 weeks	No ICU follow-up
17	30	M	Emergency	2004	12 days	None or unknown	2 weeks	No ICU follow-up
18	62	M	Emergency	2004	18 days	None or unknown	5 weeks	2 appointments
19	58	M	Elective Surgery	2004	Not reported	None or unknown	Not reported	Not reported
20	63	M	Elective Surgery	2004	Not reported	None or unknown	Not reported	Not reported
21	72	M	Emergency	2001	about 4 weeks	None or unknown	1 week	No ICU follow-up
22	71	M	Emergency	2004	17 days	None or unknown	A few days	At least 1 appointment
23	54	M	Emergency	2004	17 days	None or unknown	2 weeks	1 appointment
24	44	F	Emergency	2004	5 weeks	None or unknown	2 weeks	Physiotherapy referral after 1st appointment, GP referral for counselling
25	45	M	Emergency	2003	4 weeks	None or unknown	2 weeks	2/3 appointments
26	47	M	Emergency	2005	30 days	None or unknown	8 days	No ICU follow-up

(*Continued*)

Table 1. (*Continued*)

Patient ID	Age at interview	Sex	Admission	Year of ICU admission	Length of ICU stay	Length of HDU stay	Length of post-ICU ward stay	ICU follow up
27	68	M	Emergency	2005	2 weeks	2 weeks	Ward: 6 weeks; Rehab: 2 weeks	1 appointment
28	46	M	Emergency	2004	7 weeks	None or unknown	4 weeks	1 appointment
29	47	F	Emergency	2004	2 weeks	1 day	1 week	1 appointment, another expected
30	55	F	Emergency	2005	6 days	5 days	Discharged after HDU	2 appointments
31	71	M	Emergency	2003	2 weeks	None or unknown	3 weeks	At least 1 appointment
32	57	F	Emergency	Not reported	29 days	None or unknown	Ward: 6 weeks; Rehab: 6 weeks	3 appointments
33	43	M	Elective Surgery	2004	Not reported	None or unknown	Not reported	Not reported
34	37	M	Emergency	2001	30 days total, admitted twice	None or unknown	Several months	At least 1 appointment
35	33	M	Emergency	2004	17 days	None or unknown	Ward: 1 week; Rehab: 3 months	At least 1 appointment
36	67	F	Emergency	Not reported	Could not remember	None or unknown	Not reported	Awaiting 1st appointment
37	58	M	Emergency	Not reported	9 days	None or unknown	16 days	At least 1 appointment
38	55	F	Emergency	2005	1 week	None or unknown	2 weeks	1 appointment
39	56	M	Emergency	2005	4 days	None or unknown	3 days	No ICU follow-up
40	71	M	Elective Surgery	2005	Not reported	None or unknown	Not reported	Not reported

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from equipment, other patients and their visitors, personal (dis)comfort, and disturbance from treatments.

Many patients reported feelings of disorientation and separation whilst being treated on the ICU. Some patients were able to recall their dreams or hallucinations. Few truly distinguished between the two. Patients were able to give detailed descriptions of what they thought was happening to them at the time. Although it is possible to retrofit aspects of clinical care to some of the accounts, it was rare for specific details from patients' dreams or hallucinations to directly reflect what was actually taking place. Through the interviews there is an overwhelming sense of complete bewilderment and fear expressed in nightmares, altered realities, and false explanations. People often do not internalise the rational account of what they are seeing and instead create their own stories to fit their perceived situation.

The results presented here focus on patients' own descriptions of their emotional and sense-making experiences in the ICU including awareness of their surroundings, feelings of isolation, paranoia and blurred realities that can lead to delusional beliefs.

Making sense of the environment

Patients find the 24-hour activity cycle, bustle, frequent disturbances, and variable light levels challenging. This could be a trigger for confusion.

"there's so much going on around you"
[Patient 18];

"machines that have flashing lights and bells and all sorts of things like that"
[Patient 20];

"there always seemed to be parties going on in the ward. When I actually saw the ward. . .there was about six beds in there. . ..The way I saw it, it was huge with an upstairs"
[Patient 27];

"I found it very noisy, very hot, very busy."
[Patient 38]

Many patients were unable to recognise contemporaneously that they were ill, or in hospital, which is consistent with difficulties in interpreting the (often unpleasant) treatments that patients receive whilst on the ICU. Many patients describe feelings of bewilderment and abandonment. This often manifests in the meaning they attribute to their time on the ICU. Some patients describe going through a process of "*trying to piece together what was happening*" [Patient 06] by attempting to make sense of their unfamiliar surroundings. Reflecting themes of confusion and discomfort many report beliefs suggesting travel. Some made very specific references to being on a ship, boat, train, aeroplane, or in a spaceship.

"I thought I was on a hospital aeroplane and that I was being looked after by kind of air hostesses/nurses/doctors. . . it is quite hard to kind of switch off."
[Patient 06]

Some believed they had been abducted, others talked of their feelings of restraint and imprisonment.

"I couldn't move, couldn't move at all, I felt my throat, and I knew that I had a pipe into my throat, a thick pipe. I could feel the wires, I could see all the wires in my arms and my legs, I just didn't know what had happened, I was just, I just didn't know. I just didn't have a clue. And I thought, I thought aright I've been kidnapped, and I'm in a clinic, and I'm somewhere like Dubai or somewhere like that, but I know my family will be looking for me"
[Patient 05];

"I was I think in India I think, I don't really know where I was. There was, high up a mountain, there was lots of little places and there was people, oh people were looking for me, that's right yeah, people were looking for me, so she [the nurse] was hiding me as well. . .I was imprisoned and just couldn't, people were sitting on me and I just couldn't get out, because I was restricted where I was and I couldn't move."
[*Patient* 07]

Even those who understood they were in hospital experienced vivid dreams (rarely did patients differentiate between dreams and hallucinations in their accounts, it is possible these were hallucinations) in which they reported similar sensations of victimisation.

"Part of the nightmares that I'd had. . .was that I had been kidnapped by triads, don't ask me where they came from. I dreamt that they cut off my little finger, when I woke up no matter how

many times I counted them there was only four. . .so I was convinced that had truly happened"
[Patient 05];

"I'd have this nightmare about tubes and oh, God, it was crazy. And like I'd, I'd wake up thinking I was somewhere else and I don't. . .it was totally weird."
[Patient 12]

Some reported actively trying to avoid sleep to escape their dreams.

"Each time I went under, the nightmares flooded back. So when they were telling me to sleep, I couldn't sleep because a blackness just come back over me, so I stayed awake."
[Patient 07]

The origin of some patients' delusions seems consistent with plausible clinical events of their admission. This account for example could be linked to changes being made to ventilator settings.

"I felt I was something like a washing machine built into a shop or something. And I was just plugged in to the system and people every now and again came and twiddled my, made adjustments here and there."
[Patient 02]

Others were more inexplicable. Some of the descriptions offered by the patients were specific but surreal, and difficult to attribute to any particular event but continue to convey a sense of loss of autonomy.

"a person finding himself in tubes, metal tubes, ice tubes, not able to get out them, going round and round. And I know exactly where these tubes are . . . junction 22 of the M62 motorway."
[Patient 27]

Some patients feel reassured when they recognise they are in hospital. They can attribute genuine and accurate meaning to their experiences. There seems to be a release of tension as their sense of anxiety and threat is reduced.

"once I was convinced I was in hospital I did start to feel a bit more secure. But until then I didn't."
[Patient 05]

The realisation of being in ICU is not reassuring for all patients. Some explained that seeing sick patients around them forced them to reflect on their own condition. If the patients around them looked near to death then they must also be in a similar situation.

"I'm looking round and you can see all, everybody looks dying so I'm thinking I'm dying here."
[Patient 28]

Isolation

A number of them felt particularly isolated and vulnerable, mostly due to the difficulties involved in communicating their fears and discomfort to the staff caring for them.

"I couldn't make anybody understand. I couldn't make my family understand. I tried to tell them, I couldn't talk."
[Patient 29]

While patients were in the ICU they seemed unable to place events going on around them into context. Some expressed distress at not knowing whether the tasks around them were routine or more significant. Their inability to ask questions of their carers was also a source of difficulty. In retrospect patients felt excluded from their care.

"you were isolated. They would come round and fiddle with things behind you, but you couldn't see what was there and you weren't actually told what was there. And for a long time of course with the tubes in my mouth I couldn't ask"
[Patient 30];

"you can't really see all of the kind of equipment which, you know, presumably because they don't want to scare the living daylights out of you"
[Patient 06];

"you hear something bleeping and you think on what-what's happening, but you couldn't do anything about it."
[Patient 34]

Some tried to express how profoundly debilitating their ICU experience had been, stripping them of dignity and their ability to perform basic human tasks, like talking, eating, sleeping. Patients' descriptions suggested that their individuality, even their humanity, was lost to them while they were in the ICU.

"I felt like a lump of meat on a butcher's table with the real me inside but not able to get out- . . .. . .I was part of this and yet I wasn't part of it"
[Patient 27];

"I was out, as this fish, in a boat, a glass-bottomed boat. But I was in the boat and people were looking through the glass bottom at me, as opposed to the other way round."
[Patient 26]

Paranoia

Many patients expressed a sense of paranoia. They attributed conversations amongst and between staff members to them and describe what in other contexts would be described as 'persecutory delusions' and 'delusions of reference' [60].

"they were looking at something in the magazine together and they were laughing, and I thought they were laughing, that I was in the magazine and they were laughing at me. And I thought that I had a cat's nose painted on and whiskers and that I was in the magazine like that that and they were laughing at me. . .I imagined that they were talking about me all the time, saying that I was a drug addict and I shouldn't even be in there"
[Patient 05];

"I thought the nurses had this little bit at the front where they sat and wrote their reports and did whatever they had to do and I thought they had some sort of game that they were playing on the wall, making patterns. Obviously I mean that's ridiculous but, you know, it's the way you think. And I thought oh well that's something to keep them occupied while they're waiting for all these people to do what ever they're going to do."

[Patient 02]

A number of patients expressed a sense of direct threat coming from the staff.

"I remember one of the doctors that was on Intensive Care, who I really thought was trying to kill me. He was, I don't think he actually did any treatment on me, but every time I saw him I was terrified. . .if he came anywhere near me, I thought he was trying to switch the tubes off that were feeding me or helping me to breathe or whatever. . .[I] was absolutely convinced it was real and would have rather gone home and died that have him touch me"

[Patient 29];

"the nurse . . . got a gun to me head trying to kill me. . .and I'm frightened because I think people are trying to kill me."

[Patient 28]

Blurred reality

Several patients were able to explain that they knew the lines between reality and their understanding were blurred. Although these accounts are retrospective, patients describe being aware at the time that they were confusing their own realities with information they were seeing or hearing from televisions, or visitors. Despite this, they were still unable to fully understand the difference between fact and fiction.

"kind of like being in a Twilight Zone it's, "Have I dreamt that or did it happen? Or is this real? Or have I imagined it?" So you need telling not once but several times"

[Patient 01];

"I'm thinking, like we're in the jungle and then everything was on fire, and everything was getting mixed up with the dreams and I was worried that the triads were coming back and the nurses were in cahoots."

[Patient 05]

Some patients only understood afterwards that their version of events was not real.

"I thought I had a necklace on that was too tight. And it was only afterwards I realised it was because it was a tube that I was breathing through. . .and I couldn't understand why she was letting me sleep with a necklace that was so tight"

[Patient 29];

"I can remember sort of vivid people. . .but to me they were plasticine. They weren't real. But obviously they were real because they were obviously talking to me. So the words registered but the mind didn't take in that they were actually real people. They were like Wallace and Gromit type characters."

[Patient 23]

Even apparently innocuous stimuli were sufficient to provoke abnormal thoughts or distress amongst some of the patients.

"I'd wake up in the night and I'd look at things and think it was something entirely else, you know. We had a balloon, one of the balloons, Get Well balloons which we had up. I could see that and as far as I was concerned that was a Bogey Man or whatever, you know what they call that, that was floating around and that in the middle of the night, that really worried me"
[Patient 07];

"Lights play tricks on the mind, so that in the middle of the night when the lights are on in the ward, lights suddenly become faces, which are quite scary."
[Patient 27]

Many patients who were able to describe their "mad bizarre dreams" [Patient 05] were aware, with hindsight, that these were a result of either their illness, or the medications used to treat it.

"I don't know it at the time but they put that many drugs in to me that I'm tripping, like hallucinating things and I don't know what's what."
[Patient 28]

However, this realisation after the event can have no impact on the reality of very real fear at the time. In fact some patients felt that too much emphasis was placed on trying to convince them that their fears were not real.

"I felt they should have understood that from my point of view it was true, and nobody was going to convince me otherwise. And it still feels true. Although I know now with hindsight it can't have been, it still feels true to me when I think about it."
[Patient 29]

Discussion

Delirium and delusionary experiences have been recognised for thousands of years and it is more common in the contemporary ICU than many realise. Previous research has focussed on the staff experience of delirious patients, including aetiology, treatment, and diagnosis. This may be a result of an emphasis on treatment for patients with hyperactive delirious symptoms who may present an overt danger to themselves and staff. This study uses the rich data provided by the patients themselves to paint a vivid picture of what the ICU can be like from their perspective. This previously unreported patient perspective demonstrates that whilst no two patients' are identical, there are similarities in both the detail and underlying beliefs. This makes it possible to contemplate ways in which the patient experience of the ICU could be improved.

Even when patients recognised they were seriously ill, they did not necessarily associate this with being in hospital. The general public is unlikely to have a great deal of exposure to a real ICU environment. Media portrayals seldom closely depict the reality of day-to-day clinical practice. For many patients, their admission to ICU is often unexpected and far removed from even a routine hospital admission, where patients tend to be fully aware of their circumstances.

Participants therefore sought alternative explanations which, when fused with the dream-like, part-sedated state, became very powerful. One explanation for the recurring idea of being

trapped in the transport system is the constant activity in the ICU. For many people their normal interactions with non-stop activity, people, sounds and lights involve transport hubs such as airports, train stations, and ferry terminals. This may go some way to explaining why many patients, even those who recognise that they are critically unwell, do not make the association that they are being cared for in a clinical environment. As more than one patient mentioned in the interview transcripts, constant reminders of what is happening, where the patient is, and why they are there could help self-orientation and situational understanding.

The thematic analysis identified two recurring themes: dissociation and lack of control. This appears to reflect the inherent human fear of complete loss of autonomy. In their recreation of the patient experience of ICU Johansson *et. al.* describe the ICU as a "brutal and ruthless uncontrollable barrage". They summarise their patient interviews by composing a representative sample of transcripts as a single patient experience reflective of the totality of those interviewed. This composite patient experience [61] is similar to the experiences of the interviewees who also describe feeling trapped, terrified, and alone.

Many patients found their restriction of movement and inability to perform basic activities that are taken for granted as a healthy functioning adult shocking and intolerable. Unable to sit up, eat and drink unaided, or move about at will, they describe an unsettling window to the edges of life. The indignities and shock that they experience seem to trigger a sense that they are somehow no longer civilized beings [62]. Similar, although more persistent, social stigmas and lifestyle changes enforced by debilitating illness have been described in more detail elsewhere [63, 64].

Unnerving and distressing situations that patients experience could lead to a state of heightened arousal and hyper-vigilance. On-going anxiety, also described as a persistent awareness of possible future danger [65], will increase an individual's negative interpretation of events. Where individuals feel isolated the 'threat belief' is likely to flourish [66]. The narratives we analsysed confirm that many patients retain awareness whilst on the ICU.

Current guidelines indicate that lighter sedation is related to shorter durations of ventilation and intensive care, and better patient outcomes [30, 67–70]. Although research indicates that daily sedation holds do not increase the likelihood of future post-traumatic stress disorder [68, 71], in our cohort of interviewees the moments of awareness during procedures or exposure to intrusive alarms do seem to lead to patients making interpretations that can cause anxiety. Repeated reminders could help self-orientation and situational understanding.

Patients treated on ICUs have little personal control, are frequently subjected to invasive procedures, and are given a number of drugs with varying effects on consciousness and cognition. The unfamiliarity of the environment and the difficulties in communicating with staff compound their sense of disorientation and isolation. The complexity and constraints of the equipment to which the patients are attached for physiological support and monitoring, probably contribute to the feelings of persecution, kidnap, and restraint expressed by a number of patients.

Humans have been referred to as the 'story telling ape' [72], needing to find narrative explanation for situations and events. Patients are therefore making sense of their extraordinary circumstances by creating personal explanations that may seem irrational to others. If one considers that our identities are formed through narrative interpretation of our experiences [73], patients unable to match their vivid memories with any factual account of their experience are left unable to cope. Memories are malleable [74–76]. Those which are continually replayed, either in the mind or in conversation with others, are perhaps more susceptible to change as each cycle of repetition provides a new opportunity for modification [77, 78]. This hypothesis drives some post-traumatic stress disorder treatments designed to block the memory reconsolidation process and disrupt fear memory retention [79]. The unresolved tension between a

personal narrative and the factual account may be the source of some patients' ongoing psychosocial difficulties.

The very specific nature of ICU-acquired delirium and the transient but acute exposure to disrupted cognition could indicate a need for psychological support earlier than is traditionally offered. This could be as simple as working with the patient to cope with their anxieties whilst in the unit through early intervention strategies [80, 81], using patient diaries to maintain a detailed narrative of their stay [82] and offering opportunities for discussion in follow up clinics [83] although evidence for these is, at present, limited [84, 85].

The strength of this study lies in the breadth of first-hand experiences available in the archive. However, these data were not collected expressly to study delirium and sleep disturbances. Although a great number of such experiences were described, they were not necessarily prompted by questioning, and it is therefore possible that some patients did not share this aspect of their ICU experience during their interview. These are self-reported accounts and we cannot comment on the extent to which patients' experiences may or may not have been exacerbated by the medications they were taking. We also cannot confirm delirium diagnoses in this cohort as patients were not asked to disclose this information during their interviews, and their medical records were not reviewed. The strength of qualitative data is that it can offer rich sources of information and insight into the lived patient experience which can offer a better understanding of a topic, in this case being critically ill and treated in an ICU. The nature of qualitative research means participants' voices remain individual throughout the data collection, analysis, and dissemination process and offer potentially rich insights. Reporting such a study does not aim for statistical significance through a numerically representative sample. We acknowledge the limited clinical conclusions that can be drawn from these data, however the patient voice can raise awareness in the clinical community of the ideas that may lead to delirious and delusional behaviours.

Benefits of secondary analysis include a reduction in the burden of research for participants and their families, economic and resource benefits for research institutions, and long-term use of relevant data. There are some inherent limitations associated with the qualitative approach that may affect the validity of any work undertaken outside of the original study aims. In this case we were able to assess the quality of the original dataset [86] and determine that the initial data collection was rigorous and that the data could reasonably be expected to include information relevant to the new focus. Whereas original researchers have the benefit of a direct connection with the interviewees, secondary analyses are conducted solely on the interview transcripts. The researchers are at a greater distance from the data and it is likely therefore that some meta-data (for example body language, intonation, and researcher reflexivity) is lost which may affect interpretation [87]. Conversely, the distancing effect of analysis performed by a researcher outside of the original team offers validation of the initial study [86, 88, 89]. Our secondary analysis has critically assessed the evidence as presented through the verbatim transcripts and we have situated the patient experiences within a wider social context [90].

Conclusions

Through a comprehensive review of all the interview transcripts available to us we have been able to present a compelling insight into patient experiences of the ICU which could be invaluable for staff caring for them. This paper therefore offers a description of how patients can feel during their stay on the ICU, what this might mean sociologically, and how clinical teams might approach the care of patients with suspected or confirmed delirium.

Patients and their family members are often concerned about their mental state. It is clear from their interviews that patients do not want empty reassurances that their experiences are

"normal". Instead they express the need to have their interpretation of events acknowledged; for them, these thoughts are anything but "normal". Screening tools can offer reassurance that mental health is being monitored alongside physiological variables. Routine delirium testing also provides a structured opportunity to engage patients in their care, and to encourage them to share their thoughts and fears. The staff members working in ICU are therefore ideally positioned to recognise anxieties, and could be trained to work with patients to develop coping strategies whilst they are in the ICU. Early mobilisation, a clearly defined daily structure, repeated orientation and noise reduction have all been shown to reduce the incidence of delirium in, and outside of, the ICU [91, 92].

Most people who develop ICU-acquired delirium or experience delusions do not suffer persistent effects, but those who find it difficult to come to terms with their experiences are at risk of developing post-traumatic stress disorder, and other associated mental health problems [93]. Although many ICUs hold follow-up clinics which do identify those with longer term issues, these interviews, along with other accounts of ICU-psychosis [23], and the original exploration of these interviews which found that patients continue to feel isolated and frightened after discharge to a general ward [50], indicate that there are many more patients whose experience of the ICU could be improved with earlier support.

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Author Contributions

Conceived and designed the experiments: JLD. Analyzed the data: JLD LH. Wrote the paper: JLD. Reviewed, contributed to, and commented on the manuscript: PRG JDY LH SV.

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Acoustic source localization with microphone arrays for remote noise monitoring in an Intensive Care Unit

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ABSTRACT

An approach is described to apply spatial filtering with microphone arrays to localize acoustic sources in an Intensive Care Unit (ICU). This is done to obtain more detailed information about disturbing noise sources in the ICU with the ultimate goal of facilitating the reduction of the overall background noise level, which could potentially improve the patients' experience and reduce the time needed for recovery. This paper gives a practical description of the system, including the audio hardware setup as well as the design choices for the microphone arrays. Additionally, the necessary signal processing steps required to produce meaningful data are explained, focusing on a novel clustering approach that enables an automatic evaluation of the spatial filtering results. This approach allows the data to be presented to the nursing staff in a way that enables them to act on the results produced by the system.

1. Introduction

High noise levels in Intensive Care Units (ICUs) have been reported as a possible contributing factor to patients' poor physiological recovery [1]. It is thought that these high noise levels can increase the risk of disturbed sleep patterns, hallucinations and periods of delirium [2,3]. While the World Health Organization (WHO) recommends that sound levels in patient areas should remain below 40 dB(A) [4], this limit is often exceeded in ICU environments [5,6].

A number of strategies have been attempted to reduce sound levels in ICUs. Building design and materials [7,8], reducing patients' perception of noise with earplugs or headphones [9,10] and staff education [11], have all shown variable effectiveness, as has the manipulation of alarm thresholds and volumes [12]. A recent review of noise-reducing measures comes to the conclusion that when patients experience lower noise levels through the use of earplugs, the risk of delirium can be reduced [13].

To better identify the contributing noise sources and explore ways of reducing them, a more detailed understanding of the distribution of acoustic sources over time and space is necessary. Currently, studies use individual sound level meters at discrete positions in the ICU to record the level variation over time [14]. While this offers insight into the periods over which the overall noise activity is higher, it cannot provide information about the distribution of specific sources in time or space. An additional problem is that in order to obtain representative data, sound level meters have to be installed close to the patients' beds. This often leads to spurious unrealistically high peak levels when staff come into contact with the audio equipment or the supporting structure.

A solution to the problem of using local sound level meters lies in the application of spatial filtering methods such as beamforming to discriminate acoustic sources in space from a remote location [15]. The use of array signal processing methods allows the ICU environment to be scanned for sources with an (almost) arbitrary resolution in a non-intrusive way.

Microphone arrays in combination with spatial filtering methods have found widespread usage in recent years. Typical scenarios where beamforming is used include industrial and environmental noise source identification as well as automotive and aeroacoustic applications [16–20]. In most of these cases, a manual evaluation of the results in terms of source maps per third-octave band is usually necessary, hence requiring an expert to make sense of the data. Automatic source localization is a problem often encountered in speech signal processing [21,22], but the approaches are not always generally applicable because of underlying assumptions about the array geometry or the number and type of source signals.

In this paper, a microphone array system designed for the task of automatic source localization is presented and described in detail, with a specific focus on the array signal processing. A modified formulation

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of the standard Delay-and-Sum beamforming algorithm is presented to increase the computational performance. A deconvolution algorithm usually employed for aeroacoustic measurements is applied here in the context of the ICU environment, leading to increased spatial selectivity. For an automatic evaluation of the beamforming result, a novel clustering approach is described in detail, enabling a display of the results that is easy to understand for non-acousticians.

The outline of the paper is as follows: in Section 2 the setup of the audio hardware of the array system is described. The design of the microphone array is presented in Section 3. The beamforming strategies including the data clustering approach are described in detail in Section 4 together with simulated example data. In Section 5 selected results of measurements made with the system installed in the adult ICU of the John Radcliffe Hospital in Oxford are shown. The paper finishes with concluding remarks in Section 6.

The descriptions in this paper will be useful for replicating the presented array system, and the clustering approach helps to automatically evaluate the result of beamforming calculations and make it presentable to non-technical personnel. Practical considerations for the array system as well as the restrictions imposed by the environment are addressed specifically.

2. Hardware setup

To provide insight into the practical setup, a general plan of the ICU environment and the location of the hardware is shown by a schematic diagram in Fig. 1. This includes the location of the beds, microphones and cables.

As a cost-effective means to capture audio signals, electret microphones were used. To obtain the best result under the circumstances prescribed by the application, two steps had to be taken. Firstly, the microphone capsules were connected with an electric circuit, which lowers the phantom voltage of 48 V down to the supply voltage of approximately 4 V, enables longer cables between the microphones and the pre-amplifiers and provides a balanced signal for improved

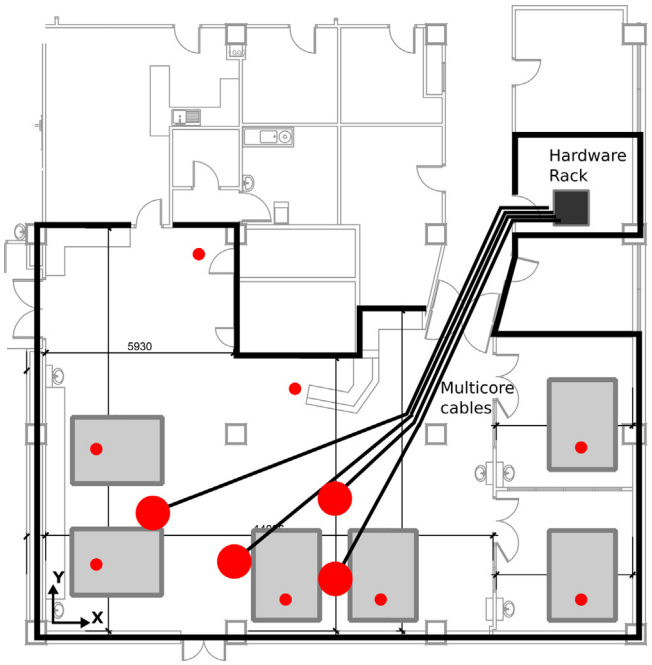


Fig. 1. Schematic of the floor plan of the ICU at John Radcliffe Hospital including the location of the beds (grey squares), the microphones (arrays: large red circles; individual: small red circles), the multi-core cables (black lines) as well as the hardware rack. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

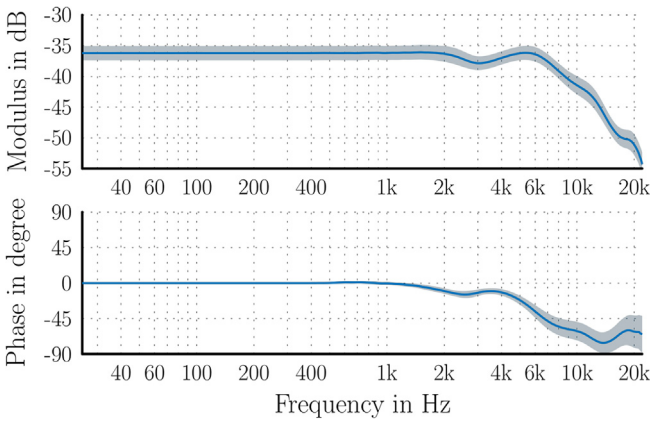


Fig. 2. Microphone sensitivity in dB re V/Pa: average result, with standard deviation across all microphones represented by shaded region.

interference rejection. Secondly, all microphones were calibrated over the entire frequency range to match the level and phase response for an optimum beamforming result. It has been shown that the phase response has to be matched for all array microphones to obtain beamforming results of high quality [23]. The broadband calibration was carried out in the small anechoic chamber at the ISVR by measuring the frequency response of a Genelec 8010A [24] with each microphone and comparing this to the response measured with a *Brüel & Kjær* $\frac{1}{2}$" free-field measurement microphone with a flat frequency response. The average sensitivity response in dB re V/Pa is plotted in terms of the modulus and phase as a function of frequency in Fig. 2. The shaded area represents the standard deviation across all microphones. The calibrated responses were combined with the measured pre-amplifier gains and inverted to obtain equalization filters that are applied to the audio input data in the frequency-domain to convert digital signal levels into sound pressure levels before any further processing takes place.

To avoid spending time developing bespoke hardware, off-the-shelf audio equipment was chosen to provide the microphone pre-amplifiers and digital conversion. To process the microphone signals and provide phantom power, a total of nine Focusrite OctoPre MKII [25] were used, each converting the input voltage of eight microphones into a digital ADAT stream. The eight ADAT streams for the 64 array microphones were then combined into one MADI stream with the RME ADI-648 [26]. For an additional eight microphones distributed in the ICU, a second MADI stream was provided by the Ferrofish A16-MKII [27]. Both MADI inputs were fed to the RME MADI FX sound card [28] to provide digital audio for further processing.

The connection between the hardware rack and the microphones was achieved with five 16-channel multi-core cables of 30 m length each. Four of these cables were used to connect to the four sub-arrays (see Section 3) and the fifth combined the signals from the eight individual microphones distributed in the ICU (see the schematic in Fig. 1).

3. Array design

As the microphone system was not supposed to interfere in any way with the daily operation of the medical personnel or the patients, the ceiling was chosen as the location of the microphones. This means that a planar array configuration had to be used. Due to the large spatial extent of the ICU (approximately 12 m× 8 m), four clusters of 16 microphones were distributed throughout the ICU to cover all of the patients' beds (see Fig. 1). For an additional, separate level monitoring, eight individual microphones were also installed in the ceiling above the beds and the nurses' station. The individual microphones were used for stationary level monitoring above the beds, including beds in two separate rooms that cannot be covered by the array system.

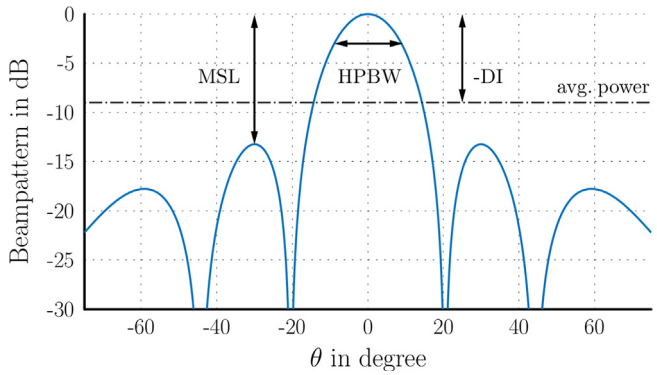


Fig. 3. Beampattern for a linear array, and array performance parameters.

For convenient installation, each of the four array clusters of 16 microphones was fitted into a single ceiling tile, with approximate dimensions of 0.6 m× 0.6 m. This – together with the number of microphones – was the restriction for the design of the array configuration. The array performance was measured with typical parameters based on the beampattern of the array [29, Section 2.4.1]: the Half-Power Beamwidth (HPBW) in degrees as a measure of spatial discrimination; the Maximum Sidelobe Level (MSL) in dB as a measure of the dynamic range of the beamforming result; and the Directivity Index (DI) in dB as a measure of the spatial focusing (see the plot in Fig. 3 explaining the parameters for the beampattern of a linear array). For the data presented here, the performance parameters were evaluated on a hemispherical grid with a radius of 1 m and 1 deg angular resolution. The results were chosen as the worst-case across all directions, to obtain a lower limit of the performance.

Of the many possible planar array geometries – such as the regular grid, cross grid, logarithmic spiral array, circular array and random array – the circular array and logarithmic spiral array were regarded as relevant in this project. These two array geometries yield a spatial selectivity that does not vary too much with the azimuthal steering angle and are relatively easy to build. Several combinations of array radii and distribution of sensors were tested for each of these two array types and rated according to the aforementioned performance parameters.

For a further analysis, three designs were selected: two versions of the logarithmic spiral array (Fig. 4 a and b) and a circular array (Fig. 4c). In the plots, the arrays are shown together with the boundary of a ceiling tile to indicate the design restrictions in terms of array size, where a safety margin of 4 cm was left on all sides to prevent problems during the installation of the tiles. The two logarithmic arrays differ by the radii of the concentric circles: the array in Fig. 4a has more microphones concentrated in the center, whereas the one in Fig. 4b has two circles with larger radii and the rest of the microphones in the center.

Among the three selected designs, the array in Fig. 4b offers the best spatial resolution, due to the higher number of sensors with a larger radius. However, at the same time this also leads to the worst Maximum Sidelobe Level (MSL) among the three tested arrays. The logarithmic spiral in Fig. 4a and the circular array in Fig. 4c perform similarly, although the logarithmic spiral has the best MSL at high frequencies, whereas the circular array has a narrower beamwidth.

For the three designs chosen according to their broadband performance, the improvement achieved by using frequency-dependent shading weights for the individual circles of microphones in each array was analyzed. The operating range of the array (400–10,000 Hz) was chosen for this analysis. By choosing cut-on and cut-off frequencies for each of the circles of microphones, the effective outer diameter and number of sensors could be controlled and hence an optimal trade-off between the beamwidth and height of the sidelobes of the beampattern could be achieved. It was found that the exponential distribution of the array radii of the first logarithmic spiral array (Fig. 4a) is beneficial for

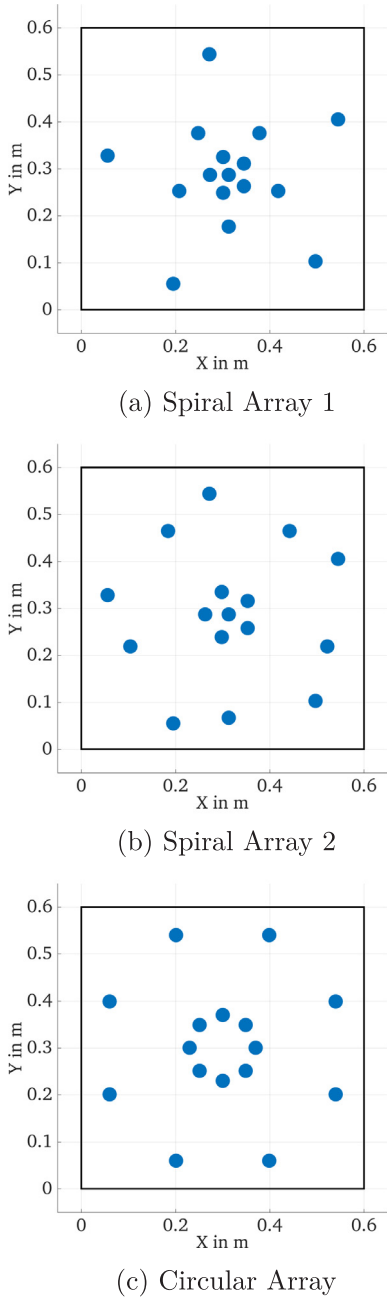


Fig. 4. Three array geometries selected for optimization of shading weights, shown together with the ceiling tile boundaries (rectangle).

frequency-dependent control of the beampattern. Also, since the logarithmic spiral array has one more circle of microphones compared to the circular array, this offers an additional degree of freedom for deriving the frequency-weights. Thus the logarithmic spiral array was chosen as the final layout. The design parameters for the ring radii as

Table 1
Microphone ring radii and corner frequencies for the shading weights.

Radius (in m)	Cut-on Frequency (in kHz)	Cut-off Frequency (in kHz)
0.0	2 kHz	–
0.04	2 kHz	–
0.11	–	–
0.26	–	4 kHz

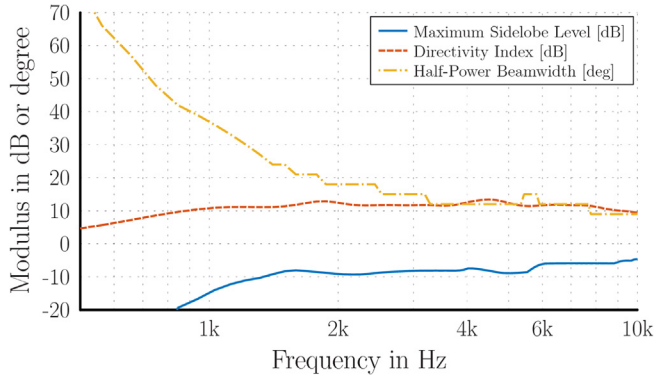


Fig. 5. Array performance parameters of the array depicted in Fig. 4a, using frequency-dependent shading weights.

well as the shading weights are listed in Table 1. The resulting performance parameters are shown as a function of frequency in Fig. 5.

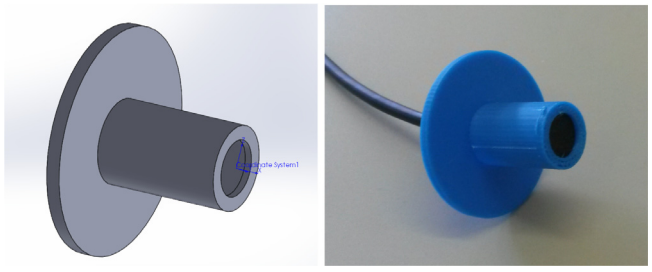
It can be seen that the shading weights provide an almost constant MSL (solid line in Fig. 5) and DI (dashed line) and a smooth increase in resolution towards higher frequencies, as can be seen from the decreasing HPBW values (dash-dotted line). This ensures an optimum performance in the operating frequency range under the given constraints.

For the construction of the array, the microphone positions were marked on the ceiling tile by a laser-cutting machine to achieve the highest precision. The holes had to be cut by hand as the tile could not actually be cut by the laser. Nevertheless, it could be ensured for each 16-channel array that the positions were accurate within a tolerance of approximately 1 mm. To mount the microphones, a 3D-printer was used to build inserts that enable a precise microphone placement and an easy exchange in case of malfunction. The CAD model and the actual print with a microphone inserted are shown in Fig. 6a and b, respectively.

4. Beamforming

With the calibrated audio data available from the array microphones, beamforming was used to determine the location of the most prominent acoustic sources. Different approaches to combining the microphone signals of the four array clusters were tested, such as independent beamforming using each cluster and the subsequent combination of the four outputs. However, the best results were achieved when all 64 microphones were used simultaneously as a single large array. For the processing steps and the results presented in the rest of this paper, this configuration was chosen.

To include early reflections in the beamforming processing, a relatively large block size of 8192 samples at a sampling rate of 48 kHz (corresponding to a block length of 171 ms) was chosen. Including early reflections could lead to improved spatial filtering results when a beamforming algorithm that takes advantage of source-coherence is used, as the sound from early reflections is coherent with the original source signal. This will be discussed further in Section 4.2.



(a) CAD model (b) 3D-printed version

Fig. 6. Microphone insert used to place microphones into the ceiling tile.

A running estimate of the cross-spectral matrix $\mathbf{C}_n(k)$ in the frequency domain is calculated based on the pressure data from all microphones $\mathbf{p}_n(k)$ at time instant n, with a half-block overlap. Here, k is the wavenumber in rad/m. Using exponential smoothing, the estimate of the cross-spectral matrix at time instant n is

$$\mathbf{C}_n(k) = (1-\alpha)\mathbf{C}_{n-1}(k) + \alpha\,\mathbf{p}_n(k)\mathbf{p}_n^H(k), \tag{1}$$

where $()^H$ is the complex conjugate transpose and α is the smoothing factor; its value was chosen here as 0.157, which corresponds to a filter decay time of 0.5 s given the previously mentioned block size.

As most scan points are in the near-field of the array microphones, the steering vector for spherical wavefronts without distance compensation is used. An initial comparison showed that this method achieved an improved spatial filtering result compared to that obtained with a plane-wave steering vector, but this could be further explored for the installed system in a future study. For all beamforming calculations, the steering vector is thus calculated as (formulation I in [30]):

$$\mathbf{w}_i(k) = \frac{1}{M}\mathrm{e}^{-\mathrm{j}k\mathbf{d}_i}, \tag{2}$$

where M is the number of microphones and $\mathbf{d}_i$ is the vector of Euclidean distances between all microphones and the scan point with index i.

For this study, a total of 375 scan points on a rectangular grid at a height of 1.2 m above the ground were chosen to cover the main area of the ICU with a 0.5 m spacing. With a ceiling height of 2.6 m, the distance between the plane of the array microphones and the scanning grid was 1.4 m. The grid spacing of 0.5 m was chosen as a compromise between calculation times and spatial resolution. An optimal value for the spacing of the scanning grid could be determined in a more detailed follow-up study.

Source localization is achieved by performing calculations on the scanning grid in three consecutive steps, which are described in the following subsections.

4.1. Delay-and-sum beamforming

In the first step, the beamforming output power $B_{n,i}(k)$ with conventional Delay-and-Sum beamforming is calculated in the operating frequency range for the audio block with index n and for each scanning point with index i:

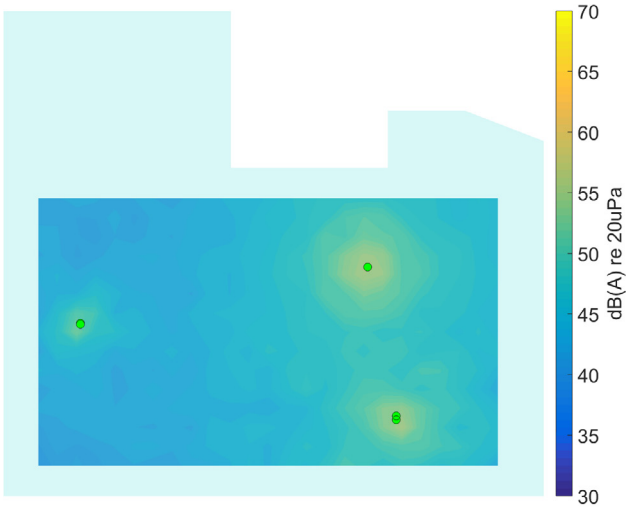
$$B_{n,i}(k) = \mathbf{w}_i^H(k)\mathbf{C}_n(k)\mathbf{w}_i(k). \tag{3}$$

As the continuous, real-time operation of the system is important, some considerations on the computational complexity were made to determine the best algorithm. It was found that the computation of the cross-spectral matrix (Eq. (1)) takes up most of the processing time, and hence a simpler version of Eq. (3) was also implemented:

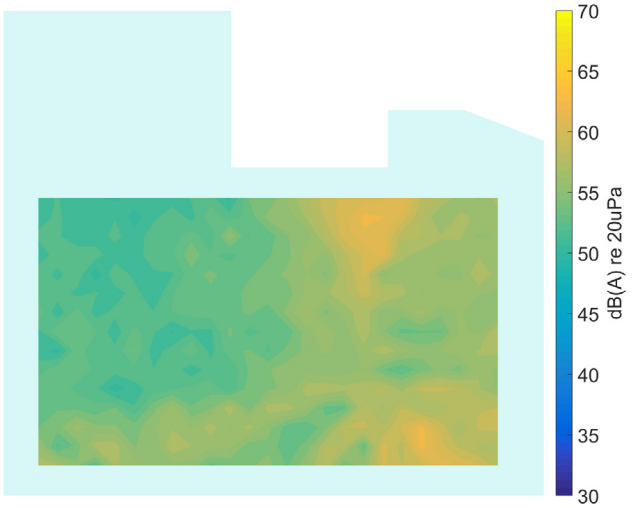
$$B_{n,i}(k) = (1-\alpha)B_{n-1,i}(k) + \alpha\,|\mathbf{w}_i^H(k)\mathbf{p}_n(k)|^2. \tag{4}$$

This version does not make use of the Cross-Spectral Matrix and hence no information about the cross-correlation between the microphones is available. It does however give exactly the same result as in Eq. (3), because the cross-correlation is not actually exploited in that algorithm. In comparison to Eq. (3), the implementation of Eq. (4) saves approximately 75% of the computation time.

To give an idea of the processing output under ideal conditions, Fig. 7 shows an example for a simulation of the ICU environment, including actual recorded sounds and a simple room acoustics model. The model uses image sources [31] for the early reflections and adds statistical reverberation for the late reflections, using noise that is shaped to match the measured reverberation time in the ICU. In all of the following examples, the broadband, A-weighted sound pressure level (SPL) in dB(A) re 20 μPa is plotted. The broadband result for the



(a) Sound Pressure Level in the room, active sources marked as green circles.



(b) Delay-and-Sum beamforming output

Fig. 7. Processing example for a realistic simulation of the ICU environment (broadband levels are shown).

simulated sound pressure magnitude $P_{n,i}(k)$ and the beamforming power output $B_{n,i}(k)$, respectively, is calculated for each scan point i as

$$L_{P,n,i} = 10\log_{10}\left(\frac{\sum_k w_A(k) P_{n,i}^2(k)}{p_0^2}\right), \tag{5}$$

and

$$L_{B,n,i} = 10\log_{10}\left(\frac{\sum_k w_A(k) B_{n,i}(k)}{p_0^2}\right), \tag{6}$$

where $p_0 = 20\,\mu\text{Pa}$ is the reference sound pressure and $w_A(k)$ is the squared magnitude of the A-weighting filter at wavenumber k [32].

In Fig. 7a the broadband SPL is plotted at a chosen time instant with three active sources. Please note that the location of these sources has been chosen as a hypothetical example to illustrate the processing steps and the source positions are not consistent with those in the following experimental results. Fig. 7b shows the broadband output level of the Delay-and-Sum beamformer. It becomes clear that this beamforming result cannot be used directly for an automatic, accurate source localization. The necessary post-processing steps are described in the following subsections.

4.2. Deconvolution (CLEAN/CLEAN-SC)

The result of the Delay-and-Sum beamformer for all scan points $\mathbf{B}_n(k)$ can be regarded as the spatial convolution of the array response — including all sidelobes — with the source distribution $\mathbf{q}_n(k)$. It is of course this source distribution that is of interest for localization and identification.

The deconvolution problem can be solved in several ways. The DAMAS algorithm is a direct deconvolution approach, which can be calculated with the Gauss-Seidel algorithm [33], or by enforcing sparseness in the result, e.g. with the FOCUSS algorithm [34]. However, both approaches are very computationally demanding, and so an iterative solution, such as the CLEAN [35] or CLEAN-SC algorithm [36] is usually favored. The iterative algorithms are faster than the direct approaches by two orders of magnitude, taking only approximately 25% more time than the Delay-and-Sum beamformer.

While the original CLEAN algorithm performs a straight-forward deconvolution based only on the array response, CLEAN-SC takes source correlation into account by working with the cross-spectral matrix. Hence, a trade-off between accuracy and computational demand can be made by the choice of the algorithm. An important advantage of CLEAN is that the array response can be pre-computed and thus processing time can be further reduced. For the application in the ICU, it has been found that contrary to expectations the inclusion of source coherence does not yield a significant improvement and hence the CLEAN algorithm with the fast Delay-and-Sum beamformer (Eq. (4)) is used. From this point on, only the CLEAN algorithm will be mentioned, but all processing is of course equally applicable to the CLEAN-SC version.

Regardless of the choice of CLEAN or CLEAN-SC, the result of this step of processing is a sparse beamforming map with few (typically less than 10) active sources for each frequency bin. When the spectral information is summed up to yield the broadband (A-weighted) level or other derived quantities, the map becomes slightly less sparse as the location of the sources in the scanning grid may not be absolutely stable across frequency. Nevertheless, the number of relevant sources is usually far less than the number of scan positions.

In Fig. 8 an example of the output from the CLEAN algorithm is shown for the simulated data in Fig. 7a. It can be seen that the main regions of source activity can be identified. However, some spurious locations also appear, probably from data in the low frequency range where the directivity of the arrays is not high, as demonstrated in Fig. 5. In the next subsection, a data clustering approach is described to overcome this problem.

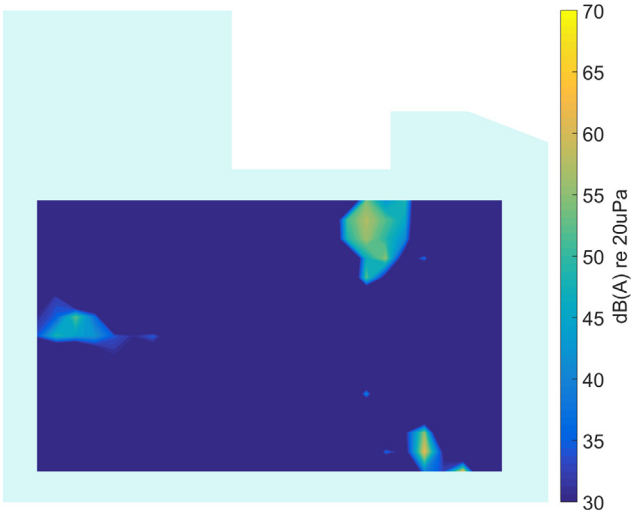


Fig. 8. Broadband output level of the CLEAN algorithm for the simulated data in Fig. 7.

4.3. Data clustering

The broadband result of the deconvolution — while relatively sparse — may not be directly useful to determine source locations automatically. This is a typical problem with beamforming results, which are usually interpreted by inspection of color maps per frequency, or frequency band. The goal of this project, however, is an automatic and autonomous localization of dominant sources, which could be used by a non-expert user, such as a member of the nursing staff.

To achieve this goal, the deconvolution results are combined using the *k-means* clustering algorithm [37]. The initialization is carried out with the *k-means++* algorithm [38]. In terms of input data for the clustering, two approaches were implemented and tested:

Variant 1: If only the broadband result of the CLEAN algorithm is available, the importance of each non-zero point in the map can only be determined from its level. The following steps are then taken:

1. Find non-zero elements and their indices in the broadband CLEAN beamforming map
2. Sort results according to level
3. Select the $N_{\max}$ highest level results
4. Extract the Cartesian coordinates corresponding to the indices determined in step 3
5. Perform *k-means* clustering while varying the maximum number of clusters as

   $$N_{\text{clusters}} = 1 \ldots \min(N_{\max} - 1, 5)$$

   and select the result with the maximum average silhouette value as the optimum [39]
6. Assign the sum of the powers of all points within each cluster as the effective cluster power

The maximum number of clusters is chosen to be equal to five as it is unlikely that there will be more than five active sources at the same time. Because the optimal number of clusters is determined automatically, the value of $N_{\max}$ is relatively unimportant, but here it is chosen to be 15.

The disadvantage of Variant 1 is that the only way to reject outliers, such as spurious peaks, is by level. Hence, if outliers with large levels appear in the beamforming map they will shift the cluster centroids and thus distort the result. A better approach is described in the following paragraph.

Variant 2: If information about the non-zero indices can be obtained for each frequency of interest, an additional pre-selection of the data can be performed in the following way:

1. Find all non-zero indices in the frequency range of interest
2. Sort the data according to the relative number of occurrences of each index across all frequencies
3. Select the indices that make up 80% of the data (based on the cumulative sum)
4. Continue with step 3 in Variant 1 above

The threshold of 80% was selected here as it yielded good results in terms of a reliable estimate of the number of active sources, but it is a parameter that can be adapted to the individual application.

By incorporating the number of occurrences across frequency, the data can be sorted according to importance and thus it is easier to reject outliers. The result of Variant 2 for the simulated data in Fig. 8 is presented in Fig. 9. Clearly, the relevant sources have been identified and outliers have been successfully suppressed. However, it should be said that in this example, the CLEAN result (Fig. 8) does not show too many spurious peaks, so in this case Variant 1 gives the same result as Variant 2. This is different in most real situations, as will be shown in the next section.

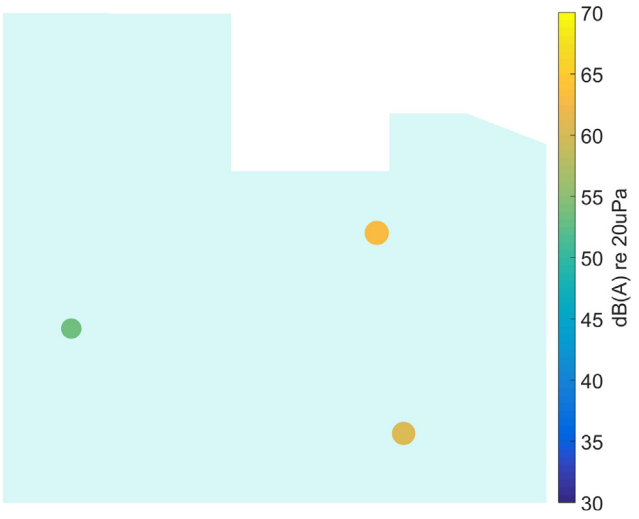


Fig. 9. Clustering result of Variant 2 for the simulated data in Fig. 8, see Fig. 7 for the actual source locations.

5. Results in the ICU

The array system described above was installed in the adult ward of the ICU at the John Radcliffe Hospital in Oxford at the end of October 2016. In this section, representative results are presented to give an idea of the actual system performance. Recordings were made during a typical shift with all beds in the ICU occupied. After applying the broadband calibration filters to the recorded data, the processing as described in Section 4 was applied.

It should be noted that the source locations identified from the recordings in the ICU (Figs. 10–14) are not expected to match the scenarios from the simulated examples (Figs. 7–9), as the simulations used purely hypothetical source locations.

The beamforming map of the Delay-and-Sum algorithm at one chosen time instant is shown in Fig. 10. As already observed for the simulated data in Section 4.1, it becomes clear that this result cannot be directly used for source localization.

In Fig. 11 the deconvolution result of the CLEAN algorithm is presented, yielding a much sparser map that shows the areas with dominant sources. In comparison to the simulated data in Section 4.2 (Fig. 8), the measured data shows more spurious peaks, which may be due to additional sources, or may be caused by array imperfections. It is



Fig. 10. Processing result of Delay-and-Sum beamforming in the ICU environment (broadband levels are shown).

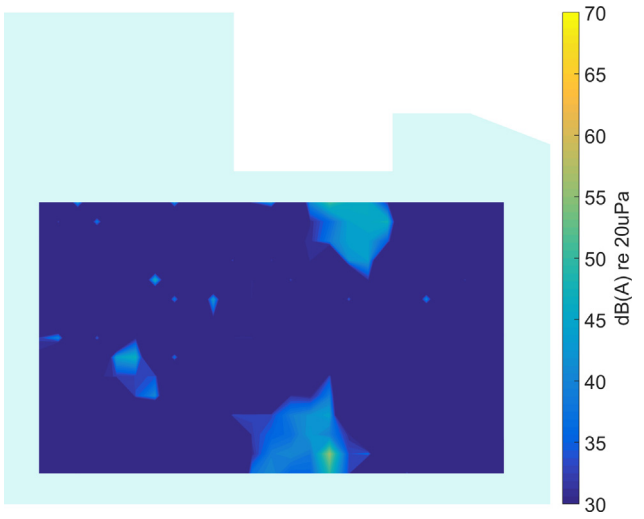


Fig. 11. Broadband output level of the CLEAN algorithm for measured data in Fig. 10.

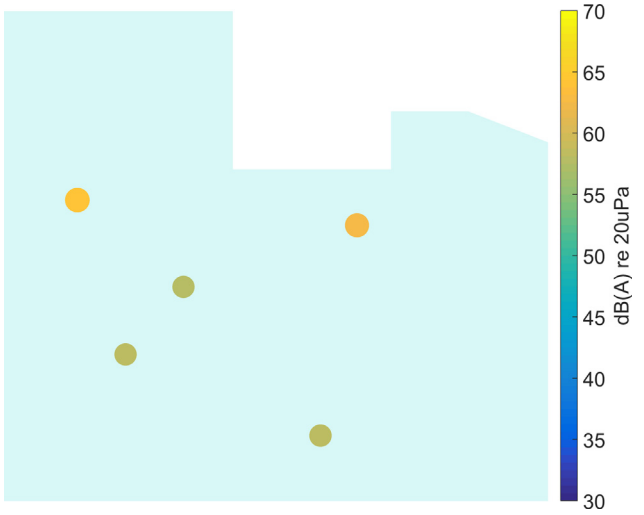


Fig. 12. Clustering result of Variant 1 for the measured data in Fig. 11.

precisely this behavior that makes it necessary to further process the data before an automatic localization can be achieved.

The deconvolution output is processed with Variant 1 of the clustering algorithm (Section 4.3) and the result is shown in Fig. 12. In comparison, the result of Variant 2 of the clustering algorithm is shown in Fig. 13 and from this results it can be seen that by only taking into account the level information, more sources are detected than are actually present. This indicates the benefit of using the additional information across frequency, as is done in Variant 2.

It seems that the relevant sources were correctly localized by Variant 2 of the clustering approach. However, it should be stressed here that the measurements were performed in a working ICU environment, which could not be controlled, so the precise number and location of active sources was not known. Further studies under controlled conditions will have to be carried out to establish the robustness of the presented approach and the ideal set of parameters.

The final display for the nursing staff, implemented in the Julia programming language [40], is presented in Fig. 14. In addition to the source locations, the average sound pressure level recorded by the microphones is shown in a bar graph on the right side of the display. The positions of the detected sources are also exported continuously, so that a statistical evaluation over time is possible.

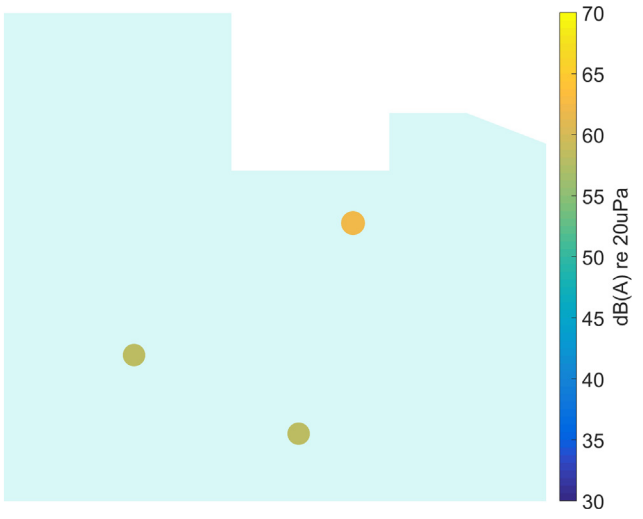


Fig. 13. Clustering result of Variant 2 for the measured data in Fig. 11.

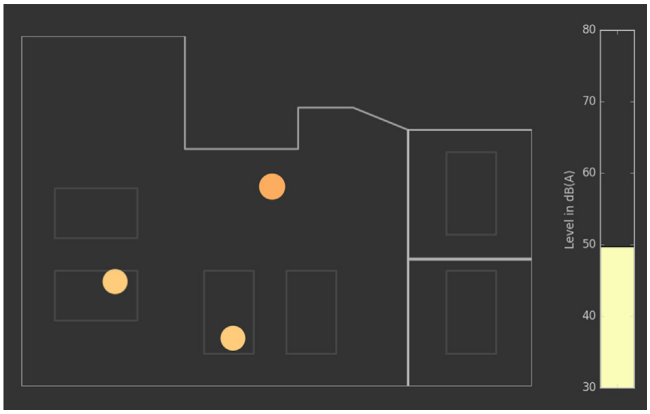


Fig. 14. The data in Fig. 13 as it appears in the display for the nursing staff.

6. Conclusions

In this paper a microphone array system has been presented that is used to remotely localize and quantify acoustic noise sources in an Intensive Care Unit. The hardware and array design for the system under the given constraints have been described. An alternative beamforming formulation resulting in faster computation has been developed and a clustering approach has been introduced to enable an automatic localization of the most dominant acoustic sources.

It has been shown that the raw result of beamforming calculations is not directly useful for unsupervised localization. While the deconvolution approach to beamforming results in a much sparser source map, spurious peaks can still influence and degrade the localization performance. The automatic clustering algorithm has been implemented in the array system. With the help of clustering, the influence of spurious peaks in the source map can be effectively suppressed. The successful application of the presented approach has been demonstrated through real measured data from the running system.

Further studies will be necessary to confirm the validity and robustness of the automatic localization approach, as the data gathered so far was not obtained under controlled laboratory conditions. The optimum number of clusters and its dependence on the environment and the number of array sensors will have to be investigated.

The system described here is currently used in the John Radcliffe Hospital in Oxford to obtain a better impression of the acoustic source distribution in the ICU. This information will be used to devise

measures to provide an overall reduction in background noise levels, hopefully leading to improved patient recovery. At the moment, the possibility of classifying individual sources by combining the spatial filtering presented here with machine learning is being investigated. This additional information would enable the nursing staff to, for example, distinguish between medical equipment and speech, making it easier to implement changes to reduce the noise level.

Before the system described in this paper can be deployed in additional ICUs or similar healthcare environments, its effectiveness and influence on staff and patients will have to be determined. This will require a long-term study, which will then hopefully establish whether the array-based system can assist medical staff in reducing the ICU noise levels.

Acknowledgments

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The Journal of Health Design

RESEARCH INSIGHT

Using patient narratives to design an intervention to reduce noise in the intensive care unit

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SUMMARY

- Patient narratives can be used effectively to guide improvement in the National Health Service the health service.
- The accelerated experience-based co-design (AEBCD) mixed methods approach is feasible and effective.
- The Healthtalk.org archive includes a wide variety of health topics that can be used to create resources for quality improvement projects.
- Including patients and staff in the design team kept the focus meaningful and ensured that the intervention was both acceptable and deliverable.
- Clear opportunities for individual professional development may be effective incentives to encourage local staff to engage fully with the AEBCD process.

Key Words
Patient narratives; co-design; mixed methods; patient involvement; adult education

INTRODUCTION

Including patients and the public in research design is widely referred to as PPI (patient and public involvement). There has been growing acceptance that listening to patients is central to formulating health policy and research projects are encouraged to embrace significant "PPI", although there is little consensus for exactly how this should be achieved. PPI therefore can take many forms, have varying levels of involvement, and generate mixed opinions of success.

PPI is often misunderstood to mean that patients value the broad topic of a research project. This is an unnecessarily narrow definition of a valuable resource. Patient involvement at the design stage ensures interventions are both meaningful and acceptable to those who will experience them. Patients also bring fresh insights and a perspective on healthcare that clinicians seldom share.[1]

For the National Institute for Health Research (NIHR) Research for Patient Benefit funded SILENCE project (PB-PG-0613-31034) we used the NIHR patient and public involvement advisory group INVOLVE's broad and inclusive definition: "research being carried out with or by members of the public, rather than to, about or for them".[2]

SILENCE is a feasibility study designed to identify appropriate patient-oriented outcome measures and a proof of concept intervention for a future study to reduce noise levels in the intensive care unit (ICU). We took a mixed methods approach. This included secondary analysis of patient narratives, ethnographic observations of the ICU, focus group discussions to explore staff perceptions, and continuous sound pressure level (SPL) monitoring. We ran the project as a local quality improvement initiative.

SUMMARY

Following principles of accelerated experience-based co-design (AEBCD),[3] we re-analysed interviews with former ICU patients from an archive of patient interviews and identified significant "touchpoints" (specific areas with potential for quality improvement) from their experiences of noise, which were created into a trigger film. We presented this film to the co-design group that included staff from the ICU, patients and family members, and researchers. Trigger films are an effective mechanism through which discussion of often difficult topics can be approached. The interviews were originally recorded for a national study of patient and relatives' experiences of intensive care. This original study

received ethical approval from the Eastern MREC (ref: 03/5/016). Results were published in 2006 and a representative sample is available on the Healthtalk.org website. Healthtalk.org interviews are copyrighted and archived at the University of Oxford. For this project, access was granted by the archive custodians, the Health Experiences Research Group.

In undertaking local improvement initiatives, it might be expected that views from local patients would resonate more highly with staff. However, recent work confirmed that national patient narratives resonated as powerfully as when local patients were interviewed.[3] Using the archive allowed us to create resources more quickly than recruiting new people to share their experiences. This approach has clear economic benefits for public-funded research.

We supplemented the patient narratives with new insights collected in parallel with the secondary analysis. Discussion with local staff and ethnographic observations from the ICU confirmed the key sources of noise and disturbance identified in the narratives were still current. SPL values allowed us to quantify the problem of noise in the ICU. Although World Health Organisation guidelines recommend a 24hr average of 35dBA for patient areas, levels were found to be much higher, similar to those found in a busy restaurant with peaks >85dBA occurring up to 16 times per hour overnight.[4]

Although the patient interviews were recorded across the UK, the co-design group recognised that problems of noise and disturbance had wide resonance and also affected their local unit. The experiences were therefore demonstrably generalisable. Noone in the trigger film was known to the co-design group. This ensured neutrality to the touchpoints raised for discussion. The group were therefore free to discuss topics without bias.

The group proposed a multi-factorial intervention to raise awareness of the effect that high noise levels in the ICU could have on patients. This included simple environmental changes (eg, plastic-lidded soft-close bins, alarm management guidelines, and better night/day differentiation), new teaching materials (including a live-action session during which staff experience the ICU from the patient perspective, and an e-learning module on environmental noise), and a visual display of live sound levels in the ICU. To ensure maximum impact, subsequent development and deployment of the intervention referenced the patient narratives and collaborative co-design nature of the project.

We included patient narratives from the trigger film in the e-learning module. We also drew from these experiences when scripting the immersive educational activities. This gives credibility to the teaching materials, as staff are able to reflect on their own clinical practices in relation to real patients' experiences. Reflection is a key feature of effective adult education and good quality reflection is more likely to lead to sustainable change.[5]

Interim SPL analysis indicated a reduction of approximately 4dB after four months. Ongoing continuous monitoring will enable long-term evaluation of the full intervention as the final phase (visual display of noise) is deployed.

LESSONS LEARNED

Whilst we followed the principles of AEBCD closely, we modified the methods for practical reasons. We chose to present the trigger film in several short segments (eg, Alarms, People, Lighting, etc.), rather than watch the full 15-minute feature without a break. We felt this enabled more focused discussion on each touchpoint.

Supplementary information presented outside of the trigger film complemented the touchpoints in the film. This combination of specific local information and wider broad-spectrum of patient experiences created a balanced overview of the problem of elevated noise levels in the ICU.

We struggled to fully involve anyone outside the main team when deploying the intervention. Although we had strong support from senior clinical staff, the nursing faculty found it difficult to dedicate resources to the project. This issue

of apparent limited support raises challenges to how much engagement there is across the system for this kind of innovation work. Development opportunities for identified individuals with associated protected non-clinical time may have improved practicability, but is difficult to sustain in a resource-limited NHS. We thought we had addressed many barriers to innovation,[6] but ultimately there was insufficient support and enthusiasm to overcome the perceived additional burden.

CLINICIAN INSIGHT

Noise levels in the intensive care units are known to be high, with studies consistently showing levels above World Health Organisation (WHO) guidelines average noise of 35 dBA during the day and 30 dBA at night.[1–2] Staff activities and alarms are primary sources of disturbances in intensive care units,[3] but noises from other patients and infrastructure also contribute. Staff and patients may be in a chronic state of alertness when alarms are constantly sounding. Alarms share characteristics with the human scream and tend to activate areas of the brain that recognise danger. Volunteers exposed to simulated intensive care environments show disturbed sleep and biochemical markers of stress,[4] and patients attribute difficulties with sleep to disturbances around them. A recent meta-analysis confirms the link between patient exposure to high noise and delirium.[5] Between 30 per cent and 75 per cent of patients experience at least one delirious episode while in intensive care. These patients tend to have longer hospital stays and long-term health problems after they have been discharged home.[6] Lowering environmental noise levels may help patients sleep and results in fewer episodes of delirium.

In my experience, changing culture has been one of the hardest barriers to overcome. Staff education without definitive process change is unlikely to produce a sustained improvement in the noise level. AEBCD is useful in highlighting the problem, although instituting change requires strong leadership with both top-down and bottom-up approaches, and with effort concentrated on high-impact interventions, when change is inevitable.

A potential high-impact area, fixing a problem at its root, is a change of monitoring standards accounting for physiological effects of noise. Local process changes may include having a designated “no talking” area around the patient bed at an allocated time to promote sleep with visual display of live sound levels for the purpose of providing immediate visual feedback, promoting compliance and source of audit; and allocating designated new admission bed areas for overnight admission. The reality of clinical care in the critical care environment with its inherent unpredictability is that these changes are difficult, though not impossible, to implement.

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PEER REVIEW

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CONFLICTS OF INTEREST

The authors declare that they have no competing interests.

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ETHICS COMMITTEE APPROVAL

The project was run as a local quality improvement project (Oxford University Hospitals NHS Foundation Trust Datix ref: 3247)

governance framework and requires continued monitoring.

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Using the experience-based co-design method to design a teaching package

Julie L Darbyshire, Lisa Hinton, J Duncan Young & Paul R Greig

What problems were addressed? The World Health Organization recommends average noise levels in patient care areas no higher than 35 dB, with peaks below 40 dB. In reality, most intensive care units (ICUs) worldwide average 55-60 dB, with peaks up to 120 dB. Staff acclimatise to this, often rationalising high noise levels as necessary because of the equipment and monitoring needs of patients. There is limited awareness that many sources of noise are modifiable, understanding of the patient experience of intensive care is low, and prior to training there is little motivation to implement change. The objective of this training was to facilitate reflection on the patient experience, with a view to enabling self-directed change to reduce noise levels in the ICU.

What was tried? Building on interviews with former ICU patients[1] and ethnographic observations, we used the experience-based co-design method to create a training course to increase knowledge about noise in the ICU. A collaboration between patients, clinical staff, researchers and medical educationalists ensured learning objectives were relevant, practical and of high educational quality.

The course combines a multimedia e-learning package and an *in situ* simulated patient experience that combines a binaural soundtrack of ICU noises with live-action nursing activities. The e-learning takes approximately 20 minutes to complete and individual experiences last 15 minutes, which includes post-experience debriefing. The authenticity of teaching materials is ensured by using real patient experiences and replicating behaviours observed during ethnography sessions.

An online self-assessment is included because formative assessment is both motivational and guides onward learning. Assessment points were mapped to course materials using a curriculum blueprint, and participant feedback was used to refine the simulation experience.

What lessons were learned? The simulation invoked feelings of worry, fear, stress, confusion and loneliness. This maps well to patient narratives and indicated our simulation had been successful despite only lasting a few minutes. Post-experience debriefing allowed participants to decompress before returning to work. The negative emotional component was intended to prompt staff reflection, as per Kolb's learning cycle, and proved effective. All 116 participants described the experience as useful, >90% reporting they should do more to improve the environment for their patients.

After the experience, 97% of staff indicated they would modify their behaviours, and this appeared to be carried into practice. Noise level monitoring confirmed a perceivable drop of ~4 dB from a baseline of 57.0 to 53.2 dB during the 4-month post-intervention period.

We have been unable to incorporate this training into recurring education sessions. The *in situ* experience is heavily workload dependent, requiring a bed space and members of the education team to be free at an appropriate time. This requires a flexible, imaginative and highly motivated faculty member to deliver training opportunistically; it was therefore difficult to embed. We are now exploring alternative models to enable stand-alone delivery of this innovative training.

We have been able to demonstrate that meaningful teaching can be delivered even in a tightly compressed time format, and that this can successfully modify behaviour. This makes this style of teaching practical in a busy unit, but maintaining momentum after the initial wave of interest remains challenging.

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Measuring sleep in the intensive care unit: Electroencephalogram, actigraphy, or questionnaire?

Julie L Darbyshire[1], Mark Borthwick[2], Peter Edmonds[3], Sarah Vollam[1], Lisa Hinton[4] and J Duncan Young[1]

Abstract

Background: Studies consistently report deranged sleep in patients admitted to intensive care unit. Poor sleep has harmful physical and cognitive effects, and an evidence-based intervention to improve sleep is needed. It is, however, difficult to measure sleep in the intensive care unit. 'Gold standard' monitoring (polysomnography) is unsuitable for usual care.
Methods: We collected concurrent sleep data from electroencephalograph recordings, activity monitoring, and nurse- and patient-completed Richards-Campbell Sleep Questionnaires (RCSQ).
Results: Electroencephalograph data ($n = 34$) confirm poor sleep. Individual bouts last approximately 1 min and around 2 h of sleep overnight is common. Correlation between electroencephalograph, self-report, nurse-report, actigraphy and overall activity score is low ($\rho = 0.123$ ($n = 24$), 0.127 ($n = 22$), and 0.402 and -0.201 ($n = 13$), respectively). Correlation between nurse and patient assessment is limited ($\rho = 0.537$ ($n = 444$)).
Conclusions: No current method of sleep monitoring seems suitable in the intensive care unit. However, to facilitate comparison across studies, the patient-completed RCSQ seems the most meaningful measure.

Keywords

Sleep deprivation, polysomnography, sleep monitoring, critical care, observational study

Introduction

Sleep is important for recovery and general well-being.[1] This is particularly true of patients admitted to hospital.[2] Poor sleep has harmful effects on patients, both physical and cognitive,[3] and there is a strong interest and need for a well-designed, evidence-based intervention to improve sleep and, by default, sleep monitoring on the intensive care unit (ICU).[3,4]

The 'gold standard' for sleep assessment is polysomnography (PSG)[5] and a number of small-scale studies have successfully measured ICU patient sleep using PSG. All of these studies have indicated abnormal sleep patterns in patients being treated on the ICU.[6] PSG is impractical for routine use in the ICU environment where patients have complex care needs, and the proximity of a range of electronic devices can cause interference with the recordings.[6–10] Reliable methods to enable simple routine monitoring of sleep in the ICU are needed.

The Richards-Campbell Sleep Questionnaire (RCSQ) is designed for patient use in the ICU and is a composite measure of sleep derived from five visual analogue scales (VAS). This is generally considered the most clinically useful sleep observation tool for use in the intensive care unit.[11,12] A nurse-completed version is available for when patients cannot complete it themselves.[13]

Simplified PSG units with fewer connecting electrodes are available for general use (Sleep Profiler, Advanced Brain Monitoring Inc., Carlsbad, CA, USA). Wrist-worn activity monitoring devices are also commonly used to determine sleep patterns in

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the general population. Given the impracticalities of widespread PSG in ICU, we designed a study to investigate the feasibility of using these simpler devices to measure sleep in the ICU population. Metrics from these devices can be tested against both patient- and nurse-completed RCSQ questionnaires, with the intention of determining if such equipment has a role in ICU sleep measurement.

Methods

For the purposes of familiarising ourselves with the equipment, and to collect baseline comparator sleep data from healthy adults, we recruited 27 volunteers prior to recruiting patients from the ICU. Approval for this preliminary study was given in March 2014 by the University of Oxford Medical Sciences Inter-divisional Research Ethics Committee (ref: MSD-IDREC-C1-2014-033). All volunteers provided written informed consent to take part in the study.

The subsequent observational study had two primary objectives. The first was to use electroencephalograph (EEG) monitoring to objectively assess the duration and quality of sleep in patients admitted to the ICU. The second was to compare sleep results from other, more practical and cost effective, means of measurement. We collected concurrent sleep data using a wrist-worn activity monitor (MotionWatch 8, CamNtech Ltd, Papworth Everard, UK) and the Richards Campbell Sleep Questionnaire.[14]

This was a multi-site observational study. We aimed to recruit approximately 500 non-sedated/ventilated patients to assess nurse- vs. patient-completed RCSQ correlation (cohort 1: questionnaire only). This was a convenience sample, as it was not possible to determine a statistically accurate sample size from existing available data. Due to the practicalities of equipment and software availability, patients from one site (Oxford University Hospitals NHS Foundation Trust (OUH)) were recruited to wear the EEG and activity monitoring equipment as well as complete the RCSQ (cohort 2: questionnaire plus electronic monitoring).

We proposed to recruit 50 patients to wear the EEG monitor. This was a convenience sample size based on other similar studies reported in the literature. A sub-set of these patients also agreed to wear the activity monitor. We also intended to recruit about 10 patients to the EEG monitoring arm who were sedated and ventilated. This was to assess if sleep patterns for sedated patients are similar to those for patients who are not sedated.

Unless patients were being palliated, or language barriers were present, all patients admitted to the ICU for at least one overnight stay were eligible. If patients could not wear a monitor, for example for reasons of their condition, anatomy, or care requirements, they completed the questionnaire only. All patients with capacity gave written informed consent at the point of recruitment. For patients without capacity, favourable opinion was sought from an appropriate relative acting as 'consultee'.

In addition to sleep measures, we also collected demographic data and information on delirium screening, pain scoring and medications for pain and sedation for the day before and after the monitored night.

Simple statistics describe the population. Correlation analysis and tests of agreement were performed to compare the sleep efficiency index as recorded by the EEG monitor with the RCSQ scores reported by the patient and the nurse. Further correlation analyses and tests of agreement were performed to compare activity-determined sleep patterns as recorded by the wrist-worn monitor against the EEG monitor data and the RCSQ scores. All p values are two sided; proportional data were compared using chi squared tests; continuous data were analysed by t-tests/ANOVA or a suitable non-parametric alternative where necessary.

Results

There are two study cohorts; the multi-site group who completed the RCSQ only (Table 1) and the single site group who were recruited to electronic monitoring in addition to questionnaire completion (Table 2).

Table 1. Patient demographics (cohort 1).

	All patients	Did not complete study	Completed study
N (male/female)	582 (308/273)[a]	96 (45/51)	485 (263/222)
Median age (min, max, IQR) in years	63 (17,98,25)	61.5 (19,91,27)	63 (17,98,24)
Surgical admission, N (%)	302	46 (15.2)	256 (84.8)
Medical admission, N (%)	279	50 (17.9)	229 (82.1)
Median (min, max, IQR) ICU stay in days	4.5 (0,183,6)	4 (0,62,7)	5 (1,183,6)
Alive at discharge from ICU, N (%)	483 (83.1)	22 (4.6)	461 (95.4)

ICU: intensive care unit.
[a]Gender not recorded for one patient.

There were no significant differences between demographics of patients recruited from different sites.

Continuous data were not normally distributed; therefore, median and IQR are quoted. Of the 45 patients recruited from OUH, 34 wore the EEG monitoring overnight. From almost 611 h of recording, approximately 16% was categorised by the software as 'invalid' and unsuitable for analysis. The median sleep per patient overnight was 2 h, 6 min (IQR; 3.5 h). Of this time, 7 min (5.6%), 13 min (10.2%) and 1.5 h (69.2%) were spent in rapid eye movement (REM) sleep, slow wave sleep (SWS) and non-REM (stages 1 and 2) sleep, respectively. Median (IQR) individual bouts of sleep were 1 min (45 s).

For the three patients who were sedated/ventilated while they wore the EEG monitor, their total recorded sleep times were 12:38:30, 00:28:30 and 09:46:30. Of this time, 04:53:30 (39%), 00:02:00 (7%) and 00:33:00 (6%) was spent in REM sleep, 01:53:30 (15%), 0 (0%), and 04:19:00 (44%) was spent in SWS, and 10:45:30 (85%), 00:26:00 (90%) and 04:12:30 (43%) in non-REM stages 1 and 2.

Table 2. Patient demographics (cohort 2).

N (male/female)	45 (27/18)
Median (min, max, IQR) age in years	60 (18, 91, 27)
Surgical admission, N (%)	23 (51.1)
Medical admission, N (%)	22 (48.9)
Median (min, max, IQR) ICU stay in days	5 (1, 42, 12)
Alive at discharge from ICU, N (%)	43 (95.6)

ICU: intensive care unit.

Figures 1 and 2 illustrate the difference between sleep experienced by a patient in the ICU and a healthy volunteer. The healthy volunteer spent much more time in both REM and slow-wave sleep and experienced fewer awakenings per hour.

Patients and nurses who completed the RCSQ did not always complete every question. N values for analysis sets therefore vary. Correlation (Spearman's Rho) analyses between the EEG monitoring and nurse- and patient-completed total scores from the RCSQ are $\rho = 0.127$ ($n = 22$) and $\rho = 0.123$ ($n = 24$), respectively.

Of the 34 patients who wore the EEG monitor overnight, 13 also wore the activity monitor. Non-parametric correlation for EEG vs. actigraphy measured duration of sleep = 0.402. Correlation of EEG measured duration of sleep and overall actigraphy score = −0.201.

The RCSQ is a continuous visual analogue scale that reports sleep assessment scores between 0 and 100. Both nurses and patients recorded maximum (100) and minimum (0) scores when assessing sleep. The mean (95%CI, SD) score reported by patients was 53.1 (50.5–55.7, 27.9). The mean (95%CI, SD) score reported by nurses was 61.0 (58.6–63.4, 25.7). The overall correlation between nurse and patient completed RCSQ was $\rho = 0.537$ ($n = 444$). See Figure 3 for scatter plot of results. Individual RCSQ question correlation results were lower than the combined mean (see Table 3).

The highest pain scores in the previous 12 h were reported at baseline, and at the beginning and end of the monitored night. Completion rates were good at

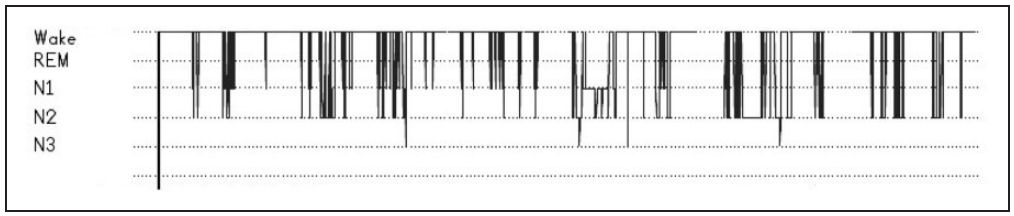


Figure 1. A night's sleep report from the EEG device for a patient in the ICU.

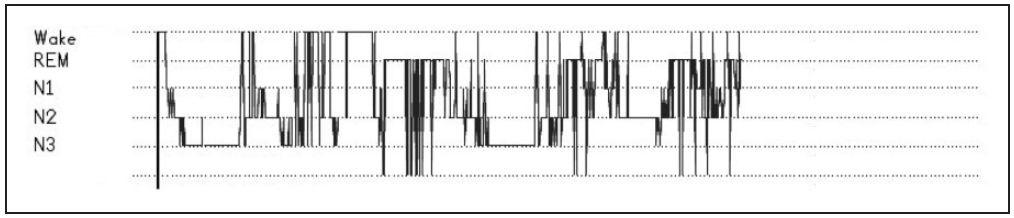


Figure 2. A night's sleep report from the EEG device for a healthy volunteer.

95.3%, 87.7% and 88.9%, respectively. The Confusion Assessment Method for the Intensive Care Unit (CAM-ICU) was completed at baseline and the day following the monitored night. Completion rates were 97.7% and 91.6%, respectively. Two patients tested positive for delirium at baseline and two (different) patients tested positive the following day.

Linear regression analysis found no relationship between either analgesic or sedation medication given to patients, or their delirium status and their reported sleep either before or after the monitored night.

Although we used relatively simple EEG monitors with just three leads, it became apparent quite quickly that the system is still too complex, too cumbersome and too expensive to use on all patients routinely.

Discussion

It is clear from all the information available that patients admitted to the ICU experience very poor sleep. Results from this study add to the body of evidence, confirming that sleep is short and highly fragmented with inadequate rapid eye movement or deep sleep. This is consistent with other studies that have measured sleep in this population and which have been summarised elsewhere.[6,8]

The duration and quality of sleep indicated by the EEG results in this study are comparable to other studies that have used more complex PSG systems to measure patient sleep in the ICU.[9,15,16] The monitoring equipment we used was able to recognise and interpret 84% of the data recorded from these patients. In theory, this indicates that the simplified EEG monitoring devices are suitable for use in the ICU; however, it is relatively expensive, requires expertise to use, is not 100% reliable in the environment and patient tolerance is an issue with almost a quarter of patients being unable to wear the monitor overnight. A small-scale study (n = 5) suggests that single channel EEG data could be a plausible means to estimate at least depth of sleep in the ICU.[17] This form of monitoring may be better tolerated by patients but has limitations in measurement capabilities.

We only recruited three patients to wear the monitor who were sedated/ventilated. Their sleep recordings were quite different from each other. With such a low number and no clear pattern to the data, we can make no generalisations about sleep duration or quality for these patients.

We conclude that EEG and actigraphy correlate poorly, and this is consistent with existing data.[18] Actigraphy can be a useful alternative to EEG monitoring for hospitalised patients outside of the ICU.[19] However, unusual activity patterns seen in ICU patients seem to render standard sleep detection algorithms inadequate, leading to a tendency to overestimate sleep in the ICU population.[16]

Although the RCSQ is widely regarded as the best option for measuring patient sleep in the ICU,[8,11] it is only suitable for patients who have the cognitive abilities to complete it. Nurses can use the same questionnaire to assess patient sleep. Prior to this study,

Table 3. Correlation results for nurse- vs. patient-completed RCSQ.

Question 1: Depth of sleep	ρ=0.424 (n=428)
Question 2: Initial sleep latency	ρ=0.394 (n=434)
Question 3: Duration of sleep	ρ=0.448 (n=437)
Question 4: Sleep latency after awakening	ρ=0.396 (n=429)
Question 5: Overall sleep quality	ρ=0.478 (n=439)

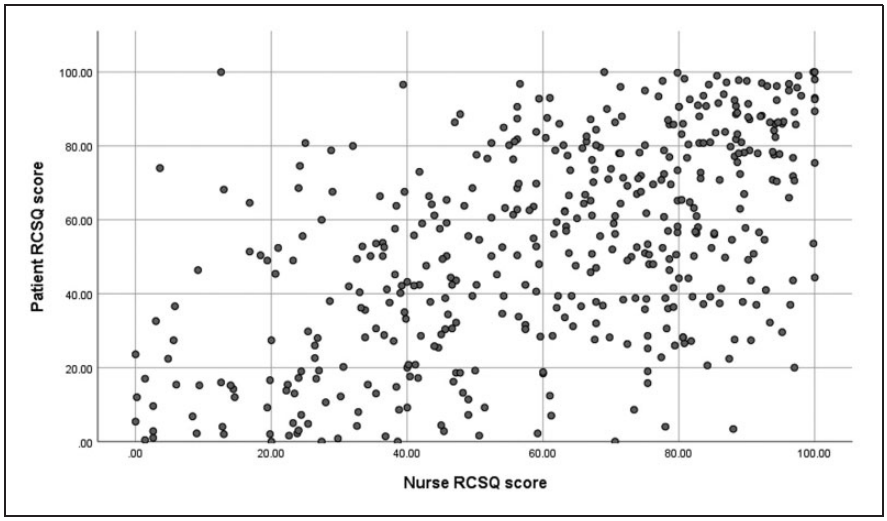


Figure 3. Plot of nurse and patient RCSQ results.
RCSQ: Richards-Campbell Sleep Questionnaire.

three small-scale studies (N = 31,[20] 33,[21] and 151,[22] respectively) had published correlation results between nurse- vs. patient-completed RCSQ. These data were conflicting. It was unclear from these studies whether nurse-completed questionnaires are a realistic interpretation of patient sleep. This much larger, multi-site study has conclusively demonstrated that the nurse- and patient-completed RCSQ are not interchangeable. In line with other third-party reporting of subjective measures (e.g. pain[23,24]), these study results indicate that it is likely that nurses will report better sleep (both in quality and quantity) than patients themselves. This should be taken into consideration when interpreting results from the RCSQ.

A number of studies have now demonstrated that neither full (20 lead) PSG nor actigraphy are reliable practical measures of sleep for the ICU patient population. We have also demonstrated that even simplified EEG monitoring is unlikely to be suitable for usual care.

Limitations

We acknowledge the high withdrawal rate from the electronic monitoring arm, and significant numbers of nurses and patients from this arm did not complete their RCSQ. This affected the analyses, as from 45 patients recruited to the study we were able to correlate paired data for just 24 patients. Also, only 13 patients wore the actigraph in addition to the EEG monitor; therefore, our denominator for these analyses is much lower than we had expected. We did not formally collect reasons for failure to complete the study, but we believe that the majority of the 16.5% of patients who did not complete their questionnaires were discharged to the ward between agreeing to take part in the study and being able to complete their sleep assessment. This was always a risk with this cohort of patients as because they need to be cognitively alert to self-assess their sleep, they represent some of the less sick patients in the ICU. We cannot guarantee that nurses did not collude with patients when completing their RSCQ but believe that if they had, the correlation values would be higher.

Conclusions

This study demonstrates clearly that nurse- and patient-completed RCSQ results are not interchangeable. With limited correlation between the EEG monitoring and any other verified measure of sleep, we are also hesitant to recommend any method of sleep monitoring for use in the ICU. However, to maintain consistency in reporting in a way that enables useful comparison across studies, we believe that the patient-completed RCSQ is the most reliable measure of sleep in the ICU. Where self-reporting is not possible, we propose that nurses complete the RCSQ on behalf of their patients but that care is taken when interpreting results.

Authors' note

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Authors' contributions

JLD – co-applicant on NIHR grant, devised the study and wrote the protocol, managed and co-ordinated the study, analysed the data, and wrote the first draft of the article; MB, PE, SV, LH – advised on study direction as members of the study advisory committee (LH also co-applicant on NIHR grant); JDY – overall supervision of project and NIHR grant holder. All authors have read and had the opportunity to comment on and revise the article. All authors approve the final version of the article.

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Medical educational theory in practice

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Learning objectives

By reading this article, you should be able to:

- Discuss establishing aims, outcomes, and objectives for an educational session.
- Introduce adult educational theory into your practice.
- Cater for different learning styles and preferences.
- Illustrate different methods of delivering feedback.

Key points

- Aims, objectives, and outcomes represent hierarchical statements about the content of an educational encounter. They lend structure and clarity to both learner and educator.
- Learners exhibit different learning styles and preferences, and educators should design their teaching to cater for a diverse audience.
- Educators should be aware of the 'hidden curriculum', and act as good role models at all times.
- Constructive feedback can be offered at the end of any educational encounter, and is mandatory when completing a workplace-based assessment.
- Quality feedback guides the reflective process and can be delivered using a variety of models.

Teaching, training, supporting, and assessing colleagues are duties of a doctor, but historically, doctors have received little formal training in how to teach.[1] Recently, a wealth of resources have become available; many universities offer formal qualifications in medical education, and the Royal College of Anaesthetists (RCoA) run the 'Anaesthetists as Educators' (AaE) programme, which offers a series of courses designed to improve teaching skills.

Teaching in any setting, be it in a classroom or in the operating theatre, requires planning. This may be as short as 5 min discussing expectations with trainees before a list, or hours of preparation for a workshop.

Distinguishing between aims, outcomes, and objectives

The first consideration is the aim of the session. This is a general statement of intent; for example, the aim of this article is to improve readers' understanding of medical education. Trainees themselves will often specify aims, particularly in operating theatre-based training. It is useful to establish this early to ensure that the expectations of the learner and the teacher align.

Objectives are more specific statements about what the teaching will deliver. For example, the objectives here are to: (i) discuss establishing aims, outcomes, and objectives for an educational session; (ii) introduce adult educational theory into your practice; (iii) cater for different learning styles and preferences; and (iv) illustrate different methods of delivering feedback.

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Outcomes are more specific still, and the distinction between objectives and outcomes can be a source of confusion. We draw the distinction between them by considering objectives as statements of the topics that will be taught, but outcomes as those specific things that can be measured to ensure the objectives have been achieved. An example can be seen in Box 1.

Arguably, the learning outcomes are the most relevant to the trainee. The statements describe exactly what new knowledge or skills they will acquire by the end of the encounter. Having read this article, for instance, we expect that readers will be able to describe four learning styles; to explain matching teaching methods to learner preferences to maximise engagement; to be able to define terms such as 'aims', 'objectives', and 'outcomes' as they are used in a teaching context; and to list four feedback models.

Setting outcomes determines the focus of the training and clarifies the 'take-home' messages for the learner. They offer transparency because the trainees know which aspects of their knowledge, skills, or attitudes are being observed. This helps set ground rules by giving the educator permission to observe or probe trainee performance, and offer relevant feedback.

Outcomes should use specific, measurable verbs. The attainment of outcomes, therefore, enables the success of a training session to be measured. Verbs, such as 'understand' or 'know', are often written in learning outcomes, but are not necessarily best practice because it is impossible to directly measure 'understanding'. It would be better to select 'describe <condition>' or 'analyse <treatment option>'. This specificity then allows the trainer and trainee to make some assessment to determine if their learning objectives were met.

In 1956, a taxonomy of such verbs was created, and grouped by the type of knowledge or skills they access.[2] This allowed for a classification of learning objectives into areas, such as 'knowledge', 'comprehension', 'application', 'analysis', 'synthesis', and 'evaluation' according to the depth of knowledge the learner is expected to achieve. This list has been refined several times since, and an example is provided in Figure 1. Next to each heading is grouped a series of measurable verbs that can be used to specify objectives appropriate to each level. Simple factual recall, for example, represents the most basic form of learning. This may be appropriate for new topics or inexperienced trainees, but as expertise is gained a deeper level of understanding is required. Advanced learners should be able to synthesise knowledge and build links between concepts already learned.

There are many opportunities to set learning outcomes. Educational supervisors are well placed to set high-level outcomes relevant to an entire clinical attachment. It is sensible to set at least one specific objective at the start of each training list in the operating theatre that can be revisited at the end of the day. Anaesthetists may also have formal teaching responsibilities, for example delivering local teaching programmes for trainees preparing for Fellowship examinations or teaching on external courses. In many cases, learning outcomes are constrained by a training curriculum, but in each situation, specifying objectives can help both learner and trainer.

Knowing your audience

A key feature of adult learners is that they value autonomy and take responsibility for their learning.[3] In a time-pressured workplace, the personal relevance of learning must be obvious if trainees are to engage with it. It is particularly beneficial if learning outcomes can be integrated into their normal working day.[4] Some of these are highlighted in Kolb's learning cycle (Fig. 2), which considers the importance of reflecting on experiences to developing new understanding.[5] Clinical supervisors need to be able to facilitate and guide that reflective process and establish a safe environment for the learners, one in which they can freely contribute.[6]

External factors also have motivational effects; for example, professional examinations are likely to dominate a trainee's agenda for substantial periods of time. It is

Box 1
List of aims, objectives, and outcomes for a hypothetical small-group training session designed for novice anaesthetists on the subject of breathing circuits.

When designing such sessions, we tend to group learning outcomes under the relevant objectives, and have followed that convention here. Note the increasing specificity of the statements as one moves from aims, through objectives, and finally to outcomes.

Aim:	To introduce different types of anaesthetic breathing circuits
Objectives:	
(i)	To introduce the circle breathing system
(ii)	To illustrate different types of Mapleson circuits
(iii)	To demonstrate the clinical use of commonly encountered breathing circuits
Outcomes:	
(i)	To introduce the circle breathing system
(a)	List the components of a circle breathing circuit.
(b)	Draw a diagram of a circle breathing system.
(c)	Describe the function of the soda-lime canister in a circle system.
(ii)	To illustrate different types of Mapleson circuits
(a)	Draw a diagram of the six Mapleson circuits (A–F).
(iii)	To demonstrate the clinical use of commonly encountered breathing circuits
(a)	Describe why circle systems are most commonly found in theatre.
(b)	Explain why the Mapleson D system requires a much higher fresh gas flow than a circle system.
(c)	Explain why the Mapleson F system is commonly used when anaesthetising small children.

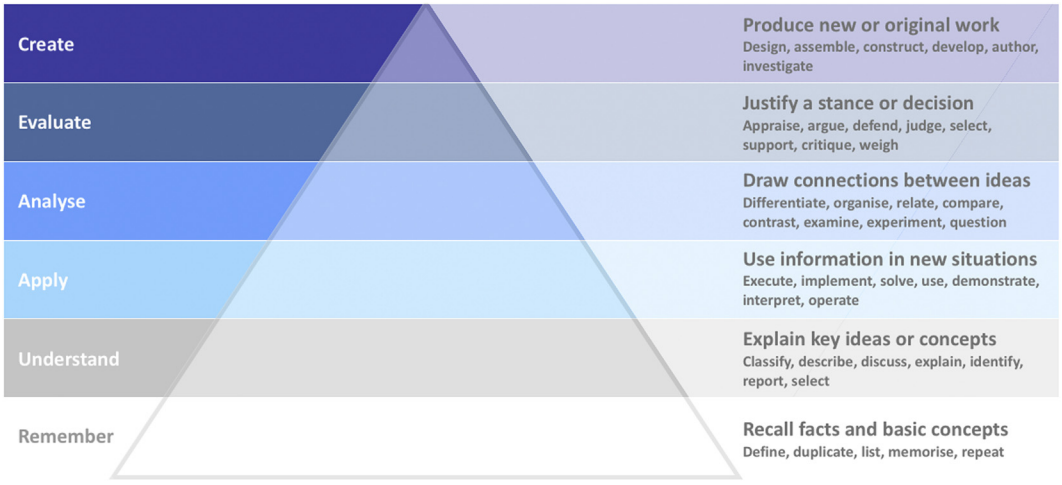


Fig 1 Bloom's taxonomy is a means of structuring learning objectives according to the depth of knowledge required. Remembering facts about a topic represents the lowest level of knowledge; the ability to create something using knowledge requires the highest levels of attainment.

therefore important that educators recognise and respond to trainees' needs, rather than encounters being overly teacher focused.

Learners tend to gravitate towards preferred methods of acquiring information, or 'learning styles'. One of the most popular methods of quantifying this is the 80-item Honey and Mumford questionnaire.[7] This identifies four learning styles: activist, pragmatist, reflector, and theorist. These styles approximate to steps in Kolb's cycle (Fig. 2).

Few learners fall exclusively into a single category, but many exhibit stronger preferences for one or two styles. Although learners adopt non-preferred learning styles at times, understanding these preferences is useful for the educator to assess whether a teaching style is appropriate to the audience. This questionnaire is also administered routinely to delegates attending the RCoA AaE programme to encourage them to reflect on their own teaching and learning practices.

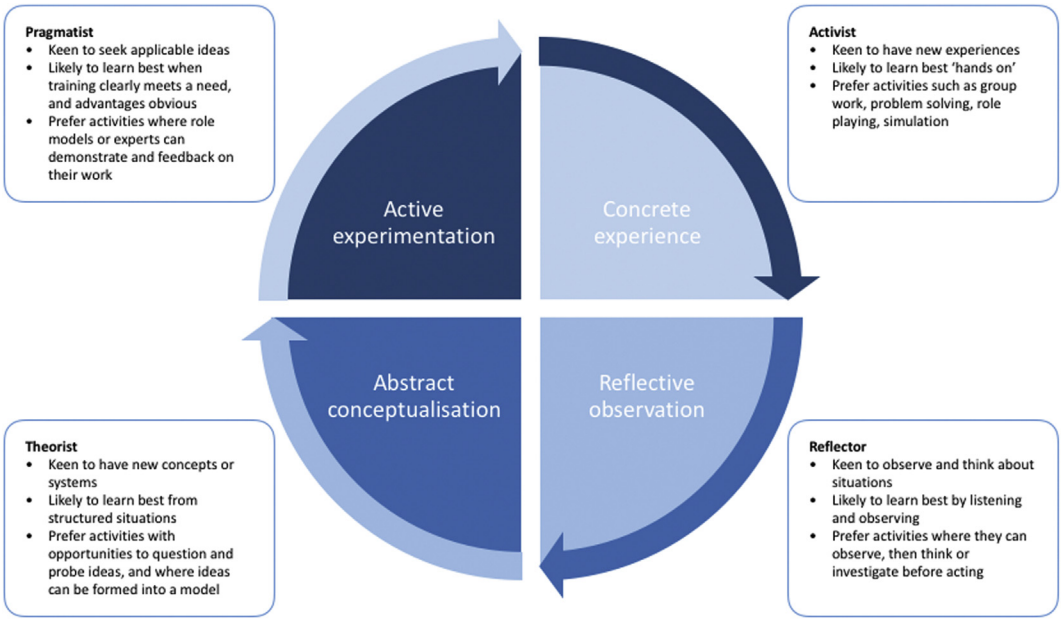


Fig 2 Kolb's learning cycle (central disc) and Honey and Mumford's learning styles (outer boxes). Kolb visualised learning as stemming from reflecting on an experience, using that reflection to find ways to modify an approach, and then testing the new approach. This then generated a new experience that could feed back into the cycle. Honey and Mumford described a series of stereotyped learning styles that learners tend to adopt, which approximate to different steps in Kolb's cycle.

When designing teaching encounters, people tend to favour learning styles to which they respond personally, but this risks narrowing methods of delivery and may reduce the impact for sections of the audience. Knowledge of trainees' preferences affords the educators a valuable and objective opportunity to appraise the variety of teaching methods they use.

These insights can be applied at many levels; educational supervisors can use this knowledge to tailor their recommendations for training opportunities, and course designers can reflect on programme content to ensure relevance for diverse audiences.

At the individual level, learning styles can assist in operating theatre settings. Consider the example of introducing a trainee to a new item of equipment; typically, the activist learner will simply want to experiment with the device, exploring functions and limits. The pragmatist will desire an understanding of the advantages the new device has over the old, but will not want a lengthy open-ended discussion about it. The theorist learner may want to understand fully the underlying principles, and how the device fits into guidelines or processes, but the reflector may wish to observe its use and be given time to consider before taking an opportunity to use it themselves. Tailoring the delivery of teaching maximises engagement by avoiding boredom or discomfort.

In addition to preferred methods of learning, people also express preferences on the format of teaching materials. Fleming's visual, aural, reading or write, and kinaesthetic system is one way of thinking about these tendencies.[8] Fleming postulates that some learners prefer visual materials (photographs, diagrams, or graphs), others auditory items (lectures, podcasts, or group discussions), and some will prefer to read (textbooks, manuals, or journal articles). Finally, some learners prefer kinaesthetic means (simulation, supervised practice, or experience). These are also not absolutes, but do reinforce the value of providing a range of materials and methods when designing educational encounters.

Teaching in the operating theatre

The curriculum for anaesthesia notes that 'anaesthesia is a craft specialty and much of the education and training is acquired through experiential learning and reflective practice with trainers'.[9] Teaching in the workplace provides the majority of educational opportunities available to trainees. The AaE course 'Teaching and Training in the Workplace' is particularly relevant to anaesthetists who regularly supervise colleagues in the operating theatre.

To maximise the educational value of such teaching, some structure is useful. As suggested previously, spending a few moments before a list begins negotiating with trainees what the learning outcomes for that day should be allows the trainers to focus their attention. Involving the trainee in this process should also improve personal relevance (and motivation). In a sense, this becomes an 'educational-WHO' which might include the following: what stage is the trainee at? What are their current educational aims? What are the specific outcomes that this encounter can deliver? Are there any WPBA forms the trainee wishes to complete? Similarly, lists can conclude with a debriefing reflecting on whether objectives were met, reviewing ongoing needs, and planning specific future learning.

These briefings and debriefings can support workplace-based assessment (WPBA) forms. Completing WPBA for trainees can sometimes feel a bureaucratic burden, but this need not impede delivery of useful learning experiences. Moving beyond a 'box-ticking' exercise, there can be value in WPBA use depending on how both trainee and trainer interact via the paperwork. Best practice recommends that WPBA be completed contemporaneously, and an agreement should be reached about what assessments will be performed prospectively as part of the brief. Agreeing to complete a form retrospectively is suboptimal; an advance agreement allows the trainer to think about assessment criteria and focus on relevant areas. It also gives the trainer permission to scrutinise the trainee's performance and implies an agreement to enter into a feedback discussion at the end of the session. This process can embed the WPBA form into Kolb's learning cycle by using it as a trigger to reflect on performance. It is important to choose an appropriate WPBA for the educational event (Table 1).

One of the more challenging sections of most WPBA forms deals with planning for future learning and development. Educational supervisors, college tutors, and annual review of competence progression panellists will be familiar with the generic phrases 'more experience' and 'more practice'. Whilst it is undoubtedly true that most trainees will need more exposure to techniques on which they are assessed, stock phrases such as this miss an opportunity to guide learning.

For more impact, trainers should consider the recommendations about simple, measurable, achievable, relevant, and time-bound (SMART) objectives. Ideally, trainees should take responsibility for setting their own SMART objectives, perhaps guided by the supervisor.

Hidden curriculum

Trainees learn from every encounter, even when specific objectives have not been set. This still happens when the trainee is not consciously learning and the educator is not actively teaching.

An important element of workplace-based teaching is socialisation, particularly for those new to a specialty or clinical area. All workplaces have individualised cultural norms, for example, attitudes towards guidelines and protocols, methods of interacting with other members of the healthcare team, or risk tolerance. Much of the process by which new staff acclimatises occurs through a 'hidden curriculum'.

The hidden curriculum describes behaviours and attitudes that are never formally taught or learned, but are nevertheless internalised through observation and experience. These factors are not explicitly communicated to trainees, thus staff (particularly senior clinicians and others in positions of authority) must be mindful to uphold high standards and act as strong role models. Tolerance of poor behaviour can contribute to inter-professional rivalries and conflict. In extreme cases this creates a culture of 'normalised deviance' where risky behaviours become such a usual part of team methods that members no longer notice poor practice.[10]

Trainers should therefore think about the training they deliver both overtly and implicitly. They must also give some thought to how training delivery impacts them personally. Teaching adds to workload, and safe delivery of clinical service remains the priority. In 1908, Yerkes and Dodson conducted an observation of learning effects in mice in varying conditions of stimulation.[11] Learning was poor when the mice were seldom stimulated because of boredom and disengagement.

Table 1 List of workplace-based assessment tools (WPBA). It is important to choose the most appropriate tool for the educational event requiring assessment.

WPBA title	Abbreviation	Representative example(s)
Direct Observation of Procedural Skills	DOPS	Used during clinical sessions; best for assessment of single, well-defined procedure, such as insertion of a spinal anaesthetic, or fibreoptic tracheal intubation; allows the trainer and trainee to focus on one specific aspect of anaesthetic practice
Anaesthesia Clinical Evaluation Exercise	A-CEX	Used during clinical sessions; best for assessment of a single clinical episode, such as caring for a patient undergoing a total knee replacement under a regional anaesthetic; feedback might touch on specific technical skills, but places them more in context, allowing trainer and trainee to take a more holistic view of a case
Anaesthesia List Management Assessment Tool	ALMAT	Used during clinical sessions; best for assessment of the trainee's management of a whole theatre session, so takes a broader view than either DOPS or A-CEX; whilst aspects of clinical care will come in to ALMAT feedback, it is likely the trainer and trainee will focus on the managerial role of the anaesthetist and the logistics of safely maintaining theatre throughput
Multi-Source Feedback	MSF	Used away from clinical sessions; best for assessment of the trainee's teamworking skills, attitudes, and place in the multidisciplinary team; allows the trainer and trainee to reflect on their Johari window
Case-based Discussion	CbD	Used away from clinical sessions; the discussion can be a retrospective review of a case, or a hypothetical presentation; best for the trainer to probe the trainee's decision-making process, judgement, or knowledge around a specific condition; allows the trainer and trainee to reflect on their performance, and to consider alternative strategies

Conversely, at extreme levels of stimulation, the mice were preoccupied and unable to engage. They concluded that optimal performance occurred at middling levels of stimulation. Similar relationships occur in the workplace.[12] However, in this context, there is the added complexity that the trainer, usually the senior clinician present, has simultaneous responsibilities to deliver safe and effective care to the patient. The trainer should ensure that the learning objectives chosen are realistic and achievable given the complexity or expected difficulty of the clinical workload.

The trainer can also be vigilant for unexpected or unusual opportunities for teaching, sometimes known as 'windfall learning'. Whilst there is value in structure and planning of teaching, this should not confine the trainer rigidly, and they should capitalise on situational factors relevant to the trainee. Most obviously, this might occur after a critical incident in the operating theatre where focus might reorientate to recognition and management of the event, but might also draw on organisational or managerial issues in the workplace.

Offering feedback

The primary aim of formative assessment is to facilitate the development of an individual, and in clinical settings can occur almost continuously.[13] This contrasts with summative assessments, such as the FRCA examination, which measure individuals against a set standard, have an important pass/fail aspect, and usually occur as specified events.

Kolb's cycle highlights that in order for individuals to develop they must reflect on an experience and use that reflection to make changes. Two types of reflection can be highlighted: reflection in action and reflection on action.[14] Reflection in action occurs in real time, during the activity in question. Reflection on action occurs later, when thinking back on an activity and its outcome. It is this reflection on action that is most amenable to constructive feedback.

Quality feedback is essential to facilitating the learning process, encouraging the trainees to reflect on aspects of their Johari window.[15] The window is a tool developed by psychologists in 1955 as a method for visualising insight into individuals' behaviours and thoughts. It groups traits as open (known to ourselves and others), hidden (known only to ourselves), and blind spots (things known to others, but hidden from ourselves). A fourth section describes those unconscious biases or motivations unknown to both others and ourselves. Good quality debriefing can encourage reflection and self-appraisal, with the intention of shrinking blind spots.

Feedback can be formal or informal, and structured or unstructured, and the method used will depend on factors such as the topic to be debriefed, the relationship between the trainer and the trainee, and the purpose of the encounter.

Formal feedback is probably most frequently used in the appraisal of skills, either technical or non-technical. Often, this will occur in the context of WPBAs, but feedback can occur in a multitude of other settings around the workplace. Clinical activities offer frequent opportunities for informal feedback, and such feedback contributes to the hidden curriculum by subtly reinforcing or correcting behaviours and attitudes.

It is a hallmark of professionals that they seek feedback and use this to improve practice, and this need not be threatening, even when performance has been poor.[16] Negotiating which behaviours or skills are open to discussion before a period of observation (as part of an educational-WHO) sets 'rules of engagement' and defines limits on topics available for discussion. In essence, one is forming a contract with the learner before starting the encounter, and this is important in establishing safety for the debriefing process.

The more experienced the recipients are, the more insight they are likely to have into their performance, and often the

facilitator's role is to encourage trainees to debrief themselves. For less experienced trainees, the feedback process may be more involved. The educator must be alert to the hierarchy gradient that often exists between the trainer and the trainee, and encourage trainees to contribute to the process wherever possible.

Trainers should also be mindful of where and when they deliver feedback, particularly if it follows a stressful or difficult experience. Although it is usually desirable to offer feedback as close to the event as possible, this may not always be appropriate, such as after particularly traumatic clinical incidents. Whether feedback is delivered one to one or as part of a group needs to be decided. Where groups are present, deciding whether other members of the team are permitted to contribute is important and highly relevant to work in an operating theatre where the actions of the anaesthetist impact on a wide variety of team members. Before embarking on debriefing, the trainers need to consider their agenda and that of the trainee, choosing a limited number of maximum value topics to prevent feedback becoming rambling and poorly focused. Selecting topics in advance allows trainers to maintain relevance and defend against being sidetracked.

Various tools are available for structuring feedback. These can provide mechanisms for exploring how trainees frame clinical situations and allow instructors to understand their reasoning. This is important because their frame of reference may differ from that of the observer. Should the trainer disagree with a trainee's course of action, it is particularly important to understand why decisions made sense to the trainee at the time. Professionals will seldom seek to deliberately make errors, thus it is risky for the trainer to make assumptions about why the trainee acted a certain way—this can be perceived as judgemental. It is much more appropriate to explore decision-making processes with the trainees, questioning and probing their thoughts whilst allowing them to verbalise their reasoning.

Some examples of feedback tools and their advantages and disadvantages are presented as follows. There is no single best method of offering feedback, but it is essential in all methods that trainee involvement is maximised, and that feedback remains non-judgemental and open.

(i) Advocacy enquiry: This involves the trainer making an objective statement about observed events (advocacy) and asking the trainees to elaborate on their thought processes at the time (inquiry). By making a factual statement about observations and by asking the trainees to describe their internal processes, it offers an opportunity to explore the trainees' mental models. This technique is often incorporated into other debriefing strategies, including debriefing with good judgement and debriefing as a learning conversation.[16,17] These techniques are flexible and non-judgemental, but have been criticised for being overly instructor focused.[18]

(ii) Pendleton's rules: Using this technique (or the similar 'sandwich technique'), the instructor and trainee comment on a positive aspect of their performance, followed by a weaker area, finishing on a positive.[19] This method is straightforward, but criticised for being inflexible, and can be artificial particularly when faced with debriefing a very strong or very weak performance.

(iii) SET-GO: This is a structured debriefing system, based on asking what the trainees saw, what else they encountered, what they thought, what their goals are, and what they offer to achieve the goals.[20] This can work well but, as with Pendleton's rules, an intention to stick to a prescribed format can be restrictive.

(iv) Chicago model: This six-step method involves (a) review of the trainee's objectives, (b) interim feedback from the instructor, (c) self-assessment by the trainee, (d) behaviourally focused feedback with (e) specific examples, and (f) specific strategies for improvement.[21] Steps (d) and (e) incorporate aspects of advocacy inquiry, meaning this can also be used to access the trainee's thought processes. The more complex format of the feedback can be a little cumbersome.

Whichever model is chosen, it is crucial that the trainer maintains credibility. At a very basic level, this means honesty and fairness. If a performance was exemplary, there is little to be gained by nitpicking out of some sense that there must always be an opportunity for development. Similarly, if a performance was very poor, then it is usually better to acknowledge this early and examine it promptly in the debriefing, rather than artificially extracting what few positives there might be. Professionals generally have insight, and ignoring 'elephants in the room' dents the credibility of the debriefer, distracts the learners as they wait for the 'other shoe to drop', and contributes little or nothing to the quality of the educational experience.

Conclusions

It need not be complicated to maximise value from educational encounters, but spending time on planning an activity will make the event more efficient. By performing a short educational-WHO at the start of an operating list to specify learning outcomes can help focus the trainer and the trainee, set ground rules, and simplify the delivery of feedback. This can also improve the impact of WPBAs.

Consideration of the different learning styles and preferences of trainees in the operating theatre during a unit of training or a period of educational supervision can help broaden the appeal of teaching, and thus, ensure maximum engagement.

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Declaration of interest

PG teaches on the Royal College of Anaesthetists 'Teaching and Training in the Workplace' and 'Anaesthetic Non-technical Skills' courses.

MCQs

The associated MCQs (to support CME/CPD activity) will be accessible at www.bjaed.org/cme/home by subscribers to *BJA Education*.

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Original Article

Mapping sources of noise in an intensive care unit

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Summary

Excessive noise in hospitals adversely affects patients' sleep and recovery, causes stress and fatigue in staff and hampers communication. The World Health Organization suggests sound levels should be limited to 35 decibels. This is probably unachievable in intensive care units, but some reduction from current levels should be possible. A preliminary step would be to identify principal sources of noise. As part of a larger project investigating techniques to reduce environmental noise, we installed a microphone array system in one with four beds in an adult general intensive care unit. This continuously measured locations and sound pressure levels of noise sources. This report summarises results recorded over one year. Data were collected between 7 April 2017 and 16 April 2018 inclusive. Data for a whole day were available for 248 days. The sound location system revealed that the majority of loud sounds originated from extremely limited areas, very close to patients' ears. This proximity maximises the adverse effects of high environmental noise levels for patients. Some of this was likely to be appropriate communication between the patient, their caring staff and visitors. However, a significant proportion of loud sounds may originate from equipment alarms which are sited at the bedside. A redesign of the intensive care unit environment to move alarm sounds away from the bed-side might significantly reduce the environmental noise burden to patients.

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Introduction

Excessive ambient noise in hospitals adversely affects patients' sleep and recovery, causes stress and fatigue in staff and hampers communication. In critical care areas, disruption of patients' sleep patterns may contribute to the development of delirium [1, 2]. Patients who experience delirium in hospital may have longer hospital stay and ongoing cognitive impairment after discharge home [3].

The US Environmental Protection Agency (USEPA) suggests sound pressure levels in hospitals should be limited to 45 decibel (dB)-equivalent continuous sound level (LAeq) during the day, and 35 dB at night [4]. The World Health Organization (WHO) advises sound pressure levels in hospitals should not exceed 35 dB [5]. For neonatal intensive care units (ICUs), an upper limit of 45 dB is recommended [6], with limits on transient loud sounds [7, 8].

In a previous study of environmental noise in five general adult ICUs in the Thames Valley region of the UK, average sound pressure levels always exceeded 45 dB, and for 50% of the time exceeded 52–59 dB in individual units [9]. Although the WHO and US EPA guidelines are probably unachievable in any acute care area of a hospital, some reduction from these high levels should be possible. A preliminary step would be to identify the location and sources of noise.

As part of a project investigating initiatives to reduce noise in a single ICU, we installed a microphone array system in a single bay containing four beds in an adult general ICU.

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This continuously recorded the location, sound pressure levels and weighted 'loudness' values of environmental sound. This study summarises the results over one year.

Noise is usually described as 'unwanted sound'. In this article, we refer to 'sound' as raw, objective values (reported as sound pressure levels, measured in decibels); 'noise' signifies a subjective response. Features of sound, such as volume, frequency (Hertz), duration and time of occurrence are likely to affect subjective impression of sound. 'Loudness' is a weighted value (also measured in decibels) that allows the subjective perception of sound to be described and quantified.

Methods

This study focussed on environmental monitoring and did not involve patient recruitment or the use of any identifiable information. The system recorded sound pressure levels only; no audio recordings were made. The local ethics policy does not require formal review/approval for studies based on environmental data as they contain no identifiable information that can be traced back to individuals.

We used a four-bed bay in the general ICU at the John Radcliffe Hospital in Oxford (UK) for the study. In addition to beds and associated equipment, the bay contained equipment racks, trolleys and a built-in counter (nursing station) that housed two telephones and a computer. Two individual patient rooms opened into the bay on one side.

The bay was of standard construction, with painted plasterboard walls, fitted vinyl flooring and a ceiling of suspended perforated fibro-cement tiles. One wall had large windows and a fire exit.

In October 2016, we installed a sound monitoring system into the ceiling of this bay. This consisted of four arrays of 16 microphones that used beam forming technology to measure horizontal locations and sound pressure levels of the five loudest sounds above 35 dB for each time-point. The system had a temporal resolution of between 2 s and 4 s, depending on the computational processing burden. The sound pressure levels and location of the five loudest sounds above 35 dB were logged for each time-point. The absolute values of sound pressure levels were then weighted to calculate 'loudness' (the loudness value being the subjective perception of sound). These weighted values were calculated using the Zwicker method, which forms the basis of the ISO standard method for calculating loudness (ISO 532-1: 2017) [10]. The details of the system have been reported elsewhere [11]. The area monitored was 14.1 × 12.7 m.

Data for this study were collected from 7 April 2017 to 16 April 2018 inclusive. Data for a whole day were available for 248 days out of the total 381 days. Data were analysed using MATLAB R2018a (MathWorks, MA, USA).

The decibel level and location data for the entire period were summarised by counting the number of times one of the five loudest sounds originated from each location in the bay, and by averaging the loudness. The resolution of the location in both X and Y axes was approximately one cm. The count and average loudness data were indicated using colour, and plotted on a heat map overlaying a floor plan of the bay.

Temporal changes in loud sounds were summarised by similar plots of counts for one h corresponding to the loudest (19h00–19h59) and quietest (04h00–04h59) one-h periods identified in the earlier study [9].

The sound level monitoring system was installed as part of a range of measures to make the ICU quieter. One element of this was the development of a wall-mounted display with the capacity to show the location and volume of sound sources to ICU staff in real time. Staff were involved in the design of this, and were shown the screen interface for short periods of time to allow them to evaluate and comment upon the utility of the data displayed. Their feedback guided design and feature iteration. The display did not run in real time during the project outside of these evaluation sessions. Frames captured from one of the display prototypes were combined to produce a time-lapse video to show the variability in sound sources and loudness over an hour.

Results

The system recorded 248 complete days of data out of a total 381 days between 7 April 2017 and 16 April 2018 inclusive. Missing days were when the system was inactive for technical development or repairs. In all, there were 12,245,708 data triplets (X position, Y position, sound pressure level) included in the analysis dataset.

During the study period, occupancies for beds A3–A6 were 85.8%, 85.7%, 87.6% and 74.6%, respectively, with an average of 83.4%. The median (IQR [range]) length of stay was 3.1 (1.7–6.6 [0.0–66.8]) days. The number of staff members in the bay was determined by the number of patients and their care requirements, and so varied during the study. The handover periods for the nursing staff were constant (07h30–08h00 and 19h30–20h00) during the study. Ward round times and durations varied with the overall number of patients in the ICU.

Figure 1 shows the frequency with which one of the five loudest noises in any 2–3-s epoch occurred in each 1 cm^2 of the monitored area. 'Hotter' colours (reds and yellows) indicate areas where loud noises were more frequent. The

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heat map was superimposed on a floor plan of the ICU bay. The uppermost wall in the graphic contained the windows and fire exit and faced southeast. This graphic can be interpreted as an average 'noisiness' map for the bay.

The beds were labelled A3–A6. In all bed spaces, the physiological monitors were mounted on the patients' right, level with or slightly behind their heads. The ventilators were positioned in front of the monitors. Beds A3, A4 and A5 had a clear area of high sound level corresponding to the monitor/ventilator position. This was less clear for A6, the least occupied bed during the study period. The area of loud noise indicated by '1' was outside the door of the side room that was preferentially used, as it had the best natural light. Area '2' was at the nursing station where the telephones were situated. The horizontal and vertical lines are artefacts of the computational methods.

Figure 2 shows the averaged loudness value of the five loudest sounds above 35 dB in any 2–4-s epoch that occurred in each 1 cm^2 of the monitored area. 'Hotter' colours (reds and yellows) indicate the areas with higher averaged loudness. The plot does not contain any information on the number of loud sounds in any one area. This graphic can be interpreted as showing how loud, on average, noises were that originated from each 1 cm^2 of the monitored area. Louder noises originated from room peripheries and were generally centred on the head area of bed spaces. Noise originating from the centre of the room was on average less loud.

Figure 3 shows a heat map of the frequency with which one of the five loudest sounds above 35 dB originated from each 1 cm^2 of the ICU bay between 19h00 and 20h00. Counts were considerably lower than in Fig. 1, as this plot only represents about 1/24th of the data in Fig. 1.

Figure 4 shows a similar heat map for 04h00–05h00.

The additional file (see also Supporting Information, Video S1) shows the locations of the five loudest sources of noise above 35 dB repeatedly superimposed on the floorplan of the ICU to form a time-lapse movie. The movie represents the period from 09h30 to 10h30 on a weekday in spring 2017. The loudness was encoded as the diameter of a red circle centred on the location of the noise source. Data from the two previous epochs are indicated by successively paler circles. The pale grey circle on the floor plan indicates where the bay co-ordinating meeting commonly occurred, and where clinical teams tended to congregate when reviewing patients in the side rooms and bed A3. From about 09h30–09h40 high noise levels from closely spaced locations (likely speech) were visible in this area. Transient noises adjacent to beds were most likely to be equipment-generated, for example, alarms from physiological

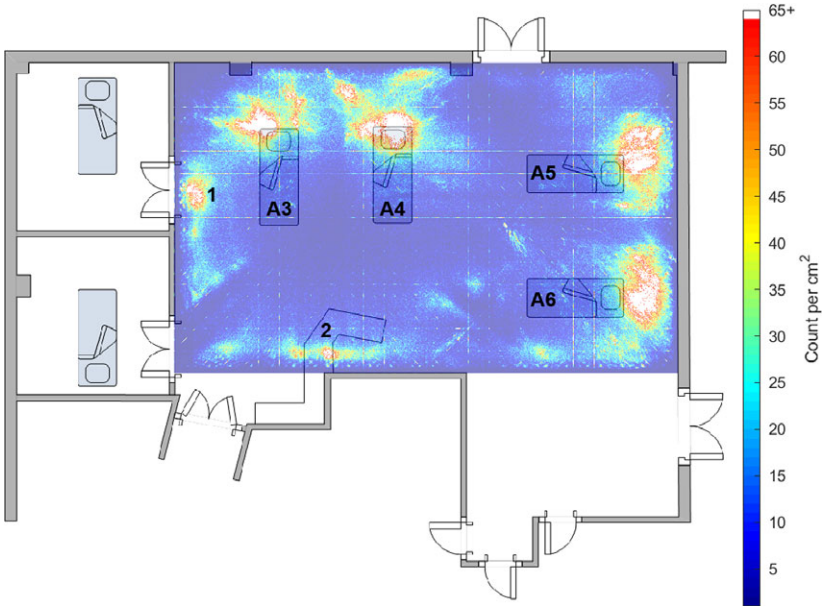


Figure 1 A heat map of the frequency with which one of the five loudest noises above 35 dB originated from each 1 cm^2 of the intensive care unit bay for the 249-day study period, superimposed on a floor plan of the bay. The position and identifier for each of the four beds in the bay is shown, as well as the work bench position. The area of noise marked '1' is outside the side room that was preferentially used, and shows where conversations between staff about the patient in the side room commonly took place. The areas of noise marked '2' correspond to the positions of the telephones. This can be interpreted as a map of the 'noisiness' of areas of the bay. The grid lines are an artefact of the computational methods.

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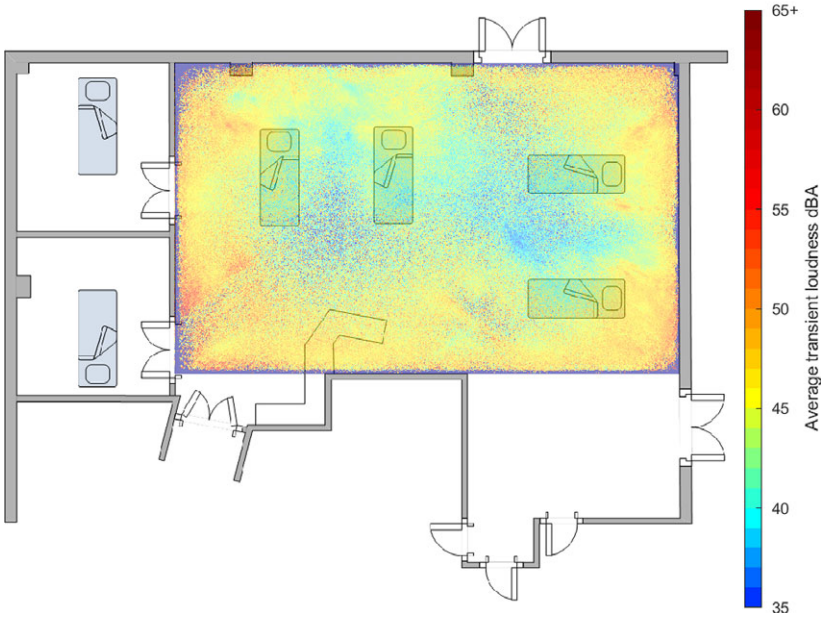


Figure 2 A heat map of the average loudness of noises above 35 dB originated from each 1 cm^2 of the intensive care unit bay for the 249-day study period, superimposed on a floor plan of the bay. The position and identifier for each of the four beds and the work bench in the bay is shown.

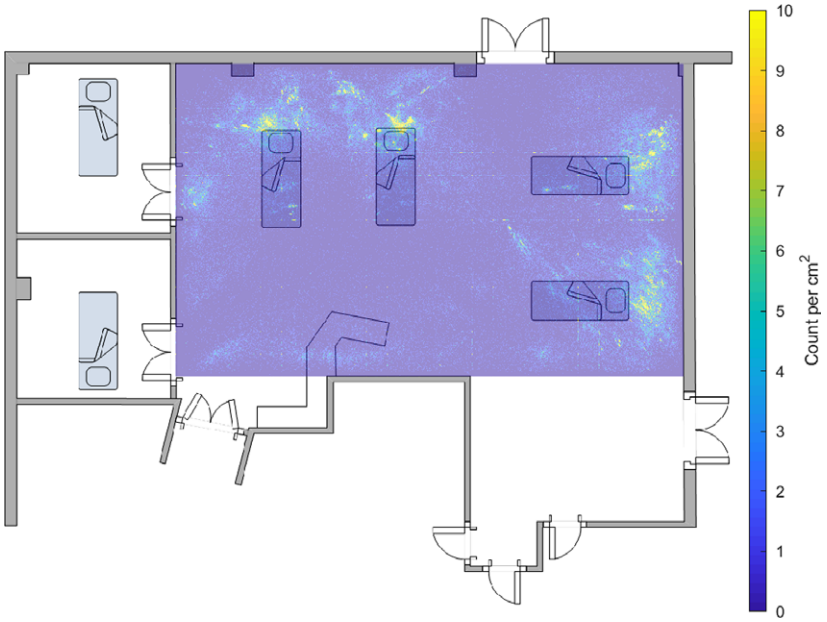


Figure 3 A heat map of the frequency with which one of the five loudest noises above 35 dB originated from each 1 cm^2 of the intensive care unit bay between 19h00 and 20h00 for the 249-day study period, superimposed on a floor plan of the bay. The position of each of the four beds in the bay is shown, as well as the work bench position. The grid lines are an artefact of the computational methods. The counts are considerably lower than in Fig. 1, as this plot only represents 1/24th of the data in Fig. 1.

monitors, ventilators and infusion pumps. Some frames (e.g. in the last second of the movie) had fewer than five noise sources above 35 dB.

The system recorded the raw sound pressure levels, loudness values, frequency spectrum and location of sounds, and could not be used to determine the originating

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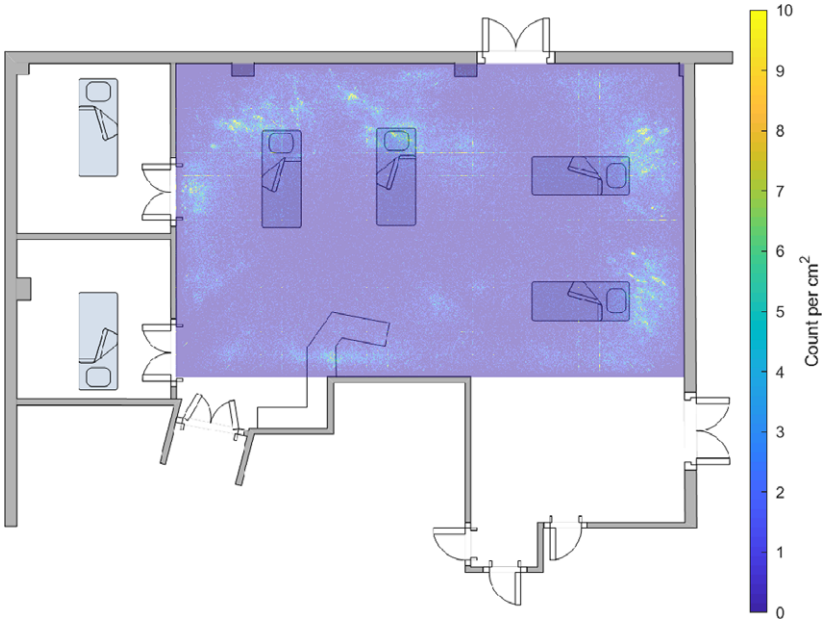


Figure 4 A heat map of the frequency with which one of the five loudest noises above 35 dB originated from each 1 cm^2 of the intensive care unit bay between 04h00 and 05h00 for the 249-day study period, superimposed on a floor plan of the bay. The position of each of the four beds in the bay is shown, as well as the work bench position.

source of the sounds directly. A machine learning approach was used to try to separate the sounds into classes (e.g. 'alarms', 'speech' or 'other'), but did not achieve reliable identification. However, an earlier phase of our project included an ethnographic study conducted between November 2014 and July 2015 [12]. This indicated that noise from equipment was pervasive. The volume of equipment-related noise was consistently high, and activity around patient bed spaces often led to alarms triggering, which were not silenced until patient care activity was concluded.

Discussion

Hospital noise is increasing. A systematic review suggested that the A-weighted SPL (corrected for the human hearing range) is increasing by 0.26 dB annually, and levels are such that both speech comprehension and communication are compromised [13].

The novel and striking result from this study was that most high levels of noise originated from extremely limited areas. Some of these areas were where staff conversations commonly occured, such as the nursing station or the area where daily group discussions take place. However, it is clear that the majority of loud sounds originated very close to patients. Some of this would have been appropriate communications between the patient, their caring staff and visitors. However, there was a clear indication that much loud sound originated from physiological monitors and ventilators, sited near patients' ears. These devices generated very little sound, except when alarms were activated. Alarms were loud (> 50 dB) and within a frequency range that humans find disturbing. Alarms of all kinds by design have sound characteristics that activate human sensitivities. The frequency range of the patient monitor alarms in the ICU (2.5–3.15 kHz) is similar to both a human scream and a baby's cry. Although this may be ideal for attracting the attention of staff members, it is far from ideal for patient rest and comfort.

The alarms on the physiological monitors default to standard volume settings on power-up, and could be adjusted as required by the nursing staff. In practice this rarely occurred. Similarly, although it was possible to adjust the volume settings for ventilator and infusion pump alarms, these were not adjusted routinely. By default, the ventilator alarms increased in volume with increased urgency.

As reported elsewhere [12, 14], our project utilised the AEBCD method [15] to design and deliver a number of interventions to reduce noise levels in the ICU. Briefly, these included soft-close plastic-lidded bins, better day/night differentiation, and alarm management guidelines that recommended 'personalising' alarm parameters and adjusting volume according to the wider environmental sound level. We also created a training package that delivered an online module and an experiential simulation

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session, giving staff members a 'patient experience' of the ICU. Interim results of this phase of our project indicated reduced SPL in the ICU by approximately 4 dB after four months (measured April 2016), suggesting that some knowledge transfer occurred as a result of the relatively simple intervention programme. Despite this, and the apparent sustained reduction in overall SPL, noise levels in close proximity to the patients remained high.

In the early hours of the morning, when patients should have been sleeping, the staff tried to keep disturbances to a minimum. However, in spite of the fact that the bay seemed quieter, and previous environmental monitoring reported average sound pressure levels reached a nadir at this time, Figs. 3 and 4 suggest the number of transient high-level noises were similar in the early evening and early morning. If average sound levels decreased but the number of loud transient noises remained comparable, the reduction in disturbance to patients may have been less than the change in average SPL suggests.

Intensive care units are particularly noisy areas of hospitals [1]. Neonatal units have average sound pressure levels of 48–61 dB for up to 95% of the time [16–19], paediatric units average 53–73 dB [20–24] and adult units are 53–59 dB [25–29]. The unit at the John Radcliffe Hospital when measured in 2012 had daytime averages of 58 dB at the desk and 60 dB adjacent to the patient [9]. There seems to be considerable concordance between average sound pressure levels recorded in ICUs in different healthcare systems, and across levels measured in the wider hospital [13].

Excessive noise in ICUs disrupts patients' sleep [1, 27, 30], increases sleep medication use [2], sedation use [24] and the incidence of delirium [2]. Ambient sound markedly reduces the intelligibility of speech in acute care areas [13], which can contribute to avoidable errors in care. To be intelligible, speech needs to be about 15 dB above ambient sound pressure levels. Conversations, therefore, increase sound pressure levels which aggravates the problem (Lombard effect [31]). High ambient sound levels also have a range of deleterious
non-auditory health effects on staff [32].

Acute care areas in hospitals rely heavily on alarms and pagers to signal urgent situations. It is, therefore, unsurprising that observational studies on ICUs identify these as major disruptive noise sources. Nearly 80% of disruptive noises are generated by monitor or ventilator alarms and speech [33, 34]. However, a significant proportion of the noise coming from speech is not required for patient care [1, 2], and almost 90% of alarms from physiological monitors are 'false positives', with no patient benefit [35].

The standard measure of environmental noise, the average daily sound pressure levels value (LAeq24), is insufficiently detailed to enable targeted noise-reduction interventions in an ICU. This may be one of the reasons why the majority of sound reduction studies conducted in ICUs have not resulted in significant change [36–38]. This study was designed to identify spatial positioning of sound sources within an ICU. This would enable interventions to be focussed on areas of high noise levels, which might lead to meaningful reduction in overall (averaged) sound levels.

Sound pressure levels increase logarithmically with proximity to the source of the noise. There is no reason for alarms from physiological monitors, ventilators or any other piece of equipment to be generated next to a patient. The primary function of alarms is to alert staff to a possible clinical problem. Arguably, there is no reason why patients need to hear these alarms at all. Hearing alarms may cause patients distress or contribute to disorientation [39]. With modern digital electronics and wireless networks, an ICU free from intrusive alarms is possible, although there are considerable commercial, regulatory and safety hurdles to overcome before this can be achieved [40]. In addition, changing a technology that has been in use for decades requires careful planning and detailed assessment of working patterns that may have evolved alongside the technology [41]. During the early phase of this project, the use of body-worn haptic alerts linked to monitoring equipment was suggested as an alternative to acoustic alarms. The nurses felt this approach would remove the multiple layers of redundancy that an alarm heard by all staff added to their practice, and would not consider this technological adaptation. Although they acknowledged the distress that alarms might cause, patients also expressed concern that urgent clinical situations might go unattended if this form of technology were adopted.

At the very least, conversations not directly involving patients or their visitors should occur away from the bed-side, and ideally outside the unit, if possible. A body-worn electronic communicator has been successfully trialled in an ICU in the USA [13], although the major gain was a reduction in overhead paging calls, which are not used routinely in the UK.

The sound location system revealed that the majority of noise in this four-bed ICU bay was generated immediately adjacent to patients' ears. This proximity maximised the adverse effects of high environmental noise, levels for patients. Paying attention to the locations of significant high noise, as well as the overall sound level, might improve both the patient experience of their ICU admission, and the general working environment for staff.

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The sound location system deployed for this study was both complex and expensive, and required minor building works to install. Although it would be ideal to repeat this work in other ICUs to test generalisability, this might not be practical. However, a simplified version of the system with single microphones near patients' heads at each bed space would be quite feasible. This would enable unit-wide evaluation of noise levels as experienced by individual patients.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Video S1. Video of noise source location.

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Noise in the intensive care unit: where does it come from and what can you do about it?

Practical measures and interventions to reduce noise levels in the ICU and to improve the patient experience.

The intensive care unit (ICU) is known to be noisy and is getting louder (Busch-Vishniac et al. 2007). Despite several trials, no interventions have been able to reduce noise levels by a meaningful amount (Li et al. 2011; Boyko et al. 2017; Johansson et al. 2017). There tends to be a view that high noise levels are to be expected in the ICU due to the level of care being delivered, and that little can be done to change this (Litton 2019). However, our recent study (SILENCE: NIHR Research for Patient Benefit ref: PB-PG-0613-31034) suggests that sound levels can be lowered if staff can be encouraged to think differently about the problem and given the opportunity to be involved in designing interventions to reduce noise levels.

We used a mixed methods approach (Cresswell 2014) to assess the ICU environment. This involved qualitative analysis of both patient and staff experiences, and quantitative measurement of the ICU soundscape. Patients consistently reported that they were frequently disturbed, unable to sleep, frightened by the unfamiliar surroundings, and, after discharge, they struggled to reconcile their memories with reports of what had happened to them (Darbyshire et al. 2016). Ethnographic observations identified that the environment is somewhat chaotic, and generally organised for the convenience of staff. Nurses strived to deliver care efficiently, but it was apparent that there were discrepancies between 'work as imagined' (staff perception of working practice) and 'work as done' (the realities in the workplace) (Hollnagel 2016).

We also noticed that these frequent patient interactions contributed to noise and disturbance over and above the sounds directly associated with the task. Alarms, frequently triggered by the staff intervention, were left to run until care activities were completed. This behaviour contrasted with staff reports that they always silenced alarms immediately. It was clearly considered 'normal' to allow alarms in these circumstances. Acceptance of practice that would be considered inappropriate in other settings is an example of 'normalised deviance,' a term coined by Diane Vaughan in relation to the NASA Challenger disaster (Price and Williams 2018). When deviance occurs, it is common for actions and behaviours to be defended as necessary and justified. In this case, it might be that the patient needs to be rolled and the alarm is triggered due to physical movement rather than physiological abnormality. Staff therefore correctly recognised that these alerts were false-alarms, but did not obviously consider their contribution to local noise pollution, or the potential effects of this on patients.

> "almost 90% of alarms are unnecessary; staff (perhaps understandably) employ the precautionary principle and are reluctant to alter alarm volumes or patterns"

Mismatches between staff perception and reality are particularly important when thinking about culture change because if interventions focus on 'work as imagined,' the realities of 'work as done' are not addressed. Equally, addressing work as done without overt reference to how this differs from 'work as imagined' is likely to have limited effect as staff may not recognise the need for change.

Quantitative measurement of overall Sound Pressure Levels (SPL) was revealing, and supported the qualitative reports generated from patient interviews. It demonstrated SPL levels persistently higher than the World Health Organization (WHO) recommendations, with peak values frequently measured over 100dB (Darbyshire and Young 2013). Patterns were observed in the data. Handover periods were consistently one of the louder periods of a shift, and it was obviously quieter overnight, although still well above WHO guideline levels. We also found that simple environmental modifications can facilitate noise reduction strategies. We saw a number of "solutions" to noise problems; for example, wadding placed in a doorway to prevent the door slamming because the soft-close mechanism was broken and the lifting of trolleys in motion to prevent the sound of a squeaky wheel. We particularly noticed that nightshifts were quieter when lights were off except to facilitate care interventions. Darkness, therefore, seemed to be an indicator to staff that patients should be sleeping and that general activity levels should be low. We also noticed that whilst it seemed to be common to turn overhead lights out overnight for patients who were

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not sedated, they were often left on above-sedated patients, thus contributing to the disruption of the circadian regulatory system (Bedrosian and Nelson 2017).

After compiling noise data and the qualitative results, an intervention strategy was designed using the principles of experience-based co-design [EBCD] (Locock et al. 2014). Simple solutions such as replacing broken metal bins with soft-close-lid plastic versions removed a key source of noise. The research group also liaised with local staff to write alarm management guidelines, incorporating individualised alerting parameters and suggesting that volume levels should be guided by changing ambient sound levels rather than simply being set to the maximum throughout the shift. We highlighted the lighting effect on night time noise to encourage better day/night differentiation and recommended that switching off main unit lights should become part of policy (Darbyshire and Hinton 2018). Finally, the research team engaged with a medical educationalist to design a teaching module comprising an e-learning package and a simulation exercise (Darbyshire et al. 2018). The experiential aspect of the immersive simulation contextualises the need to reduce noise levels in the ICU, as staff members are given the opportunity to experience the ICU from the patient's point of view. The course evaluation indicated this teaching is overwhelmingly effective at recreating the feelings reported by real ICU patients. The session could be stopped at any time by the participant, although none did so. After just a few minutes, staff reported feeling uncomfortable, confused, stressed, frightened, and alone; feelings which map closely to how patients describe their time in the ICU. In line with adult education theory (Kolb and Fry 1975), participants were encouraged to reflect on their experience and relate it to their patients who have no control over their situation, and who cannot take 'time out.'

One aspect of the simulation experience was to demonstrate the patient experience of alarms. As staff were healthy volunteers, the monitors were manipulated to sound an alarm tone while the participant was connected to it. This unexpected alarm was intended to simulate the concern that patients spoke about when they heard alarms. The disturbance caused by a noise such as an alarm is more than a simple function of volume. The intrusiveness of noise is dependent on its frequency. By design, alarms have similar sound qualities to a baby's cry or a human scream, representing primal triggers of attention in most humans. They are intended to be disturbing so that they attract attention. In open plan ICUs, this means that every alarm can be attended to by any member of staff. It also means that every alarm is heard by every patient. Even where patients are admitted to single rooms, they will be repeatedly disturbed by their own alarms.

> **"meaningful change is more likely with a wider understanding of the types of noise that are likely to be most disturbing, and better awareness of the consequences for patients of this constant disturbance"**

'Loudness' is a measure of sound that allows the subjective perception of the sound to be quantified (ISO 2017). Sounds of a higher pitch, such as alarms, are more likely to be disturbing. In our study, loudness levels showed a clear reduction of about 4dB between 1am – 4am, although this marked dip is not seen in the average decibel level which remains fairly constant (Darbyshire et al. 2019). This suggests that there were fewer alarm sounds during this period.

Implementing alarm management guidelines was challenging. While it has been reported that almost 90% of alarms are unnecessary (Gorges et al. 2009), staff (perhaps understandably) employ the precautionary principle (UN 1992) and are reluctant to alter alarm volumes or patterns. From a psychological perspective, however, this is an overly simplistic approach as auditory and visual distractors have a measurable impact on task performance (Simons 2000; Bressan and Pizzighello 2008; Molloy et al. 2015), and alarm fatigue is a well-recognised source of risk (Ross 2015; ECRI Institute 2011). Improvements then can be achieved in both patient comfort and safety through better understanding and use of alarms. Specifically, meaningful change is more likely with a wider understanding of the types of noise that are likely to be most disturbing, and better awareness of the consequences for patients of this constant disturbance.

SPL in Oxford were reduced by approximately 4dB in the four months after environmental changes were introduced, and after initial delivery of the teaching sessions.

Table 1. World Health Organization noise level recommendations

- Average patient room noise should remain at 30dB
- Below 30dB, no effects on sleep are observed except for a minor increase in the frequency of body movements.
- Below 40 dB, no evidence was found that the biological effects on patients was harmful to health.
- Noise level above 40 dB resulted in sleep disturbance, environmental insomnia, and increased use of somnifacient drugs and sedatives. Vulnerable groups may be more affected.
- Noise level above 55 dB is considered dangerous for patient health. Patients may be annoyed due to lack of proper sleep and the risk of cardiovascular disease may also increase.

Source: Night noise guidelines for Europe (2009). World Health Organization

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The final phase of the SILENCE project was to design a system to report sound levels and feed this back in real time. The research team consulted with clinical staff throughout this development period. By the end of the SILENCE project, SPL had reduced a further 7dB to ~46dB (Young et al. 2018). This drop of 11dB is a significant change, that is easily noticeable in the environment.

A recent meta-analysis of interventions limiting patient exposure to noise and disturbance through the use of earplugs and eye masks has been shown to reduce the risk of delirium (Litton et al. 2016). It is highly likely that ambient noise levels also have a significant environmental effect on sleep. SILENCE and other similar studies have consistently reported the difficulties with measuring the duration/quality of sleep in the ICU (Jeffs and Darbyshire 2017; Bourne et al. 2007; Beecroft et al. 2008; van der Kooi et al. 2012). Better measures of sleep are therefore needed for routine clinical use if we are to be able to measure the effects of changing noise levels more accurately. Future research will need to focus on patient-oriented outcomes such as sleep and delirium, and their correlation with measures of sound.

We speculate that 'making a lot of noise about SILENCE' (without explicitly dictating behavioural change), may have contributed indirectly to the local improvements in loudness and SPL, essentially by activating what is commonly termed the "Hawthorne Effect." Encouraging staff to be directly involved with practical measures to improve the patient experience of ICU having been through a visceral experience of their own (thus having a personal understanding of the problem of noise in the ICU) seems to have been the key driver for change. In conclusion, mixed methods enable richer interpretation and deeper understanding than is possible through quantitative or qualitative methods alone. Focusing on patient experiences and including those working in the environment to help design change seems key to achieving significant success. ■

"auditory and visual distractors have a measurable impact on task performance, and alarm fatigue is a well-recognised source of risk"

Key points

- Sound levels in the intensive care unit can be reduced
- It is important to consider the quality of the sound as well as the volume
- Including patients and care delivery staff in the development of interventions changes group dynamic and improves engagement
- Immersive, experiential simulation teaching is a powerful learning tool
- Educational interventions need to align with adult educational theory

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Noises in the Intensive Care Unit: What goes bump in the night?

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3 Health Experiences Research Group, University of Oxford

Background: The World Health Organisation (WHO) recommends average hospital sound levels should not exceed 35dB with a maximum of 40dB overnight[1]. The reality is that noise levels in ICUs are about as loud as the dining room of a busy restaurant[2]. This high background noise is likely to contribute to abnormal sleep and increase the incidence of ICU-acquired delirium[3]. Patients who suffer from delirium in hospital have longer stays and more health problems after they return home[4].

Aim: As a precursor to developing a practical complex intervention it was important to understand what were the main sources of noise in the intensive care unit, and which might be modifiable.

Methods: Two qualitative researchers independently conducted observations in four intensive care units (ICUs) in the Oxford University Hospital NHS Trust. Observation sessions lasted from two to twelve hours and were completed during the day and overnight, both during the week and at weekends. Using a structured form, with space for free text, observers noted types of sound (alarm, device, environmental, or staff, patient, or visitor generated), duration of sound, and how much (if at all) patients and staff seemed affected. Using the method of constant comparison data collection continued until thematic saturation was reached. Sound pressure levels (SPL) were recorded using portable sound level monitors which were calibrated before and after use. Independently, competent adult intensive care patients and their nurses were invited to complete a visual analogue scale of significant disturbances identified in other studies as likely to affect sleep in the ICU (figure 1). Nurses completed these twice each day, patients only in the morning (assessing the previous night).

Results

Observations: A total of 35 hours of observations were completed in the two general adult ICUs with shorter comparison sessions in the neo-natal unit (six hours) and adult neuro-ICU (three hours). Activity, particularly at staff handover periods and when preparing patients for transfer, and alarms were identified as the primary sources of noise disturbance. Several occurrences of 'alarm blindness' were witnessed. Supportive infrastructure in the neo-natal unit has been introduced as a response to the potentially damaging effects of noise. Illuminated signs are in use and privacy screens encourage foot traffic away from the patient cots. Neonatal staff demonstrated increased awareness of maintaining a calming environment, such as speaking quietly and holding clinical discussions away from the bed spaces.

Where lighting levels were higher overnight it was also noticeably louder. Most visitors were quiet but some seemed to have poor health literacy and were disruptive. Staff chat was predominantly focused on patient care but not exclusively. Colleagues who were also friends were observed to silence alarms for patients other than their own.

Sleep disturbances identified by both patients and their nurses have been ranked and compared (table 1).

Bleeps and handovers were more disturbing for patients than their nurses realised. Analysis also indicated good correlation between patient reported and nurse assessed disturbance caused by alarms ($\varrho = 0.639$).

Neither patients nor staff considered visitors a disturbance.

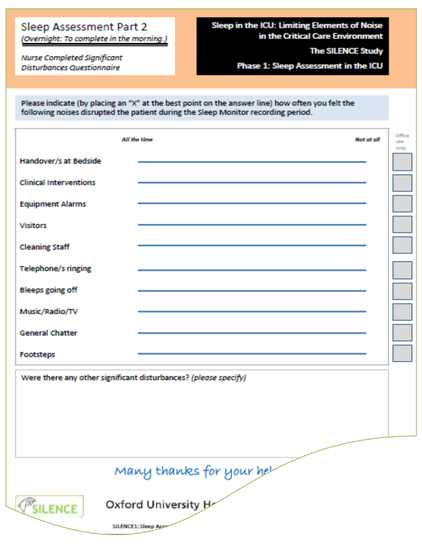


Figure 1: Sleep Disturbances questionnaire

Table 1: Sleep Disturbances ranking

Disturbance	Patient (n=9)	Nurse (n=23)
Alarms	1	3
Interventions	2	1
Bleeps/Pagers	3	6
Handover	4	8
Chatter	5	2
Telephones	6	4
Footsteps	7	5
Cleaners	8	7
Visitors	9	9
Music/Radio/TV	10	10

Sound Pressure Levels: Concurrent SPL monitoring confirmed that average daily levels in all units are much higher than the WHO recommended limit of 30dB. A total of 68 days of sound pressure levels were recorded between April and August 2015. No unit recorded a 24hour average value less than 55dB. All peak values were >100dB, the highest being 124.8dB at the John Radcliffe adult ICU (figures 2, 3, and 4).

Subjective reflection on the environmental noise levels at times contradicted the objective SPL measure.

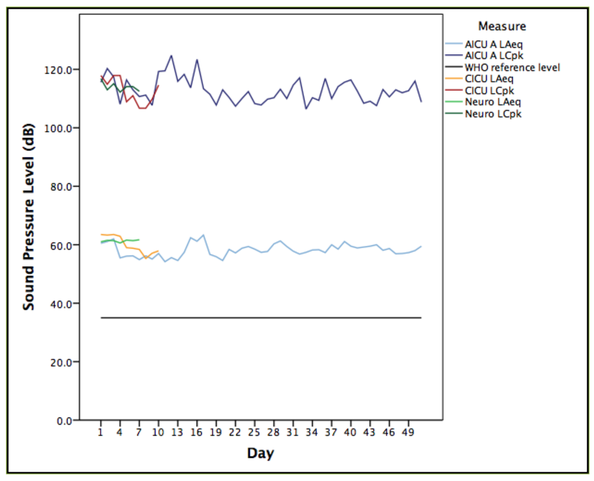


Figure 2: Sound Pressure Levels recorded in the OUH NHS Trust adult intensive care units

JR Adult ICU: 51 days*
19th April – 22nd August

Neurosciences ICU: 7 days
28th May – 2nd June

Churchill ICU: 10 days*
16th May – 13th July

* Non consecutive

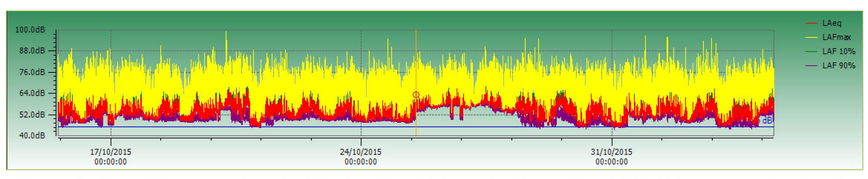


Figure 3: Sound Pressure Levels 15th October 2015 to 4th November 2015 (20 consecutive days)

LAeq: 56.3dBA

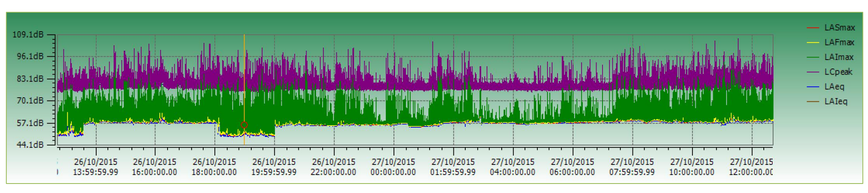


Figure 4: 24 hour Sound Pressure Levels 26th to 27th October 2015

LAeq: 60.1dBA

LC peak: 107.0dBA

Conclusions: Noise levels in the ICU remain elevated. Much of the peak noise is generated from alarms which are not silenced, thus raising the overall average, and general activity. Alerting signs raise awareness of noise, but do not achieve a lower SPL. Following the Accelerated Experience-based Co-design (AEBCD) framework[5], post-observation discussion with staff and patients has led to the development of an alarms management policy and the introduction of simple environmental changes such as switching metal bins for plastic and changing the tone of the phones and doorbell. We are also developing new teaching materials designed to raise awareness of the effects of noise and disturbances, especially overnight. Additional suggestions for future work included re-assessment of night-time illumination practices, integrated alarm systems, noise cancellation, and concentrated care areas.

Both nurses and patients recognise alarms as a major source of disturbance. Nurses underestimate the disturbance to patients from handovers but overestimate disturbance caused by general chatter in the unit.

The principles behind the AEBCD method were strongly supported by the whole group. Including patients and staff in the discussion ensures validity for changes introduced and encourages 'buy-in' to success from hospital management. Both staff members and patients reported high levels of satisfaction after the half-day mixed session.

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3. Aaron, *Sleep* 1996
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The National Institute for Health Research 'Research for Patient Benefit' programme funds the SILENCE research project at the University of Oxford and Oxford University Hospitals NHS Foundation Trust.

Acoustic Source Localisation with Microphone Arrays for Remote Noise Monitoring in an Intensive Care Unit

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Institute of Sound and Vibration Research

UNIVERSITY OF OXFORD

Problem formulation and approach

- Noise disturbance in Intensive Care Units (ICUs) is a major problem (LA_{eq} > 55 dBA)
- Noise levels significantly above WHO recommendations (LA_{eq} < 35 dBA)
- Possible relation to patients' lack of sleep and delirium
- NIHR-funded project

  "**Sleep in the ICU – Lowering Elements of Noise in the Critical Care Environment (SILENCE)**"

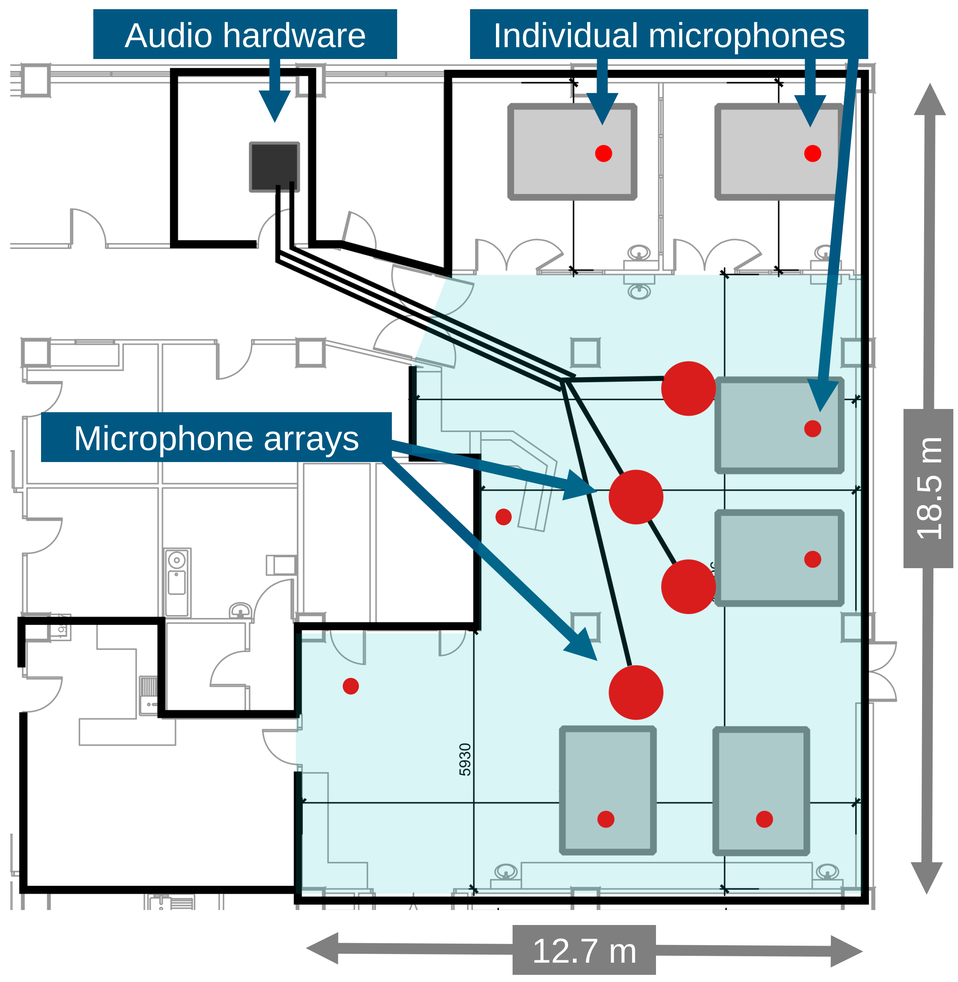
  - Reduction of noise levels in ICUs
  - Investigate connection between noise and patients' health

  → Accurate noise monitoring necessary to determine most important noise sources

- **Approach**:
  - use **microphone arrays** and **spatial filtering**
  - **continuous monitoring** and **real-time display**

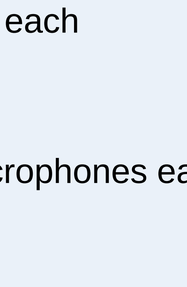
- **Test case**:
  - adult ICU at the John Radcliffe Hospital, Oxford University Hospitals NHS Foundation Trust (installation planned for Autumn 2016)

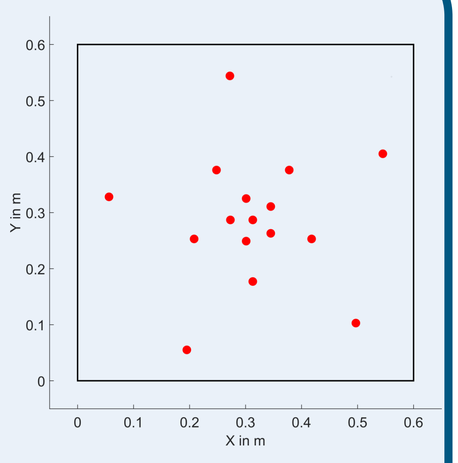
Installation setup in the ICU



Array design

- 4 distributed arrays with 16 microphones each
- Sub-array layout: logarithmic spiral
  - 3 concentric rotated circles (5 microphones each)
  - 1 center microphone
- Frequency shading optimized for broadband performance
- Microphones inserted into ceiling tiles with help of 3D-printed inserts





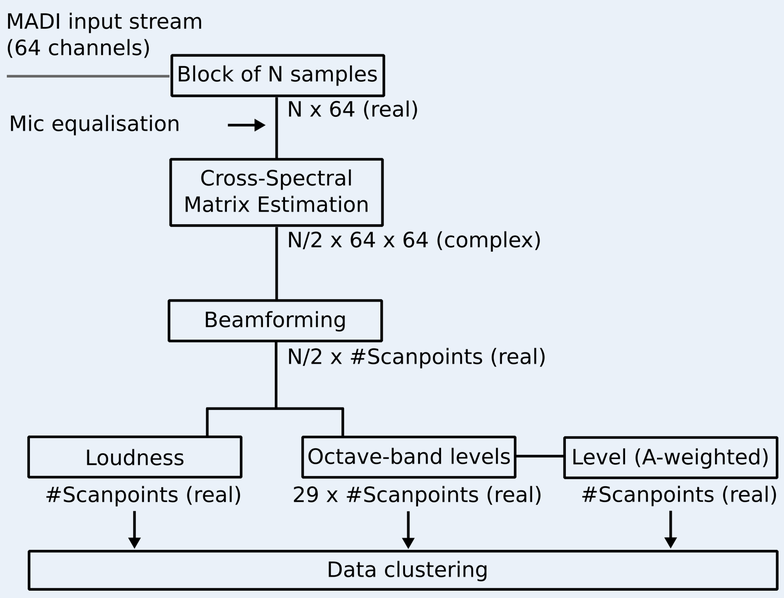
Overview of audio hardware

- RME ADI-648 MADI-to-ADAT converter (array data stream)
- Ferrofish A16 MKII converter (individual mics data stream)
- 9 Focusrite OctoPre MKII microphone pre-amplifiers (72 channels in total)
- MADI streams processed by RME MadiFX sound card

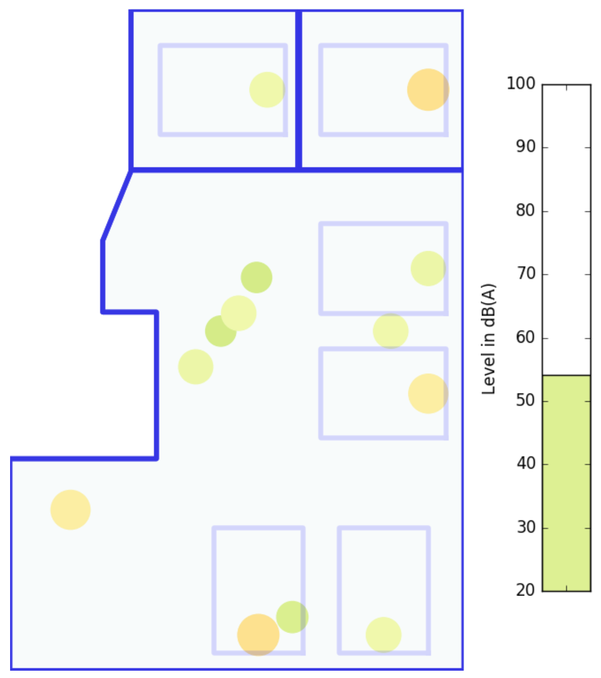


Software overview

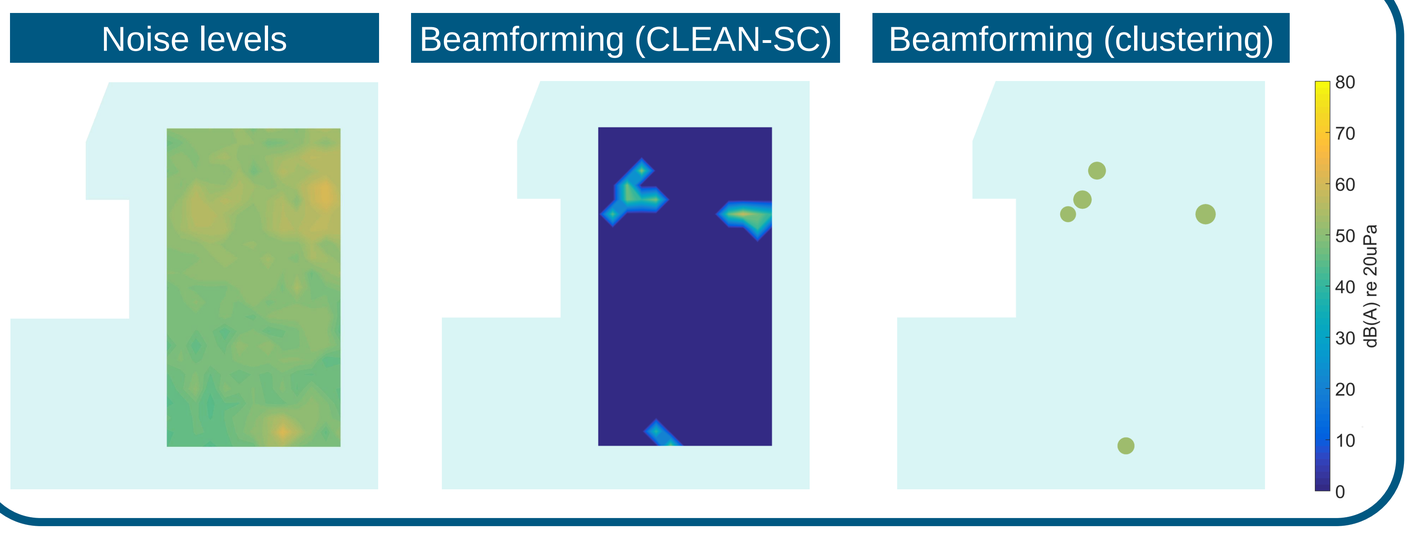
- Computer running Linux operating system (Ubuntu Studio, real-time kernel)
- JACK Audio Connection Kit used for connection to sound card
- Implementation of algorithms in julia programming language
- Many beamforming algorithms implemented
  - CLEAN-SC offers best performance
- Subsequent data clustering for presentation to nursing staff
- Server / client plotting interface using JSON messages



Client interface



Simulated results



Discussion & Outlook

- Distributed microphone arrays for noise source localization
- Beamforming in combination with data clustering for better visualization
- After installation:
  - Clinical trial to help understand effect of noise
  - Follow-up project: advanced signal processing

This poster summarises independent research funded by the National Institute for Health Research (NIHR) under its Research for Patient Benefit Programme (Grant Reference Number: PB-PG-0613-31034). The views expressed are those of the authors and not necessarily those of the NHS, the NIHR, or the Department of Health.

Funded by NHS National Institute for Health Research

“Deep experience is never peaceful”: Raising awareness of noise sources in the ICU

Darbyshire JL[1], Greig PR[1], Jeffs EL[1], Barrett C[2], Edmonds P[3], Young JD[1,2], Hinton L[4]

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Background: The World Health Organisation recommends that noise levels in hospital should not exceed 35dB, with a maximum of 40dB overnight[1]. Several studies have shown that hospitals routinely exceed this limit, and that levels in intensive care units are comparable with the dining room of a busy restaurant[2]. The hospital is not only a working environment, but must be a living space for patients. Attempting to sleep in a disruptive environment is difficult, and high background noise is likely to contribute to abnormal sleep. Disrupted sleep is common in the intensive care unit (ICU)[3], and may be associated with ICU-acquired delirium[4] which contributes to increased length of stay, and more health problems after patients return home[5].

Methods:

Accelerated Experience-Based Co-Design[6]. Members from the local patient forum, staff from ICU, and the research team agreed noise reduction strategy.

- Alarms management policy
- Encourage day/night routine
- Soft-close bins
- Bespoke noise visualisation
- Noise awareness training

Developing teaching methods:

Teaching was developed with the assistance of a medical educationalist. Learning materials were designed to cater for learners with VARK-preferences (figure 1), and varying learning styles (figure 2).

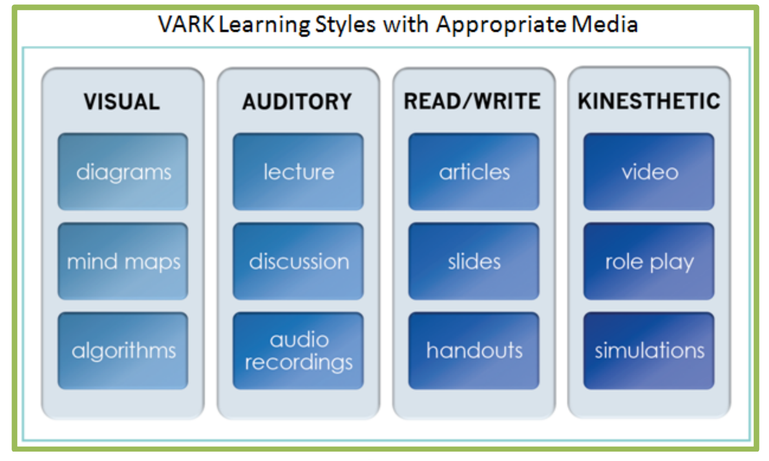


Fig 1: description of VARK preferences[7]

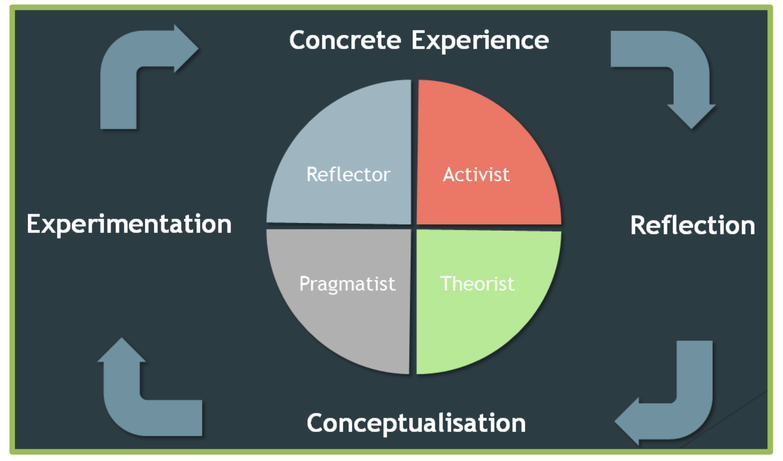


Fig 2 Kolb’s learning cycle (outer ring)[8] and Honey & Mumford’s learning styles (inner ring)[9]

The teaching materials were designed to increase staff understanding of the patient experience of noise. The intent was to enable staff to reflect on their experience with a view to motivating changes in practice, per Kolb’s learning cycle (figure 2).

The syllabus for the teaching intervention was collaboratively designed by subject experts and an educationalist. Materials were piloted and refined over two iterations based upon candidate feedback.

Rollout of teaching:

Teaching is delivered in two formats. The first was designed as an immersive learning experience, based in the workplace. The second comprises a short online e-learning package to be completed at the learner’s convenience.

Immersive learning: participants are asked to lie in an ICU bed while a 3D-audio recording of a simulated ICU environment is played back to them via stereo headphones. Participants wear glasses that replicate impaired vision, and simulated care activities such as re-positioning and equipment checking are carried out on and around the participant. The experience lasts for approximately 5 minutes per participant.

E-learning: delivered online using a commercial content-hosting platform. Materials cover the theory of sound measurement, WHO guidelines, and methods of noise-control. Multimedia content, including patient interviews, are included. Self-assessment questionnaires are included throughout the package, with feedback on answers.

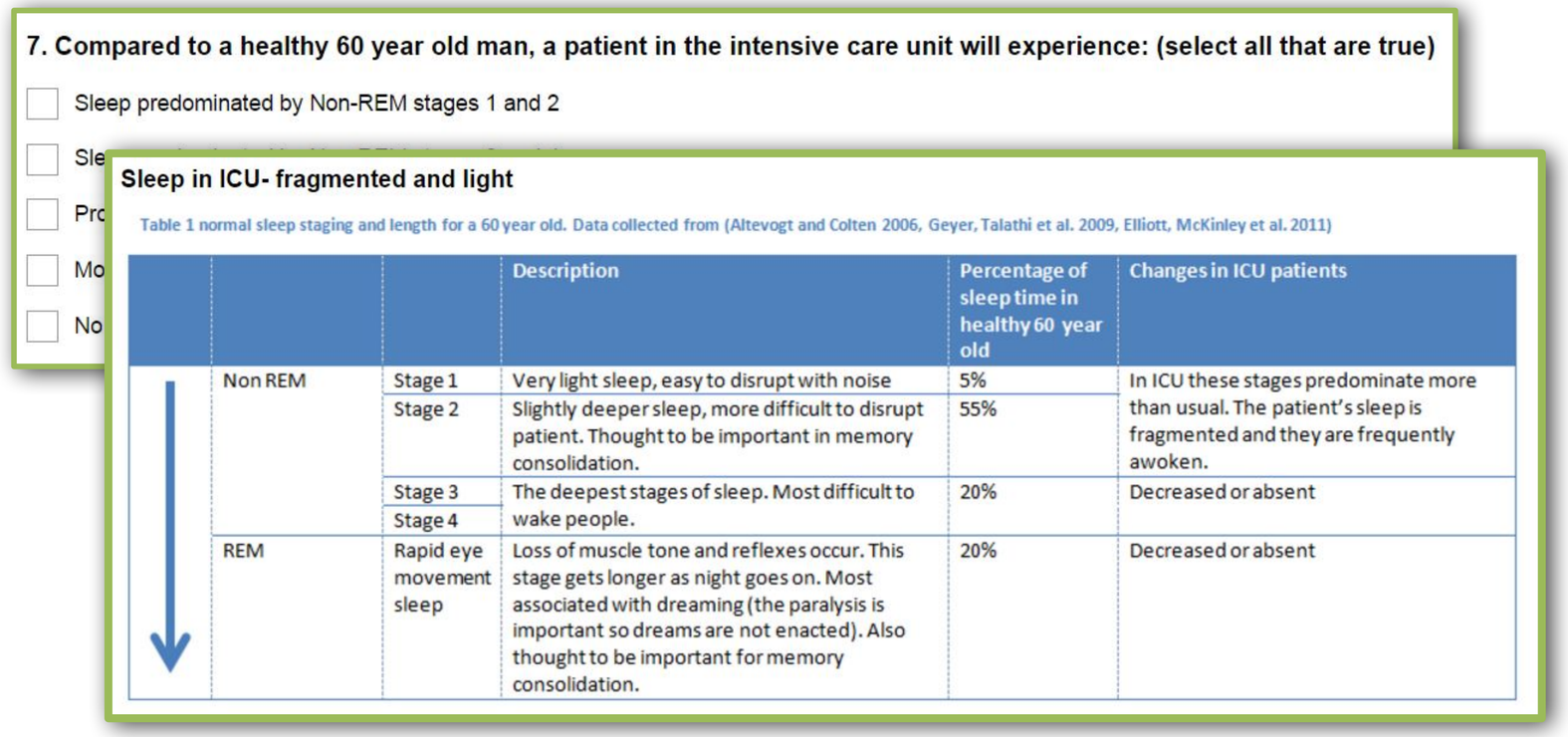


Fig 3: sample screenshots from the e-learning self-assessment

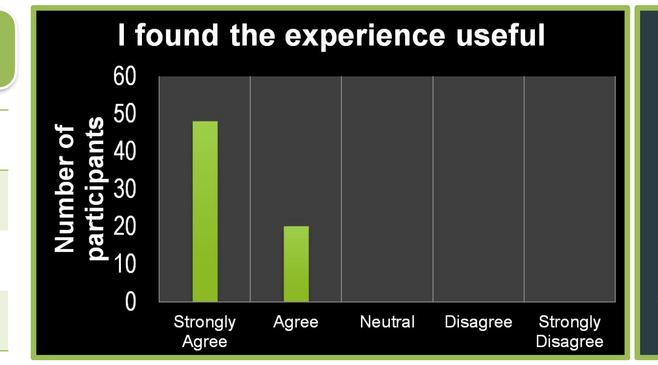
Results:

Data were collected both quantitatively and qualitatively. Most participants to date have been ICU nurses (table 1), and all participants described the experience as useful. All suggested that they would alter their practice after the experience (figure 4).

68 staff members participated

Professional background:
57 nurses
6 physiotherapists
5 doctors

Table 1: Participants’ professional background



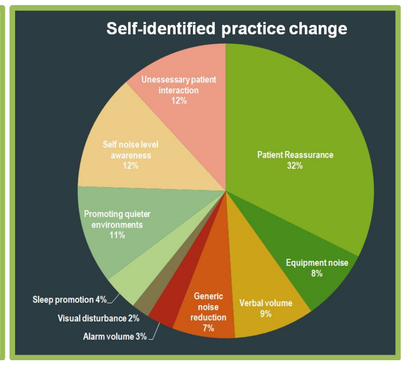


Fig 4: Feedback from experience sessions

Qualitative responses: After completing the immersive experience staff are presented with a list of words generated from patients’ own descriptions of their ICU experience and asked to choose those that most reflect their simulated experience. Most staff found the experience ‘uncomfortable’ or even ‘frightening’ (table 2).

Words that resonate	n
Uncomfortable	33
Watched	32
Alone	31
Frightening	30
Confused	28
Worrying	27
Intensive	22
Distressed	19
Scared	18
Afraid	18

Table 2: Feedback from experience sessions

Conclusion:

We believe it is important that staff understand the effect that their interventions can have on their patients, and experiential learning can be a powerful tool to achieve this.

It is encouraging that 100% of staff found the experience useful (even those that reported feeling uncomfortable), and that all members of staff reported that they would make changes to their practice in light of the teaching.

The involvement of medical educationalists is important to ensure that teaching is robustly designed and pedagogically sound.

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1. Berglund B *Guidelines for community noise* WHO; 1999
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3. Elliott R, *The quality and duration of sleep in the ICU setting* Int J Nurs Stud. 2011; 48(3): 384-400
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7. Fleming N *VARK®: a guide to learning styles* www.vark-learn.com [accessed 21/11/2016]
8. Kolb DA, *Experiential learning* Prentice Hall; 1984
9. Honey P, *Using Your Learning Styles* Peter Honey Publications; 1986

The National Institute for Health Research ‘Research for Patient Benefit’ programme funds the SILENCE research project at the University of Oxford and Oxford University Hospitals NHS Foundation Trust.

Developing a training package to reduce noise levels in the ICU

Darbyshire JL[1], Greig PR[1], Edmonds P[2], Barrett C[3], Hinton L[4], Young JD[1]

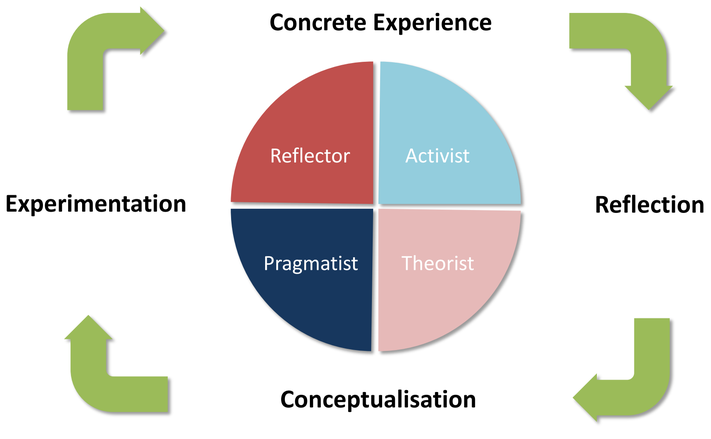
1 Nuffield Department of Clinical Neurosciences, University of Oxford | 2 Patient | 3 Adult Intensive Care Unit, Oxford University Hospitals NHS Trust | 4 Health Experiences Research Group, Nuffield Department of Primary Health Care Sciences, University of Oxford

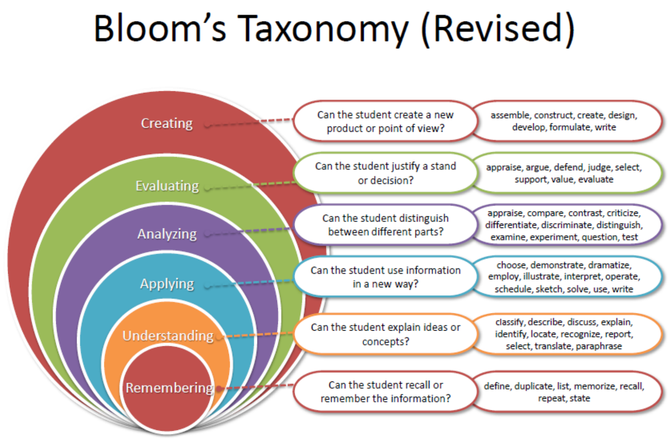
Background: The World Health Organisation (WHO) recommends average hospital sound levels should not exceed 35dB with a maximum of 40dB overnight[1]. The reality is that noise levels in ICUs are about as loud as the dining room of a busy restaurant[2]. This high background noise is likely to contribute to abnormal sleep and increase the incidence of ICU-acquired delirium[3]. Patients who suffer from delirium in hospital have longer stays and more health problems after they return home[4].

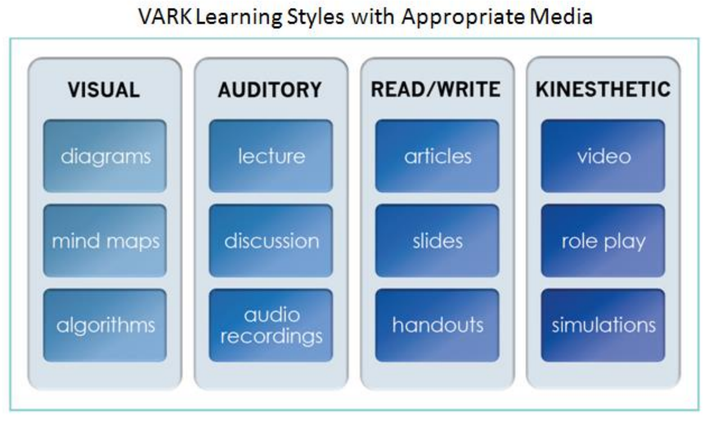
Aim: To develop an educationally sound and robust training programme designed to increase understanding of noise levels in the ICU and empower staff to make practical changes to reduce noise levels and disturbances to patients.

Methods: Using the AEBCD framework[5], we developed an intervention to address noise levels in the ICU. This included replacing metal bins with plastic, initiating an alarms management policy, and raising awareness through a new educational programme. The programme was developed in collaboration with a medical educationalist and draws on theories of adult learning[6,7]. An e-learning module includes patient interviews and evidence-based information on the effects of noise. A short simulation-based experiential session includes live and recorded sounds combined with common ICU activities. Through the simulation staff experience the ICU from the patient perspective.

Teaching Theory







E-learning module: Incorporates a variety of teaching methods[8]

- Graphs
- Video
- Transcripts
- Journal paper

Sleep in ICU- fragmented and light

Table 1 normal sleep staging and length for a 60 year old. Data collected from (Altevogt and Colten 2006, Geyer, Talathi et al. 2009, Elliott, McKinley et al. 2011)

			Description	Percentage of sleep time in healthy 60 year old	Changes in ICU patients
↓	Non REM	Stage 1	Very light sleep, easy to disrupt with noise	5%	In ICU these stages predominate more than usual. The patient's sleep is fragmented and they are frequently awoken.
		Stage 2	Slightly deeper sleep, more difficult to disrupt patient. Thought to be important in memory consolidation.	55%	
		Stage 3	The deepest stages of sleep. Most difficult to wake people.	20%	Decreased or absent
		Stage 4			
	REM	Rapid eye movement sleep	Loss of muscle tone and reflexes occur. This stage gets longer as night goes on. Most associated with dreaming (the paralysis is important so dreams are not enacted). Also thought to be important for memory consolidation.	20%	Decreased or absent

7. Compared to a healthy 60 year old man, a patient in the intensive care unit will experience: (select all that are true)

- ☐ Sleep predominated by Non-REM stages 1 and 2
- ☐ Sleep predominated by Non-REM stages 3 and 4
- ☐ Prolonged REM sleep
- ☐ More fragmented sleep
- ☐ No change in sleep pattern

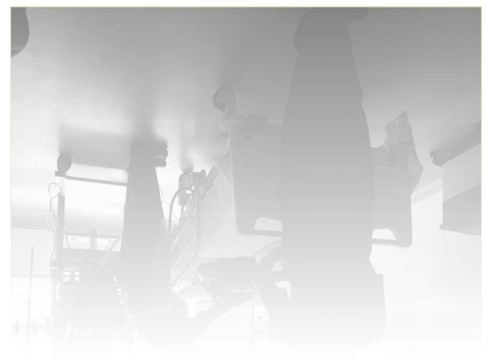
Compared to a healthy 60 year old man, a patient in the intensive care unit will experience:

- **TRUE** Intensive care patients' sleep cycles rarely progress beyond stage 2.
- **FALSE** Intensive care patients' sleep cycles do not include much time in Non-REM stages 3 and 4.
- **FALSE** Intensive care patients' sleep cycles have very short REM stages.
- **TRUE** Patients in the intensive care unit will experience highly fragmented sleep with frequent awakenings throughout the night.
- **FALSE** The sleep pattern of a patient in the intensive care unit will be very different from that of a healthy 60 year old man.

Experiential simulation: Lasts ~six minutes (extended following early feedback) and includes live action combined with binaural acoustic experience and simulated poor vision.

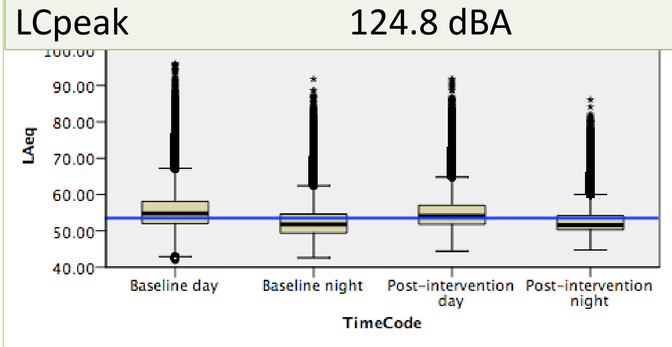
To date 116 individuals have completed the experience. Feedback indicates 100% of participants found it useful, 97% said that they would change their practice after the session, and 95% thought that staff in the ICU could do more to create a less stressful environment for patients. From a word list generated from patient reports of their experience in the ICU, the most frequently selected words by participants are 'worrying', 'frightening', 'stressful', 'confused', 'uncomfortable', 'scared', 'afraid' and 'alone'.

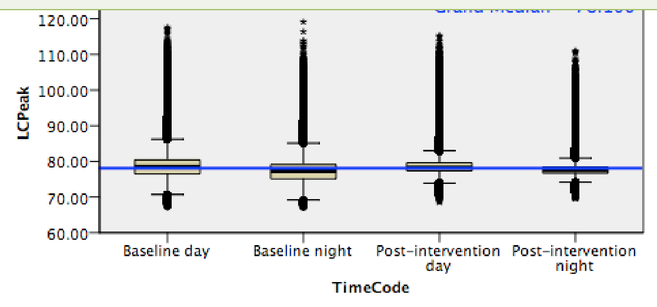






	Baseline	Post-intervention
No of days	86	70
LAeq median (IQR)	57.0 (3.2) dBA	53.2 (5.1) dBA
LCpeak	124.8 dBA	115.3 dBA





Self-identified practice change	
More patient reassurance	36%
Noise reduction	34%
Limit patient interactions	9%
Reduce verbal volume	9%
Lower alarm volume	8%
Sleep promotion	3%

Results: Post-intervention measures indicate a reduction in sound levels of ~4dB. Reflective post-experience responses indicate understanding of both source and impact of noises in the ICU.

Conclusions: Staff are unaware of how much noise normal activities create. Putting them in the position of the patient allows them to experience the ICU from a new perspective. Measurable change was achieved through robust theoretical design, a patient-focused approach, and innovative binaural recording techniques which increased the realism of the experience. We are now evaluating sustained cultural change and knowledge transfer through ethnographic observations and follow up questionnaires.

"By three methods we may learn wisdom: First by reflection, which is noblest; second by imitation, which is easiest; and third by experience, which is bitterest."

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7. Honey & Mumford, 1986
8. Fleming, YEAR

The National Institute for Health Research 'Research for Patient Benefit' programme funds the SILENCE research project at the University of Oxford and Oxford University Hospitals NHS Foundation Trust.

Oxford University Hospitals NHS Foundation Trust

NUFFIELD DEPARTMENT OF CLINICAL NEUROSCIENCES

Understanding sound pressure levels in the intensive care unit

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Unnecessary noise is the most cruel abuse of care which can be inflicted (Florence Nightingale, 1859)

SILENCE

Background

The intensive care unit (ICU) is a busy environment with sound pressure levels (SPL) persistently above World Health Organisation (WHO) recommendations for hospital environments. This may impact patient recovery by impairing sleep and increasing the likelihood of delirium (1-2).

Environmental sound levels are normally reported as the mean SPL over a 24 hour period (measured in decibels, dB). Several studies designed to lower SPL in the hospital environment have not significantly altered this 24-hour average (3-5). We hypothesised that higher fidelity reporting would enable a more detailed understanding of the environment and identify times of the day when directed interventions might have most effect.

Methods

SPL and loudness levels (SPL adjusted for the human ear, measured in dB) were recorded over the study period (October 2016 – May 2018). An array of 74 microphones (see Figure 1) was installed in a UK intensive care unit (6). The resulting data set was of a size that conventional statistics programs would be unable to analyse without considerable under-sampling. In order to analyse the full data set, we used the distributed task dispatching, parallelism and scheduling of a cluster computing framework (Apache Spark). We constructed a system consisting of a single workstation (6 cores and 32GB of RAM) running Apache Spark 2.3, sparklyr 0.8.4., and R Core 3.5. We accessed the sparklyr library via R Studio, to perform calculations using the dplyr package. Aggregate data were imported into R Core for analysis and visualisation using ggplot (version 3).

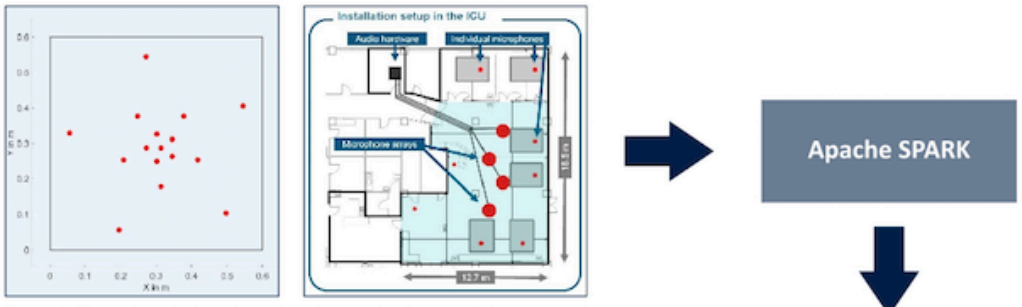


Figure 1: Floor plan of microphone locations and subsequent data processing

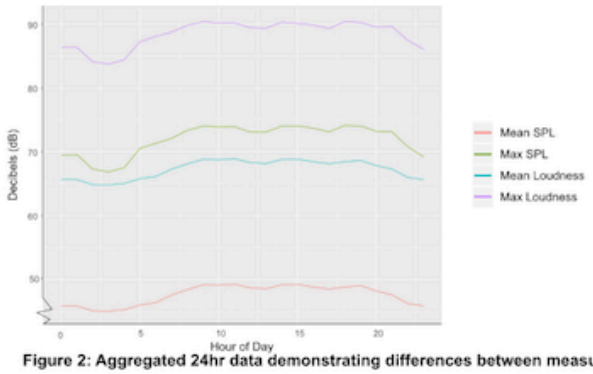


Figure 2: Aggregated 24hr data demonstrating differences between measures

Results

More detailed analyses of sound levels in ICU were permitted by implementing a parallel computing architecture using relatively modest computing resources.

Both SPL and Loudness show substantial variation across a 24 hour period (see Figure 2). SPL is always above the WHO guidelines of 35dB, with Loudness 20dB higher on average. Maximum values are noticeably lower in the early hours of the morning.

Conclusions

SPL levels are monitored for health and safety purposes to protect against damage to human hearing from accumulated exposure to sound. Sleep in the ICU is perhaps more likely to be disrupted by sudden increases above baseline levels, rather than average daily exposure. It is important therefore to understand the peaks and troughs in SPL across the day.

Loudness potentially better reflects the patient experience of noise while in ICU. We are continuing to explore the relationship between Loudness, SPL and patients' sleep patterns.

References

1. Aaron et al. "Environmental noise as a cause of sleep disruption in an intermediate respiratory care unit." Sleep 19.9 (1996) 2. van de Pol, et al. "Effect of nocturnal sound reduction on the incidence of delirium in intensive care unit patients: An interrupted time series analysis." Intensive and Critical Care Nursing 41 (2017) 3. Li, Shu-Yen, et al. "Efficacy of controlling night-time noise and activities to improve patients' sleep quality in a surgical intensive care unit." Journal of clinical nursing 20.3-4 (2011) 4. Boyko et al. "Sleep in intensive care unit: The role of environment." Journal of critical care 37 (2017) 5. Johansson et al. "Evaluation of a sound environment intervention in an ICU: A feasibility study." Australian Critical Care 31.2 (2018) 6. Müller-Trapet et al. "Acoustic source localization with microphone arrays for remote noise monitoring in an Intensive Care Unit." Applied Acoustics 139 (2018)

The National Institute for Health Research 'Research for Patient Benefit' programme funds the SILENCE research project at the University of Oxford and Oxford University Hospitals NHS Foundation Trust.

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Adult Intensive Care Units

Noise management guidelines

Ref:- N/A
Issue:- 1
Issue Date:- 4/1/15
Review Date: 4/1/18
Issued To: CICU and AICU staff

AUTHOR:-

Emma Jeffs (Research Nurse)

REVIEWED

Feedback and revision provided by: Nadeem Khan, Cherry Lumley, Alexia Douglas, Charlotte Wright, Mark Borthwick, Claire Hird, Laura Beck, Julie Darbyshire.

This Protocol/Guideline was approved by the Matron of the Adult Intensive Care Services

On:-
4/1/15

Signed:-
Lyn Bennet, Deputy Matron

Review Date	Result of Review	Summary of amendments	Distributed to	By
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	[Click and Type <<Description>> Here]			

Introduction:-

In the Intensive Care Unit, many patients describe a noisy and stressful environment. Current WHO recommendations state that ICU should aim for a level of under 35dB (Berglund, Lindvall et al. 1999). Local noise data shows these levels are frequently breached (Darbyshire and Young 2013). A patient and staff critical care service improvement meeting held in July 2015 recommended addressing alarm noise as a priority. A strategy to manage alarm fatigue is a local guideline on alarm management (Cvach 2012, Sendelbach and Jepson 2013). Further to this it is important that staff are armed with the correct information and tools to enact the policy.

Alarm fatigue is a commonly described phenomenon where alarms can be missed by clinical staff because they are overwhelmed with noise and false alarms (Cvach 2012). This negatively influences the ICU in three key ways. Firstly and most importantly patient safety can be compromised because alarms that signify true patient events (about 1-15%) can be ignored (Cvach 2012, Schmid, Goepfert et al. 2013). Secondly patient comfort is also affected, as excessive noise makes for an environment that is stressful and reduces the potential for sleep (Cvach 2012). Thirdly, staff comfort and concentration is influenced by unnecessary alarms, and adds to the stress felt on a clinical shift.

When observations of noise were undertaken in the OUH ICUs, many good practices regarding noise and alarm management were observed. This document aims to highlight this good practice with reference to the current literature to make recommendations for patient care.

The AICU intranet has documents related to the safe use of all equipment that is referenced in this guideline, including the IntelliVue patient monitor, patient ventilators, and other patient equipment. The department of clinical engineering has a 'medical devices users guide' which details reporting of faulty equipment, and the process for device maintenance.

Scope:-

- This is a guideline, not a policy or procedure. It is designed to outline good practice. It must be emphasised that before enacting any noise reduction strategy all actions regarding alarms and noise must first have a risk assessment undertaken by the member of staff.
- This guideline is for use in the Adult Intensive Care Unit at the John Radcliffe Hospital, and the Churchill Intensive Care Unit.
- This guideline is designed to be enacted in the closely monitored Intensive Care environment. It is not designed as a tool for ward based alarm management.
- This guideline refers to all patient equipment with audible alarms in the ICU.

Aim:-

The purpose of this guideline is to ensure:

- The promotion of patient comfort and sleep by reducing noise in ICU
- The promotion of patient safety by reducing staff alarm fatigue and encouraging a clear communication strategy for alarm management.
- The unit expectations of alarm management are made clear to staff
- Clinical staff are armed with necessary knowledge and tools to enact guidelines

Definitions:-

The terms in use in this document are defined as follows:

ICU- Intensive Care Unit, which in this document refers to the Adult Intensive Care Unit (AICU) at the John Radcliffe Hospital, and the Churchill Intensive Care Unit (CICU).

Alarm Fatigue- A commonly described phenomenon where alarms are not acted on by clinical staff because they are bombarded with noise and false alarms (Cvach 2012).

ECG- electrocardiograph

Responsibilities:-

All clinical staff are required to safely and effectively monitor their patients for deterioration. This is complemented by managing patient alarms and environmental noise safely.

Bedside Nurses and Health Care Assistants

- Critically appraise alarm and noise management for patients, keeping patient safety first.

Clinical educators and senior nursing staff

- Feedback about noise management guidelines is collected and integrated into future review of document.

Guideline Content :-

Training

- For training on noise management please refer to the AICU Intranet under the learning and development tab. There is no mandatory training associated with this policy.

Patient Care

- Offer patients earplugs and eye masks where appropriate
- After conducting risk assessment, consider repositioning patient experiencing sleep deprivation in quieter bedspaces.
- Where possible/ appropriate, prepare patients for clinical interventions that have to be conducted overnight.
- Consider the 'clustering' of care for patients who require interventions overnight.
- Ensuring adequate skin contact with ECG dots has shown to decrease false alarms (Sendelbach and Jepson 2013). Change ECG dots daily and ensure adequate skin contact by cleaning skin prior to ECG dot application, and shaving patient hair where necessary.

Environmental Strategies

- Current practice regarding dimming lights in the evening should continue, as it promoted an observable decrease in noise. This may not always be possible due to admissions/ departmental needs.
- Noise related to preparation of equipment or procedures were recorded to be more loud when next to a patients head compared with 1 metre away. Where safe to do so, consider preparing for these procedures on section of bench as far away from patient head as possible.
- Report noisy/ damaged/ broken equipment as soon as practical to relevant staff.

Night time alarms

- In the evenings from 2200-0600 the noise on the ICU is less than the daytime. On a night shift critically appraise the risk involved in reducing alarm volume to a level not unnecessarily loud- but a level that can still be heard over environmental noise. This level may have to be louder if nurses are caring for multiple patients, on staff breaks, or if a patient is in a side room. On the Phillips IntelliVue monitor, the icon for this is in the top right hand corner of the screen.



Alarm management

- Discuss alarm limits for vital signs during handover to ensure appropriately tailored limits for your patient. Document any changes from normal limits on CareVue. Identify the plan of care if your patient's observations fall outside of these limits. Check 'Monitor alarm parameters and volume checked' on the CareVue safety checklist.
- Alarms informing the clinical staff of the incorrect/absent application of equipment such as the SpO2 probe can often run on for long periods of time. This can be related to inadvertent dislodging as a patient moves; or agitated or confused patients purposefully removing the equipment. To manage this, conduct a risk assessment with the clinical team and bay co-ordinator. Consider the

patient safety implications of tailoring monitoring to individual patient requirements. Decisions should be documented on CareVue on the patient flowsheet.

- **NB**: In no circumstances should monitoring be 'turned off' for agitated patients who clinically require it.
- Integrate patient and family education where appropriate. Consider outlining the clinical relevance of the monitoring device to promote compliance with device. Consider patient preference for SpO2 ear probe instead of finger probe.
- Whenever possible anticipating requirements for consumables and the need to change syringes prior to the end of infusion. Where possible changing syringes or fluids when a patient is awake. Effective handover of care to colleagues was observed to reduce length of alarms from devices, as colleagues could anticipate and respond.
- When patient care is administered, there can be an increase in false alarms related to movement and disconnection of devices. Conduct a risk assessment about the likelihood of 'true' alarms and then consider: Silencing alarms for the period of time you are attending to patient care; turning off particular monitoring when removing sensing device, changing device or moving patient (i.e. changing ECG electrodes).

Patient safety considerations

- Practice vigilance in checking alarm limits have been reset between patients.
- When the volume of alarms are reduced overnight plan care so that if leaving bed space another nurse is listening for your alarms (or temporarily increase volume).
- Staff new to the unit, may require more restrictive alarm parameters to promote earlier escalation to senior staff.

Medication safety considerations:

- Unused idle full infusion syringes can present an infection control risk, clinical risk and security risk. To manage this change syringe from continuous infusions before it runs out and discard contents as per protocol
- Controlled Drugs and sedatives should be prepared in advance, but as close to the previous syringe's anticipated completion as possible.

Action	Rationale

Review :-

Due 4/1/18

References:-

Berglund, B., et al. (1999). Guidelines for Community Noise, Geneva: World Health Organization.

Cvach, M. (2012). "Monitor Alarm Fatigue: An Integrative Review." Biomedical Instrumentation & Technology **46**(4): 268-277.

Darbyshire, J. and J. D. Young (2013). "An investigation of sound levels on intensive care units with reference to the WHO guidelines." Critical Care **17**(5): R187.

Schmid, F., et al. (2013). "Patient monitoring alarms in the ICU and in the operating room." Critical Care **17**(2): 216.

Sendelbach, S. and S. Jepson (2013). AACN PracticeAlert Alarm Managment, American Association of Critical Care Nurses.

Equality Impact Assessment :-

As part of its development, this document has been reviewed for its impact on equality. No issues were identified.

Appendix:-

1) Noise management guidelines one page executive summary
2) Alert reference number: NHS/PSA/W/2015/011 Stage One: Warning
The importance of vital signs during and after restrictive interventions/manual restraint.
Released: December 3,2015

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Adult Intensive Care Units



Noise management guidelines executive summary

Patients in the intensive care unit (ICU) sleep poorly. Many factors are thought to contribute to this including medications administered, pain, light, noise, and anxiety. Many of these contributors represent essential patient care, however some of these are potentially modifiable and may promote a more sleep friendly environment.

As recommended in the literature, a guideline on alarms and noise management can be of assistance to units in reducing noise. A guideline has been developed for the JR and Churchill Adult ICUs for this reason. Information to develop this guideline has come from local data collected about noise levels, and from qualitative observations conducted on the ICUs. Much of it was developed after witnessing behaviours by staff that reduced or managed noise well.

The recommendations are:

- Offer earplugs and eye masks to all patients who are cognitively appropriate
- Individualise patient care and monitoring as much as possible taking into consideration:
    - Patient needs and safety
    - Staff needs and support
- Take all steps possible to reduce run on of low level alarms including:
    - Appropriate handover of tasks when on breaks
    - Individualising monitoring frequency and patient parameters after discussion with clinical team
- Promoting a more normal day/night routine:
    - Dimming lights in the evening
    - Where safe, reducing alarm volume at night
    - Informing patients of overnight interventions
- Demonstrating an awareness of the influence of noise on patients:
    - Completing tasks away from patient's head where possible
    - Consider position of patient with sleep deprivation in quieter bed spaces with less foot traffic

Please see the full guidelines for more information and rationale for these recommendations. It is important to take note that these guidelines reflect practice routinely observed in the ICU, but are here to assist in keeping this aspect of patient care on the agenda and to assist new starters/ those wanting a refresher.

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Adult Intensive Care Units

Classification: Official

NHS England

Patient Safety Alert

Stage One: Warning

The importance of vital signs during and after restrictive interventions/manual restraint

3 December 2015

Alert reference number: NHS/PSA/W/2015/011
Alert stage: One - Warning

Whilst a range of guidance exists on positive interventions to reduce the risk of self-harm, violence and aggression in healthcare settings [1-3], restrictive interventions, including seclusion, manual restraint and rapid tranquillisation are used as the last resort to manage a person's behaviour if they are deemed to be at risk to themselves or others. Restrictive interventions can cause psychological and physical harm [1-3] and NICE guidance [3] provides advice on a range of factors that must be considered to minimise the risk of harm to the patient during and following a period of manual restraint.

Whilst the risk of death from positional asphyxia **during** restraint has been increasingly recognised, harm can also occur in the period **following** restraint from the effect of illicit substances, alcohol, prescribed medications (including any rapid tranquilisation) and co-existing medical conditions. People with diagnoses of severe and enduring mental illnesses are at increased risk of coronary heart disease, cerebrovascular disease, diabetes, infections, epilepsy and respiratory disease [4,5], all of which can potentially be exacerbated by the psychological and physical effects of restrictive intervention; between 2008-2012 there were 11 deaths within 24 hours of restraint in mental health settings in England [5].

The risk of death after restrictive interventions may also affect people without a previous history of mental illness. Delirious behaviour that requires manual restraint or rapid tranquilisation may indicate a life-threatening underlying medical cause or head injury [6, 7]. Between 2009 and 2015 there were 19 incidents reported to the National Reporting and Learning System (NRLS) as death or severe harm possibly associated with a period of restraint in acute/ general hospital settings; a direct causal link was not always evident from the free text of the report. HM Coroner also issued a Regulation 28 report in March 2015 when a death occurred after restraint in an acute/general hospital setting.

The risk of death following restraint may be increased if the patient is also in seclusion or staff are avoiding close observation for fear of distressing the patient. NICE guidance gives advice on vital signs after manual restraint and very specific advice on the nature, frequency and duration of vital signs that should be taken after rapid tranquilisation [3]. Guidance related to vital signs in suspected delirium and head injury is also relevant [6-10] . However, vital signs are unlikely to be reliably carried out and documented unless the responsibilities for doing so are specified in local procedures, embedded in mandatory training, and routinely audited, including support for staff in managing challenging situations where attempts to record vital signs may lead to further violence or aggression.

Early response to any deterioration in vital signs is equally critical [9,10] and both the NICE guidance [3] and previous National Patient Safety Agency advice [11] emphasise the importance for all settings that undertake restrictive interventions to have access to emergency equipment (including defibrillators) and staff trained to respond to medical emergencies.

Actions

Who:

All organisations providing NHS-funded care where restrictive interventions or manual restraint are (or might be) used, including healthcare provided in prisons

When:

As soon as possible and by no later than 21 January 2016

1. Identify if vital signs during and after restraint are undertaken appropriately in your organisation.
2. Consider if immediate action needs to be taken locally to ensure vital signs are reliably recorded and acted on during and after restraint, and that an action plan is underway if required.
3. Circulate this alert to all relevant staff who may be called to support the restraint of patients or be responsible for their care afterwards.
4. Share any learning from local investigations or locally developed good practice resources by emailing: patient.safetyenquiries@nhs.net.

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Technical notes

NRLS search dates and terms

The NRLS was searched in March 2012 for incidents reported to the NPSA between 1 January 2009 and 21 March 2012 from incident location Lv 1: general/acute hospitals with the free text word 'restrain'. A second search was undertaken via SAS on 10 August 2015 for incidents with an incident start date from 01 May 2012 reported from incident location Lv 1: general/acute hospital, incident location Lv2: inpatient areas, with the following free text words: 'restrain' OR 'security'.

Terminology note

In mental health settings, the term 'observation' is typically used for visual observation, whilst in acute care settings 'observations' would typically mean physiological observations (pulse, temperature, etc.). The term 'vital signs' is used here to denote that more than visual observation is required; the detailed nature of both physiological and visual observations required can be found in the referenced guidance.

We acknowledge any definition of physical intervention/manual restraint is more complex in children, where holding safely [12] can be part of normal parental care, and note that some of the guidance below is only applicable to adults. Services providing NHS-funded care to children should be mindful of this, but the core actions required within the Alert – to review local practice and take action to improve safety if required – can be applied in principle.

References

1. Code of practice: Mental Health Act 1983. (2015) https://www.gov.uk/government/publications/code-of-practice-mental-health-act-1983
2. Department of Health (2014). Positive and Proactive Care: reducing the need for restrictive interventions. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/300293/JRA_DoH_Guidance_on_RP_web_accessible.pdf
3. NICE (2015). Violence and aggression: short-term management in mental health, health and community settings. https://www.nice.org.uk/guidance/ng10
4. The Royal College of Psychiatrists (2010). No health without public mental health. The case for action. http://www.rcpsych.ac.uk/pdf/Position%20Statement%204%20website.pdf
5. The National Confidential Inquiry into Suicide and Homicide by People with Mental Illness. Annual Report, University of Manchester, 2014. http://www.bbmh.manchester.ac.uk/cmhs/centreforsuicideprevention/nci/reports/Annualreport2014.pdf
6. NICE (2010). Delirium: Diagnosis, prevention and management. https://www.nice.org.uk/guidance/cg103
7. NICE (2014). Head injury: Assessment and early management https://www.nice.org.uk/guidance/cg176
8. The Glasgow Structured Approach to Assessment of the Glasgow Coma Scale http://www.glasgowcomascale.org/
9. NICE (2007). Acute illness in adults in hospital: Recognising and responding to deterioration. http://www.nice.org.uk/Guidance/CG50
10. Royal College of Physicians (2012). National Early Warning Score (NEWS): Standardising the assessment of acute illness severity in the NHS. https://www.rcplondon.ac.uk/projects/outputs/national-early-warning-score-news
11. National Patient Safety Agency (2008). Resuscitation in mental health and learning disability settings. NPSA/2008/RRR010. http://www.nrls.npsa.nhs.uk/resources/clinical-specialty/mental-health/?entryid45=59895&p=3
12. RCN (2010). Restrictive physical intervention and therapeutic holding for children and young people https://www.rcn.org.uk/__data/assets/pdf_file/0016/312613/003573.pdf (we understand The Council for Disabled Children have been commissioned by DfE/DH to provide additional guidance)

Stakeholder engagement

- Mental Health Patient Safety Expert Group
- Learning Disability Patient Safety Expert Group
- Medical Specialties Patient Safety Expert Group

For details of the membership of the NHS England Patient Safety Expert Groups see http://www.england.nhs.uk/ourwork/patientsafety/patient-safety-groups/

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Noise management guidelines

Introduction

Noise management remains an ongoing issue on intestine care units, not because clinicians and caregivers don't care but because best practice has been wide ranging and difficult to achieve.

Noise management is important in intensive care especially at night. Raised noises levels can negatively affect patients and staff, causing increases in stress levels. Some non-clinical studies have shown that noise levels adversely effects the physiology, motivation and general health of patients.

The aim of this document is to highlight areas of strength and weaknesses within the intensive care unit and make recommendations with the aim of improving patient care using current evidence and best practice.

The World Health Organisation (WHO) recommends the noise levels in a patient's room should remain around 30 decibels, however according to a recent study in 2012 the average noise was measured at 48 decibels but the report noted that tis maybe difficult to achieve.

Scope:

These guidelines will be used for the adult intensive care unit at Yeovil Hospital.

The following are only guidelines and aim to improve best practice. It must be emphasised that any noise reduction changes especially around alarm reduction must first have a risk assessment undertaken by the member of staff.

These guidelines refer to all patient equipment with audible alarms.

These guidelines are for use in the closest monitored intensive care unit and not for ward based noise management.

Aims:

These guidelines aim to ensure:

- The promotion of patient comfort and sleep by reducing noise in intensive care.
- Improving patient safety by reducing staff alarm fatigue and encouraging a clear communication strategy for alarm management.
- Unit expectations of alarm management which are clear to all staff.
- Clinical staff have the necessary knowledge and tools to enact guidelines.

Guidelines:

Training:

- Patient experience for all staff
- Silence File
- Ensure staff are trained and competent in recognizing and troubleshooting equipment alarm signals.

- Assess noise levels regularly throughout the night shift and also in rest hour to make staff aware.

Environmental:

- Current practice regarding dimming lights at night to continue.
- Curtains and blinds to be drawn. Side lights to be on only, not to use main lights after 23:00.
- Staff to be aware to speak in a lower tone especially in rest hour and overnight.
- Preparations of equipment or procedures should be done away from patient, if safe to do so.
- Report damaged, broken equipment as soon as possible to relevant staff.
- Turn off devices that do not need to be used at all times to reduce noise for example, suction, oxygen.

Alarms:

At night (23.00-07.00) the noise on the unit will be less than during the day. Alarms at night can be assessed for noise levels and if appropriate reduced. The alarm should be at a level that can be heard over environmental noise. This maybe higher if caring for more than one patient.

Alarm management:

- Alarm limits for vital signs must be discussed at handover to ensure appropriate limits for your patient.
- Document changes from normal limits. Identify your plan of care if the patients observations fall outside of these limits.
- Alarms can be incorrect or absent when equipment has been dislodged for example SpO2 probe, which will alarm if the patient fidgets with it or purposely removes it. This can be managed by a risk assessment with clinical staff. Consider patient safety implications of tailoring monitoring to patient needs. Always document discussions and outcomes.

NB: in no circumstances should monitoring be "turned off" for agitated or confused patients' who clinically need it.

- Patient care can increase alarms relating to movement and disconnection of devices. Consider silencing alarms whilst you are giving patient care, turning off monitoring when changing ECG dots, removing sensing devices or moving patient.
- Informing patients of the alarms and what they mean to help reduce anxiety.
- Attend to all alarms as promptly as possible including call bells and telephone calls.

Patient safety considerations:

- Staff new to the unit may require more restrictive alarm parameters to promote earlier escalation by senior staff.
- When the volume of alarms are reduced overnight plan care so that if leaving your bed space another nurse is listening for your alarms.
- Practice vigilance in checking alarm limits, ensuring alarms have been reset between patients.

Patient Care:

- Offer patients' ear plugs and sleep masks where appropriate.
- ECG dots - ensure adequate skin contact; have been shown to decrease false alarms (Sendelbach and Jepson 2013).
- Consider the "clustering "of care for patients' needing overnight interventions.
- Ensure any important clinical procedures eg: venflons have been completed.
- Review frequency (risk assess) required for observations. If cardiovascuarly stable for example then reduce NIBP and remove cuff in between for comfort.
- Assess the need for repositioning of your patient overnight. Avoid waking them where possible if there is minimal risk of pressure sore development.
- Inform your patients of the overnight plan before they go to sleep so they are aware of any interventions that may take place overnight for example, IV antibiotics, Blood gases etc.

Medications:

- Whenever possible assess requirements for overnight changing of syringes prior to end of infusions. If possible change whilst patient is awake. Effective handover of care by staff re syringes helps staff anticipate changes.
- Unused full or half used syringes can present infection control, clinical and security risks. To manage this change syringes before they run out and discard contents as per protocol.
- Sedatives and controlled drugs should be prepared in advance, but as close to previous syringe anticipated completion as possible.
- Prepare medications in the treatment room and dispose of sharps here where possible.

Software Requirements Specification

for



Prepared by Julie Darbyshire

University of Oxford

20th January 2017

Introduction

Background

This work is part of a research project funded by the National Institute of Health Research (NIHR) Research for Patient Benefit (RfPB) funding stream. The aim of the project is to reduce sound levels in the intensive care unit.

Following a staff and patient user group meeting in July 2015 a number of noise reduction strategies have been suggested and implemented at the John Radcliffe hospital adult intensive care unit. These interventions have included the introduction of patient alarm management guidelines, a night/day policy whereby lights are switched off between 9.00 and 10.00pm, new soft-close bins have been placed in the unit, and a teaching programme has been introduced to raise awareness of the issues associated with loud noise.

The final stage of this project is to present sound level information to staff working in the intensive care unit via a display.

Timeline

<table>
<tr><td colspan="2">2016</td><td colspan="7">2017</td></tr>
<tr><td>Nov</td><td>Dec</td><td>Jan</td><td>Feb</td><td>March</td><td>April</td><td>May</td><td>June</td><td>July</td></tr>
<tr><td colspan="2">Display needs scoping with users</td><td>User testing (wireframes) & display specification</td><td colspan="2">Realisation of display and deployment in situ</td><td colspan="3">Assessment of display use in practice & corresponding change in sound level/s</td><td>Final report to funding body</td></tr>
</table>

Purpose

The purpose of this display is to provide sound pressure level and noise source information to staff members working in the Intensive Care Unit**.

The intent is that by providing more detailed information on noise sources than is currently available using ‘off-the-shelf’ monitoring equipment, staff members will be able to modify their activities to improve both patient experience and improve the working environment.

To achieve this a sound monitoring system is already in place in the unit. This display will take data on sound levels and location, and present the information in an intuitive manner to members of staff.

The display will be made available to staff early in April and decibel values will be measured over the following 12 weeks. Final results will be reported at the end of July 2017.

** Future capabilities might include the option to output reports (ie weekly/monthly reports of overall decibel values by shift pattern). Although current development is limited to the display functions only, the leaving the capacity to add these functions later should be considered.

Overall Description

Product functions

The display will visualise noise levels across Bay A of the Adult Intensive Care Unit at the John Radcliffe Hospital. This is an eight bedded area comprising six patient spaces in an open bay, and two private side rooms. Over each bed has been placed a microphone, and there is an additional 4x16 array of microphones in the centre of the open bay. There are 72 microphones in total, and data from these are collected continuously in the unit. Microphones 1-64 enable noise source positioning. Microphones 65-72 record decibel levels at specific locations within the unit, representing individual bed-spaces, the nursing station, and the entry 'vestibule' that contains doors to the staff room, sluice, and neighbouring bay. This initial display will focus on the individual noise level recorded by microphones 65-72. Data are output to comma separated .txt files every minute.

User classes and characteristics

The display will be used by healthcare staff in the Intensive Care Unit. Primary users will be nurses but other members of the multi-disciplinary team such as pharmacists, psychologists, physiotherapists, doctors, dieticians, and housekeepers will also be able to review the information displayed. Users will be trained clinicians, but will have no specific training in either information technology or sound monitoring, thus the device must be as intuitive and straightforward as possible. It is not intended that users be able to manipulate the data presented on the display, nor should they be able to change the displayed information or format, beyond perhaps changing the display to a darker-coloured 'night-mode' analogous to that found in car-based GPS-systems.

User environment

The Intensive Care Unit is a busy clinical ward within the hospital. The World Health Organisation recommends that noise levels in patient care areas should average 35dBA, with peaks no higher than 40dBA. Most Intensive Care Units operate at levels considerably higher than this. Sound pressure levels of around 60dBA are common. These high noise levels are likely to affect patient sleep patterns, which in turn may have implications for their recovery. High noise levels may also affect staff well-being and increase the likelihood of alarm fatigue, and important information being missed or ignored.

Noise 'alert' signs are commercially available which indicate when noise limits are breached. These provide limited information to users in the environment which hinders reflection on action, and therefore ultimately a lack of awareness of how to successfully reduce noise levels.

Infrastructure in the environment includes a range of accessible Wi-Fi networks, hard-wired network points, and easy access to power points.

Design/implementation constraints

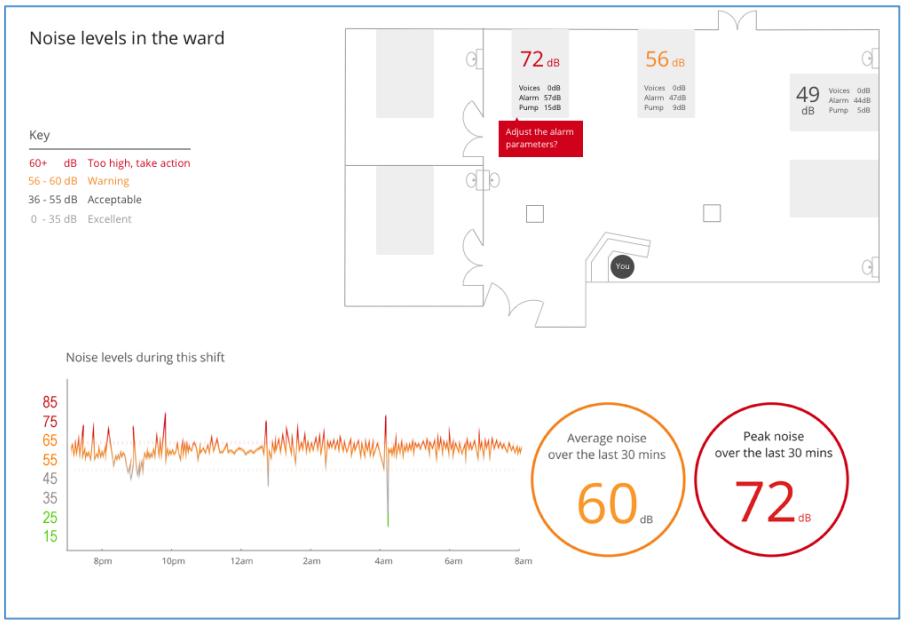
Font size/style should be easy to read from a distance of 50cm.

The option to change the display's colour-scheme overnight to limit light pollution is preferred, and it would be ideal if this transition was managed automatically, based on the system clock. Users may access the display using a variety of devices, so any interface should accommodate both touch-screen and traditional mouse/keyboard driven interactions. Primary use will be via a standard desk-top PC.

External Interface Requirements

User interfaces

See diagram for outline visual of main elements of proposed display design, developed through user discussions. *Please note that display 'real-estate' does not need to map exactly to this. Please also note that the ranges in the 'key' in this version have been updated (see 'system features' below). Finally, the specific sound channels (eg patient alarms, medical devices, or voices) do not need to be visualised as per this draft diagram.*



Hardware interfaces

Ideally the display should be hosted on an intranet server, thus primary access to the front-end will be browser-based. Multiple users may access the display simultaneously. The display may be accessed on devices with variable aspect ratios, with some 4:3 computer monitors still in use among other widescreen devices. It is likely that users will primarily access the display via PC-based systems, although it is possible that tablets (both Android and iOS) could be used.

Software interfaces

Comma separated .txt files (sample provided) saved every minute provide the raw data from which this display will process data for presentation. The recording system generates a file every minute, and within each text file data are collected approximately every second. Each individual record comprises 447 lines of data, formatted consistently. Lines 1-72 of each record represent the individual microphones in the ceiling of the intensive care unit. Microphones 1-64 provide the data to enable source location of key sounds.

All values for X & Y refer to distance from the bottom left hand corner of the floorplan which follows.

Microphones	Channel number	X in m	Y in m	Microphones	Channel number	X in m	Y in m
Array 1	1	3.27	4.51	**Array 3**	33	9.35	4.52
	2	3.30	4.49		34	9.38	4.50
	3	3.26	4.47		35	9.34	4.48
	4	3.23	4.51		36	9.31	4.52
	5	3.26	4.55		37	9.34	4.56
	6	3.30	4.53		38	9.38	4.54
	7	3.27	4.40		39	9.35	4.41
	8	3.17	4.48		40	9.25	4.49
	9	3.21	4.60		41	9.29	4.61
	10	3.34	4.60		42	9.42	4.61
	11	3.38	4.48		43	9.46	4.49
	12	3.15	4.28		44	9.23	4.29
	13	3.01	4.55		45	9.09	4.56
	14	3.23	4.77		46	9.31	4.78
	15	3.50	4.63		47	9.58	4.64
	16	3.45	4.33		48	9.53	4.34
Array 2	17	5.71	3.27	**Array 4**	49	9.29	2.63
	18	5.74	3.25		50	9.32	2.61
	19	5.70	3.23		51	9.28	2.59
	20	5.67	3.27		52	9.25	2.63
	21	5.70	3.31		53	9.28	2.67
	22	5.74	3.29		54	9.32	2.65
	23	5.71	3.16		55	9.29	2.52
	24	5.61	3.24		56	9.19	2.60
	25	5.65	3.36		57	9.23	2.72
	26	5.78	3.36		58	9.36	2.72
	27	5.82	3.24		59	9.40	2.60
	28	5.59	3.04		60	9.17	2.40
	29	5.45	3.31		61	9.03	2.67
	30	5.67	3.53		62	9.25	2.89
	31	5.94	3.39		63	9.52	2.75
	32	5.89	3.09		64	9.47	2.45

Microphones 65-72 record the SPL of each individual bed space, the nursing station, and the entrance ‘vestibule’ for Bay A.

Single microphones	Channel number	X in m	Y in m
	65	2.10	6.30
	66	2.10	3.30
	67	7.50	2.10
	68	10.50	2.10
	69	16.30	2.50
	70	16.30	6.80
	71	8.70	7.50
	72	4.50	11.70



The remaining 375 data points per second provide information on noise source location which filters through to another software programme (written in Julia) to indicate spatial features of noise.

Column A indicates the individual microphone number.

Columns B-AD indicate the dB value of each frequency band from each microphone. These data will enable future identification of dominant sound channels.

Column AE indicates the dBA value of each microphone.

Column AF indicates the loudness value of each microphone.

Overall decibel values can be calculated from the total mean value of all 72 microphones at any single time point.

System Features

- Dominant image displayed to be floor plan of Bay A
- “Current” (mean value from latest 15minutes available) individual bed space decibel values (measured in dBA); displayed as colour coded* numerical values
- Include option to touch/click on a bed space for additional information, including decibel level of specific sound channels (eg patient alarms, medical devices, or voices) to be displayed in individual bed spaces (this information may be available by late March)
- Overall decibel values for the last 12 hours; displayed on a line graph, colour coded* by measured value. X axis to be labelled time with current time displayed at the far right, y axis to be labelled decibels 0-85.
- Overall decibel levels for the last 30 minutes; displayed as a colour coded* numerical figure within a colour coded* circle
- Peak noise level in the last 30 minutes; displayed as a colour coded* numerical figure within a colour coded* circle. Include time stamp of peak noise. Tapping or clicking on this circle to bring up additional information, such as type (alarm, device, or voice) and location of noise.

- Future development of the display may include providing users with source location for the five most prominent noises and identification of sound types (will need to discuss programming schematic with project engineer from University of Southampton)

*colour coding: 0-35dB: green, 36-50dB: grey, 55-60dB: orange, >60dB: red

Functional requirements

Date/time displayed should be as close to real-time as is possible (data are displayed as hours/minutes, so there is no requirement for 'to the second' accuracy)

The alert levels (0-35, 36-50, 55-60, and >60) should be easily modifiable by a super-user, but not by users with normal access.

Performance requirements

Most recent data displayed must be credible as 'now'. As a minimum from the last minute; ideally from the last few seconds.

Budget

Expected quote in the region of ~£20-30K

Tender evaluation criteria

Criteria	**Weighting**
Resource capabilities to achieve timeline	30
Evidence of risk management strategies to meet short timeline	25
Flexible approach to allow ad-hoc iteration to visual aspects of display based on user-testing (ability to complete testing will depend on ICU workload therefore can be erratic)	20
Evidence of experience of similar work	15
Price	10

National Institute for Health Research

NIHR Research for Patient Benefit (RfPB) Programme

Final Report Form

IMPORTANT

Final reports are required from all projects funded through the NIHR Research for Patient Benefit Programme. The RfPB Programme requires a final report in order to:

- ensure accountability
- aid in appropriate dissemination of project results
- encourage quality assurance of project outputs
- assess the impact of the research supported by the Programme
- demonstrate the achievements of the Programme

Please keep these aims in mind while completing your final report.

The report needs to offer:

a) a clear summary of the project for practitioners and users of research
b) a record of challenges faced and modifications made to the study
c) a description of experience with patient and public involvement that might help identify lessons for future research
d) an impact assessment both locally and for the NHS more broadly
e) a summary of any outputs, such as publications, from the research (which should be updated as outputs occur). Completion of this report should not pre-empt any publications that have been prepared or are in preparation detailing project results.

The views expressed in this report should reflect those of the entire research team.

Following submission and assessment of this form, the final version of the scientific and lay summaries will be displayed on the NIHR CCF website and will be accessible to a wide range of interested parties.

You will be required to submit a final statement of expenditure at the same time as your final report. Please note that the completed final report along with a final statement of expenditure is required prior to release of the final project payment.

For further guidance or information on completion of your final report, please contact the regional Programme Manager at NIHR CCF, using the details below:

Dr Ramnath Elaswarapu
Programme Manager for the South Central region
ramnath.elaswarapu@nihr.ac.uk
Telephone number: 0208 843 8066
NIHR CCF help line: 0208 843 8057

National Institute for Health Research

NIHR Research for Patient Benefit (RfPB) Programme

Final Report Form

IMPORTANT

Note the maximum field sizes shown include both printing and non-printing characters such as spaces and carriage returns.

Reference Number PB-PG-0613-31034

Region South Central

Date submitted

For office use

1. Project Details

Project Title*:	Sleep in the ICU: Limiting Elements of Noise in the Critical Care Environment (SILENCE): a feasibility study		
NHS Contracting Organisation*:	Oxford University Hospitals NHS Foundation Trust		
Project Duration*: (months)	30 months	Grant Value:	£278,670.00
Start Date:	02 February 2015	Agreed Extension (months):	8 months
End Date:	31 July 2017	Revised End Date:	31 March 2018

2. Grant Holder's Details

Title*:	Prof		
Surname*:	Young	Forename*:	J Duncan
Department*:	Nuffield Department of Clinical Neurosciences		
Role in Project*:	Chief Investigator		
Institution*:	University of Oxford		
Street*:	c/o Kadoorie Centre, Level 3, John Radcliffe		
Town/City*:	Headley Way, Headington, Oxford County*: Oxfordshire		
Post Code*:	OX3 9DU		
Telephone*:	01865 231409	Extension:	N/A
Email Address*:	Duncan.Young@ndcn.ox.ac.uk		

3. Details of the Research Team

Co-applicant 1

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Role in project:	Lead Researcher	

Co-applicant 2

Title:	Dr Surname: Hinton	Forename: Lisa
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Organisation:	University of Oxford	
Telephone:	01865 289304	Extension: N/A
e-mail address:	Lisa.Hinton@phc.ox.ac.uk	
Role in project:	Qualitative Research expertise	

Co-applicant 3

Title:	Please select.. Surname:	Forename:
Post held:		
Department:		
Organisation:		
Telephone:		Extension:
e-mail address:		
Role in project:		

Co-applicant 4

Title:	Please select.. Surname:	Forename:
Post held:		
Department:		
Organisation:		
Telephone:		Extension:
e-mail address:		
Role in project:		

Co-applicant 5

Title: Please select.. Surname: Forename:

Post held:

Department:

Organisation:

Telephone: Extension:

e-mail address:

Role in project:

Co-applicant 6

Title: Please select.. Surname: Forename:

Post held:

Department:

Organisation:

Telephone: Extension:

e-mail address:

Role in project:

Co-applicant 7

Title: Please select.. Surname: Forename:

Post held:

Department:

Organisation:

Telephone: Extension:

e-mail address:

Role in project:

4. Changes to the Research Team

Please outline any changes that have been made to the research team, including an explanation of why these changes were required.

None

5. Lay/Plain English Summary*

Please provide a summary of the project, including background, findings and conclusions. It is essential that you make the content of your summary and the implications of your research evident to the lay public. It should avoid technical terms and should be written in an accessible style and emphasise in particular the potential for patient benefit arising from the study.
(Maximum 2,500 characters)

The purpose of the SILENCE project was to investigate techniques to decrease noise levels in intensive care units (ICUs). We also wanted to find out the best way to measure patients' experiences of noise.

The World Health Organisation recommends that ambient noise levels in hospital wards should be around 35 decibels (dB), with peak noises no louder than 40dB. Past research suggests that ICUs are much noisier than this, around 55-60dB, with peak noises >100dB.

Patients, relatives, and staff co-designed a mixed methods approach to the problem of reducing noise in ICUs. We developed a training programme for ICU staff to increase their understanding of the effect of noise on patients. We also made some simple changes to equipment in our ICU in Oxford and wrote alarm management guidelines to encourage natural day/night sleep patterns. We designed, built, and installed a new noise measuring system with a display screen to help staff visualise noise levels in the unit.

Noise levels were monitored throughout the project in the Oxford ICU. At the start noise levels were most commonly around 57dB with peaks to 125dB. After changes were put in place noise levels were about 53dB with peaks to 115dB. The final level achieved was 46dB (peak 99dB).

We learned from patients they are affected by noise in two main ways; disturbed sleep and confusion (delirium). We wanted to measure the quality of sleep for patients on ICUs so we could determine the effects of noise reduction initiatives. There is no measure used routinely, so we looked at measures based on EEGs (brainwaves, the gold standard outside ICUs), and questionnaires (Richards Campbell Sleep Questionnaire or RCSQ) completed by patients and nurses. 22 patients wore EEG equipment for one night. There was very little agreement between the EEG results and the nurse-completed questionnaires. Agreement between nurse-completed questionnaires and patient-completed questionnaires for 444 nights was better but not good enough to be used interchangeably.

In the UK, NICE guidelines recommend all patients treated on ICUs are tested twice daily for delirium using the "Confusion Assessment Method-ICU (CAM-ICU). We studied routinely collected CAM-ICU results from 20 ICUs. About 90% of patients had at least one CAM-ICU assessment each day. This indicates that delirium, as measured by the CAM-ICU, might be a better way to measure the effect of ambient noise on patients in ICUs, rather than measures of sleep quality.

6. Keywords*

Please provide up to 8 keywords that relate to the research undertaken in this study.

Intensive Care Unit
Sound Pressure Levels
Noise
Patient experience
Mixed methods
Sleep measures

7. Summary of Research and Findings*

Please provide a structured summary of the research including background, aims and objectives, methods, key findings, expected impact on the relevant field and conclusions.
(Maximum 10,000 characters)

Background:
The World Health Organisation (WHO) recommends ambient noise levels (LAeq24) in patient areas should be ~35dB, with peak noises no louder than 40dB. ICUs are much louder than this with ambient noise levels of 55-60dB, and peak levels over 100dB. We confirmed this in 2012 when we measured noise levels in five ICUs in the Thames Valley region (doi:10.1186/cc12870).

Aims:
To identify ways to reduce ambient noise levels in ICUs and to evaluate measures of the effects of ambient noise on patients.

Methods overall:
Mixed methods multi-phase project including an accelerated experience-based co-design component.

Methods 1: Secondary analysis:
To understand patients' experiences of noise in an ICU we conducted secondary analysis of anonymised interview transcripts from a 2005 project that had explored the overall patient experience of being treated on an ICU (http://www.healthtalk.org/peoples-experiences/intensive-care/intensive-care-patients-experiences/topics). We explored experiences related to noise.

Results 1: Secondary analysis results:
Noise directly, or indirectly, clearly affects patients in an ICU. Patients and their families felt constant noise in the environment prevents sleep. They also identified the most intrusive and disturbing sounds including monitoring alarms, bin lids, and disruption from other patients and visitors. We also found patients found it particularly hard to sleep when lights were left on. Some patients spoke about nightmares and being too frightened to sleep. These findings were published in PlosOne (doi:10.1371/journal.pone.0153775).

Methods 2: Ethnography:
To confirm issues raised in 2005 were still current, we spent 45 hours in the ICUs in Oxford observing activity and noise levels. We focussed on the general adult ICU but spent time in the neurosciences and neonatal ICUs to compare different environments.

Results 2: Ethnography results:
We confirmed that noises mentioned by patients in 2005 remained a problem. We also found that staff working in the ICUs knew it was noisy and tried to make it quieter, but struggled to know what to change, or how to monitor noise levels.

Methods 3: Focus group:
We conducted a focus group with ICU staff to explore their experiences of noise.

Results 3: Focus group results:
We identified themes which mapped well to our existing analysis frame. Staff members were keen to reduce noise levels but admitted they didn't really know what to do. They also felt a certain amount of noise was unavoidable.

Methods 4: Co-design:
We prepared a "trigger film" from Healthtalk.org interviews that had been audio or video-recorded. We presented this and composite data from the interview analysis, ethnography, and focus group to a group of staff and patients to help plan the intervention to reduce noise in the ICU.

Results 4: Co-design results led to the following work:
- Simple environmental changes

- Swapped metal bin lids for plastic soft-close
- Proposed a ‘lights out’ plan to encourage natural circadian rhythms
- Wrote alarm management guidelines suggesting volume appropriate to background noise and individualised settings to reduce unnecessary alarms
- Training programme for ICU staff to highlight effects of noise on patients in the ICU developed with medical educationalist to ensure curriculum design in line with adult education theory
- Teaching materials provided in a variety of formats to maximise appeal, recognising that people gain knowledge and understanding through different processes
- Course consists of e-learning module and experience session
  - e-learning includes clips from patient interviews, information about noise levels, sleep in the ICU, and self-reflection opportunities
  - experience session, lasting 6 minutes, puts staff member in position of a patient in the ICU (in bed, wearing glasses to disturb vision, listening to sounds of the ICU, connected to monitoring equipment) and subjected to live (inter)action as faculty perform activities around the bed (eg. opening/closing of drawers/cupboards/blinds, rustling packets, running water, wheeling trolleys, raising/lowering bed, activating blood pressure monitoring, re-positioning ‘patient’, general chat around the bedside).
- 116 individuals have completed the course; all found it useful, 97% said they would change practice, and 95% thought staff could do more to create a less stressful environment for patients
- Participant feedback mirrors patient experience; primarily feel ‘worried’, ‘frightened’, ‘stressed’, ‘confused’, ‘uncomfortable’, ‘scared’, ‘afraid’ and ‘alone’
- Designed, built, and installed a noise measuring system with display screen to help staff visualise noise levels in the unit
- ‘Off-the-shelf’ alert signs have not been shown to affect noise significantly.
  - may be too responsive to noise
  - by the time a busy workforce is able to check visual alert, noise no longer elevated
- We set out to create a display capable of visualising a meaningful ‘lag’ to capture noise over time
- Following principles of user-centred design we worked closely with ICU staff to understand what information they wanted to see, and how they might use it
- Final iteration incorporates two views; both screens predominantly ‘dark’, minimising light emission and disturbance to patients
  - Primary screen displays noise levels for 'shift' & 'hour', with trend graphs
  - Secondary screen displays a floorplan layout overlaid with individual source points of noise. These points use a traffic light colour scheme to depict levels of noise, and fade over time. This allows fast identification of potential 'hot spots' of noise in the unit

Methods 5: Measuring noise levels:
Noise levels were monitored initially with single point noise monitoring devices positioned centrally. From November 2016 we used a multi-point microphone array enabling noise location as well as noise level. We developed this system in collaboration with the Institute of Sound and Vibration Research, University of Southampton. The full report for the acoustic development work is included as Appendix A.

Results 5: Measuring noise levels:
Baseline median LAeq24 (24 hour average) was 57.0dB (IQR 3.2), with a minimum and maximum LAeq24 of 53.0dB & 63.3dB respectively. The maximum peak was 124.8dB. Interim measures (April 2017) suggested a reduction of ~4dB. Median (IQR) was 53.2dB (5.1). Minimum & maximum LAeq24 were 44.4dB & 91.8dB respectively. Maximum peak was 115.3dB. Final measures (January-March 2018) indicate further reductions with a median (IQR) of 46.1dB (5.7) and a maximum of 99.3dB.
Sound levels have been continuously recorded since installation. Analysis and development of visualisation methods continues.

Methods 6: Evaluate Patient Related Outcome Measures:
We learned from patients, both directly and through secondary analysis, two key areas of the patient experience are affected by noise; 'sleep' and 'delirium'.
For patients able to complete it themselves, the Richards Campbell Sleep Questionnaire (RCSQ) (ISSN:1061-3749)) is widely considered the best option. We wanted to know if nurse-completed RCSQ correlated with EEG sleep monitoringand if nurse and patient-completed RCSQs correlated with each other. Good correlation might indicate nurse completed sleep measures could be used routinely in the ICU. We recruited 44 patients to wear 3-lead EEG monitoring.

Results 6: Evaluate Patient Related Outcome Measures:
Sleep patterns for patients in the ICU were extremely poor. The median (IQR) sleep time was 02:05:45 (03:30:30) with individual sleep bouts of 1 minute. In total patients had 7 minutes (5.6%) of REM sleep and 13 minutes (10.2%) slow wave, or deep, sleep per hour. Patient tolerance of EEG equipment was low. For the 24 patients who wore the device overnight and completed the RCSQ, correlation was limited (Spearman's Rho -0.123). A second phase of sleep monitoring included actigraphy. For the 13 patients who wore actigraphy and EEG monitoring, correlation of sleep duration was not good (Spearman's Rho 0.577). We expanded our single-site project via the NIHR local clinical research network, ultimately recruiting 582 patients from 20 sites. Correlation analysis confirmed nurse completed RCSQ is not appropriate as a surrogate measure for patient-reported sleep in the ICU.
In the UK, NICE recommends all patients treated on ICUs are tested twice daily for delirium. We recorded routinely collected delirium screening results as part of the multi-site study. This indicated >90% of patients have at least one assessment per day. Delirium could therefore be an appropriate outcome measure for a future study.

Key Findings:
- Experiential simulation of the ICU is feasible
- Patient experiences are a valuable resource to motivate and drive practice change
- User-centred design principles worked well in this context
- Patient sleep in the ICU is extremely poor
- Robust routine measures of sleep in the ICU are still not available
- Nurse completed RCSQ not suitable as surrogate measure for patient-reported sleep
- Most patients admitted to the ICU have capacity assessed at least daily
- Education can reduce ambient noise

Impact:
This was a feasibility study so impact is limited, however the study has generated both professional and media interest.
The DIPEx charity is keen to use SILENCE expertise to expand their remit more widely to include educational materials and resources. This would need input from and liaison with the Health Experiences Research Group (University of Oxford) who own the interview archive dataset.

Conclusions: It is feasible to deliver a well-designed training curriculum within a time and resource constrained ICU. It is also possible to create an intuitive user-defined visualisation of noise. Further development work is needed before this system can be more widely deployed. Sleep remains difficult to measure in the ICU. Delirium could be a suitable endpoint for a future study.

8. Changes in the project since initial approval*

Please summarise any changes made to the project as outlined in the original proposal and outline the reasons for these changes. If there were no changes to the original plans, write 'not applicable'. **(Maximum 2,500 characters)**

Aims and objectives:
Not applicable. The aims and objectives remain unchanged.

Research Plan and Methodology:
We proposed our initial idea of 'porting' the sound of monitor alarms to hand-held devices which would vibrate silently. As each patient in the ICU is looked after by a single nurse, we felt that this would be a good technological approach to changing the environment. However, this was universally felt to be the wrong approach and had no support from either the staff or the patients. Instead the group was unanimous in agreement to raise awareness of the effect high noise levels has on patients. There was also good support for a more informative visual display of environmental noise levels.

Investigation of the cost of implementing this ported alarms was undertaken. Estimates of £0.25-0.4M were obtained from appropriate suppliers. With no support from patients and a high cost this approach was abandoned.

9. Patient and Public Involvement*

The RfPB Programme is particularly keen to learn from the experiences of research teams regarding patient and public involvement (PPI) and contribution from PPI members involved in the research is encouraged when completing this form. Please provide comment on your experiences with PPI, any changes made and lessons drawn. Please include detail of PPI with dissemination and with trajectory into practice both in the project and beyond. **(Maximum 5,000 characters)**

We had a strong PPI plan for this project. From the outset, patient involvement was built into the design method. Experience-based co-design brings patients and staff together to develop quality improvement projects. We worked closely with the Oxford University Hospitals NHS Foundation Trust Intensive Care Unit Patient Forum throughout the project. This forum includes ex-patients and their families. They meet on a regular basis to advise on clinical care and relative support, and to help guide research studies. We included them in the joint patient/staff meeting organised early in the project and their input directly shaped the direction of the project. Perhaps most obviously this manifested in the lack of support for the original proposal outlined in the grant application and the guidance towards an alternative approach.

Our patient member of the research team (Peter Edmunds) was fully involved in the project from the beginning. He helped the research team identify appropriate quotes from the patient interviews to include in the 'trigger film' shown at the patient/staff meeting. He has also been a key part of the project's interactions with the media and has been a co-author on a number of publications. Having this level of patient support has made the project stronger and has helped engage clinical members of staff.

To ensure maximum impact, subsequent development and deployment of the intervention has made continued references to the patient narratives and the collaborative co-design nature of the project. Throughout the project we have therefore been able to ensure focus and relevance to the needs of both staff and patients

The local ICU patient forum were invaluable to the success of this project. They were fully engaged from the outset and have remained interested throughout. Their insight with regards to how patients and visitors might interpret information on the visual display changed the default view for the prototype system. Specifically we initially presented a version of what is now the 'secondary' screen as the default view. This displayed clear decibel values for each bedspace. Patients and relatives felt quite strongly that this information would be used as evidence to support requests to move bedspaces. This, they felt, would be an inappropriate use of the data. To resolve this we have presented the generic, non-specific location screen as the default. Staff have to actively select the floorplan layout display.

The SILENCE project was one of the first to involve the local patient and family group. Since then, the group has been approached by many more teams and 'research review' now forms part of their formal remit. As a group, they are pleased to be able to be in a position to influence future care of patients in the ICU.

Amongst other post-project activities (for which we have negotiated retention of project underspend) we are planning a joint dissemination event with the HPNoSS team (Kings College London). This is another project that has been evaluating the problem of noise in the intensive care unit and we feel that the work is synergistic. This will enable us to discuss study results with stakeholders (patients, staff, and industry partners). We expect that these discussions will guide the direction of potential future research collaborations.

10. Next Steps to Patient Benefit*

Please provide comment on the likely implications for practice which may result from the outcomes of this project and the next steps to be taken to ensure patient benefit both locally and more broadly. Steps already taken and planned for the future should be included. While in funding research, RfPB emphasises a 3-5 year trajectory into practice, it is important not to 'overclaim' and care should be taken to cover the limitations of the study and any risks associated with implementation. Where the project is a pilot, include details of plans for a definitive study, including the likely funder and timetable for its submission. Please give reasons if there is no plan to go forward to a trial at this stage. **(Maximum 5,000 characters)**

We have demonstrated that it is feasible to deliver a well-designed training curriculum within the time and resource constrained ICU. We have also shown that it is possible to create an intuitive user-centred visualisation of noise. Future plans include developing both these areas further.

An ideal scenario would be a cluster randomised trial of a complex intervention. This would include both the training and the noise display. We would realistically expect to submit an application to the NIHR Health Technology Assessment funding stream within two-three years, with a view to final results being shared with the clinical community in 2024/25. An alternative approach might be to consider a Programme Development grant and complete the necessary refinements over the first two years before running the RCT. This would be a similar timeframe to delivery, but with a simplified approach to the funding required.

Prior to delivery in multiple NHS Trusts, the background technology implementation for the display system needs to be simplified. The current prototype system is too complex and expensive for multi-site deployment. The next step would be to work with a multi-disciplinary team to reduce both the hardware and software needs. We have discussed this with our existing partners who have confirmed they would be interested in submitting a joint funding bid, perhaps through the NIHR Invention for Innovation fund, or as part of a wider Programme Development grant. We have also been approached by other institutions who are interested in the field. This may lead to a national collaboration project to further develop the information that can be displayed visually.

Results from the SILENCE project indicate that increasing staff understanding of noise can have an effect on the noise levels in the ICU environment. We are in touch with Oxford University Innovations with a view to creating a stand-alone training course that would include both modules developed during the SILENCE project. There are three possible business models that will be explored. The simplest would be to develop an in-house course, delivered through the Oxford Simulation, Teaching and Research Centre (OxSTaR). This would generate funds for the OxSTaR centre through course fees. An alternative model would be to develop an associated 'train the trainer' course through which we could give external NHS Trust groups the materials to train their own staff, either as an ad-hoc basis, or as part of local induction. The final approach would be to establish a training delivery HQ, using the ALERT model (http://www.porthosp.nhs.uk/departments/alert/alert.htm). Associated with this, we are also in discussion with DIPEx, the charity behind healthtalk.org. Clips from interviews with patients describing their experiences of intensive care form the basis of the training modules. Similar interviews have been created on a diverse range of health topics. DIPEx is keen to use the expertise from the SILENCE team to help them develop a business case to expand their remit more widely to include educational materials and resources. This would need input from and liaison with the Health Experiences Research Group (University of Oxford) who own the interview archive dataset.

11. Key Presentations and Publications*

Please list here any presentations and publications which have resulted from the work. This should include journal articles, conference proceedings, press releases and all publications in the lay and scientific press, including website links to published articles if appropriate. Items that are forthcoming should also be included. **Please note you are contractually obliged to provide 28 days notification prior to any publication.**

Author (s)	Title	Reference/Further Details
Senaratne DNS et al	Sleep in the ICU: Recovering patients continue to experience sleep deprivation	Oral presentation, 33rd Congress of the Scandinavian Society of Anaesthesiology and Intensive Care Congress; Acta Anaesthesiologica Scandinavica 59:41, June 2015
Hinton L et al	Patients and staff join researchers to design environmental changes in the Intensive Care Unit	Oral presentation; The Kings Fund: Transforming Patient Experience, November 2015
Darbyshire JL et al	Noises in the Intensive Care Unit: What goes bump in the night?	Oral presentation; Thames Valley Clinical Research Network Critical Care Research Symposium, November 2015
Jeffs EL et al	Measuring sleep in the Intensive Care Unit: A systematic review of the literature	Poster presentation; Thames Valley Clinical Research Network Critical Care Research Symposium, November 2015
Darbyshire JL et al	Noises in the Intensive Care Unit: what goes bump in the night	Poster presentation; Intensive Care Society State of the Art conference, December 2015; Journal of the Intensive Care Society, November 2015 16: 104-128, doi: 10.1177/1751143715615287
Darbyshire JL	Excessive Noise in intensive care units	Editorial; BMJ 2016;353:i1956 doi: 10.1136/bmj.i1956
Hinton L	The intensive care unit was so noisy I couldn't sleep	Views & reviews; BMJ 2016;353:i:2150 doi: 10.1136/bmj.i2150
Darbyshire JL et	"I can remember sort of vivid people…but to me they were plasticine." Delusions on the Intensive Care Unit: What do patients think is going on?	Published 20 April 2016; doi: 10.1371/journal.pone.0153775

Publications (cont.)

Author(s)	Title	Reference/Further details
Darbyshire JL et al	Experiential learning in the ICU: Using the AEBCD approach in practice	Oral presentation; 31st Annual British Association of Critical Care Nurses conference, Glasgow, September 2016
Mueller-Trapet M et al	Acoustic Source Localisation with microphone arrays for remote noise monitoring in an intensive care unit	Poster presentation; MENSUS Industry Showcase, Southampton, October 2016
Mueller-Trapet M et al	Acoustic Source Localisation with microphone arrays for remote noise monitoring in an intensive care unit	Poster presentation; Thames Valley Clinical Research Network Urgent Care Research Symposium, Oxford, November 2016
Hird C et al	An audit to review rehabilitation practices within intensive care	Poster presentation; Thames Valley Clinical Research Network Urgent Care Research Symposium, Oxford, November 2016
Darbyshire JL et al	Sleep deprivation in the Intensive Care Unit	Oral presentation; Thames Valley Clinical Research Network Urgent Care Research Symposium, Oxford, November 2016
Hinton L	Experiential learning in the ICU: Using the AEBCD approach in practive	Oral presentation; DiPEx International Meeting, Tenerife, November 2016
Darbyshire JL et al	Deep experience is never peaceful: Raising awareness of noise sources in the ICU	Poster presentation; Intensive Care Society State of the Art conference, London, December 2016
Mueller-Trapet M et al	Machine listening in combination with microphone arrays for noise source localisation and identification	Oral presentation; 173rd Acoustical Society of America, Boston, June 2017; The Journal of the Acoustical Society of America 141, 3964 (2017); doi: 10.1121/1.4989025
Jeffs EL, Darbyshire JL	Measuring Sleep in the Intensive Care Unit: A critical appraisal of the use of subjective methods	Published June 20, 2017; Journal of Intensive Care Medicine; doi: 10.1177/0885066617712197
Darbyshire JL et al	Patient sleep in the intensive care unit remains elusive	Poster presentation; 30th Annual Congress European Society of Intensive Care Medicine, Vienna, September 2017
Darbyshire JL	Lights, sound, action!	Panel presentation; Intensive Care Society State of the Art conference, London, December 2017

Darbyshire JL et al	Developing a training package to reduce noise levels in the Intensive Care Unit	Poster presentation; Royal College of Nursing Education Forum National Conference & Exhibition, Newcastle, March 2017
Mueller-Trapet M et al	Acoustic Source Localization with Microphone Arrays for Remote Noise Monitoring in an Intensive Care Unit	Published April 2018 Applied Acoustics 139:93-100 DOI: 10.1016/j.apacoust.2018.04.019
Darbyshire JL et al	"You gain strength, courage, and confidence by every experience in which you really stop to look fear in the face": A training package for the ICU	Oral presentation; 33rd Annual British Association of Critical Care Nurses conference, Bournemouth, September 2018

Future planned publications

Author (s)	Working Title	Reference/Further details
Darbyshire JL, Hinton L	Using patient narratives to design an intervention to reduce noise in the Intensive Care Unit	'research insight' article submitted to Journal of Health Design (for Care Foundation guest edited issue, November 2018)
Darbyshire JL et al	Evidence-based co-design for an ICU learning package	'really good stuff' article aiming for November 2018 issue of Journal of Medical Education
Darbyshire JL, Greig PR	Adult education theory in the healthcare environment	Proposal accepted for British Journal of Anaesthesia (Education)
Darbyshire JL, Hinton L	Mixed methods approach to noise identification in the ICU	Aiming for submission to BMJ
Darbyshire JL et al	Using the Richard Campbell Sleep Questionnaire to assess sleep in the ICU: correlation between measures	Aiming for submission to Critical Care Forum
Darbyshire JL, Young JD	Literature Review of intensive care unit sound pressure levels	Aiming for submission in Critical Care Forum

Future planned dissemination activities (negotiated retention of project underspend to fund events and conference attendance)

Event/publication	Location/Date/Details
Joint stakeholder dissemination event with HPNoSS team (Kings College London)	London, Summer 2018
Intensive Care Society State of the Art conference,	London, December 2018
Final results presentation event for multi-site sleep assessment study	TBC
Press release to accompany mixed methods results article	
Press release to accompany sleep assessment results article	

Lay press/media publications from the project

Type	Title	Further details
Press Release, November 2014	Researchers at the University of Oxford are looking to help patients sleep better during their stay in hospital.	https://www.ndcn.ox.ac.uk/news/researchers-aim-to-help-patients-sleep-better-during-their-stay-in-hospital
Press Release, April 2016	Researchers target intensive care's intensive noise problem by working with staff and patients to make the intensive care unit a quieter place to recover	http://www.ox.ac.uk/news/science-blog/intensive-care-delusions-hamper-recovery
BBC Radio 5 Live Breakfast Show	1st April 2016	Interviews with Julie Darbyshire & Peter Edmonds
BBC2: Victoria Derbyshire Show	1st April 2016	Interview with Julie Darbyshire (short clip: http://www.bbc.co.uk/programmes/b07z45x4)
Several local radio stations	1st April 2016	Interviews with Julie Darbyshire & Peter Edmonds
A number of national newspapers also picked up the story	April 2016	Amongst others we featured in the Telegraph, the Daily Mail, and the Sun
BBC World Service: Health Check	June 2016: Switching off the noisy alarms in hospitals which don't aid recovery	Interview with Julie Darbyshire & Lisa Hinton http://www.bbc.co.uk/programmes/p03wwcmq
BBC Radio 4: Inside Health	4th October – noise levels in the ICU	http://www.bbc.co.uk/programmes/b07wt5v1
BBC Radio 4: Inside Health	18th October – ICU delirium	http://www.bbc.co.uk/programmes/b07z45x4
Press Release, October 2016	Dr Mark Porter from BBC Radio 4 Inside Health talks to the SILENCE research team about the problem of high noise levels in the intensive care unit (ICU)	https://www.ndcn.ox.ac.uk/news/noise-sleep-and-delerium-in-intensive-care
ITV local news	15th June 2017: What can be done about noise in hospitals	http://www.itv.com/news/meridian/update/2017-06-15/what-can-be-done-about-noise-in-hospitals/

SILENCE Project Report

Design, Implementation and Installation of a Microphone Array for Noise Source Localisation

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1. Introduction

This document summarizes the work carried out for the SILENCE project from December 2015 to November 2016. The goal of this project was to design, create and install a microphone array system to automatically localize and quantify noise sources in one bay of the adult Intensive Care Unit (ICU) at the John Radcliffe Hospital in Oxford.

After a brief overview of the theoretical background in Chapter 2, especially regarding various beamforming algorithms, the microphone array design is described in Chapter 3. A simulation model for the ICU environment is presented in Chapter 4.

A detailed description of the array system follows with the design of the audio hardware in Chapter 5 and an overview of the software that has been created to process the audio data and display the results in Chapter 6. The actual installation in the ICU is covered in Chapter 7. The project outcomes are summarized in Chapter 8.

The document is concluded with an appendix outlining the practical aspects of installing (Chapter A) and running (Chapter B) the system.

2. Theoretical Background

This section gives an introduction to array signal processing, specifically different algorithms belonging to the topic of beamforming. A good general overview of the fundamentals of beamforming, and the basis of much of what is described here, is given by Johnson and Dudgeon [1] and Van Trees [2].

2.1. Preliminaries

Before discussing the algorithms in detail, several general variables have to be introduced to establish a common nomenclature.

2.1.1. Steering Vector

A fundamental part of beamforming calculations is the so-called *steering vector* $\mathbf{w}_i(k)$, which models the transfer function between the M microphones and the *scan point* with index i, where an acoustic source is assumed to be located:

$$\mathbf{w}_i(k) = \frac{e^{-\mathrm{j}kd_i}}{M}\,, \tag{2.1}$$

or, including the attenuation according to distance,

$$\mathbf{w}_i(k) = \frac{e^{-\mathrm{j}kd_i}}{d_i \cdot \sum 1/d_i^2}\,. \tag{2.2}$$

Here, $k = 2\pi f/c$ is the wavenumber, and $c \approx 343\,\mathrm{m/s}$ is the speed of sound. The distance d_i between the scan point with index i and the microphones is calculated with the *Euclidean norm* $\|x\|$ as

$$d_i = \|\mathbf{r}_{\mathrm{scan,i}} - \mathbf{r}_{\mathrm{mic}}\|\,, \tag{2.3}$$

where the locations of the array microphones in three-dimensional Cartesian coordinates are denoted by the vector $\mathbf{r}_{\mathrm{mic}}$ and the locations of the scan points, where the beamforming results will be evaluated, are denoted by $\mathbf{r}_{\mathrm{scan}}$. The factors M and $\sum 1/d_i^2$, respectively, are the normalization factors for level estimation.

The choice of distributing the scan points determines the spatial resolution in the beamforming map and thus in a way the accuracy of the beamforming result. At the same

time it determines the computational effort, as the beamforming equations have to be calculated separately for each scan point.

2.1.2. Beampattern and Performance Parameters

A quantity to evaluate the performance of a microphone array for beamforming applications is the *beampattern*. The beampattern is defined as the array response to a unit source in a specific direction:

$$A_{i,j}(k) = \left| \frac{\mathbf{w}_i(k)^H \mathbf{w}_j(k)}{\|\mathbf{w}_j(k)\|^2} \right|^2 , \tag{2.4}$$

where $\frac{\mathbf{w}_j(k)}{\|\mathbf{w}_j(k)\|^2}$ is the modelled pressure produced by the unit source and $\mathbf{w}_i(k)$ is the steering vector in different directions. An example of the beampattern plotted in dB together with three performance parameters is shown in Figure 2.1 as a function of the steering angle. The source is located at 0 degrees.

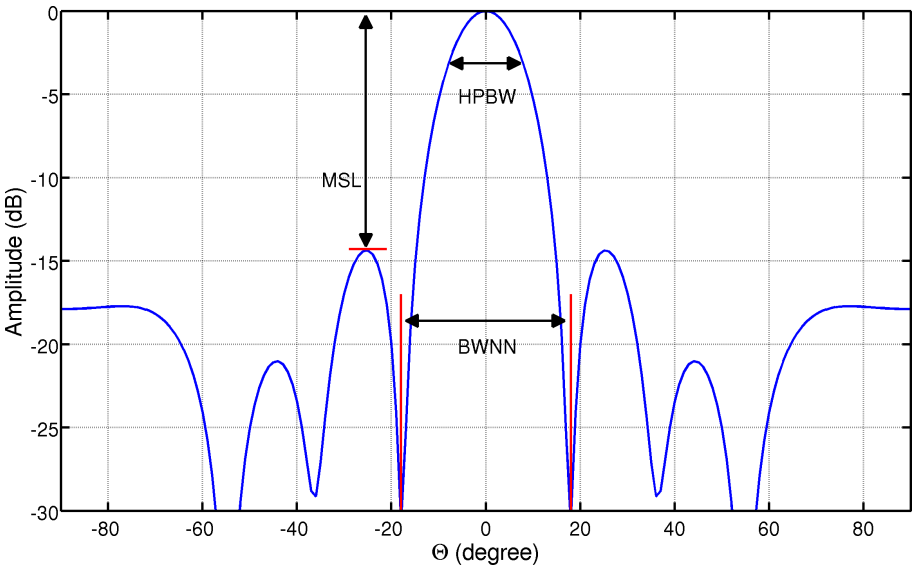


Figure 2.1.: Exemplary beampattern together with array performance parameters: Maximum Sidelobe Level (MSL), Half-Power Beamwidth (HPBW), Beamwidth Null-to-Null (BWNN)

Maximum Sidelobe level (MSL): As one of the most important array parameters, the MSL represents the dynamic range between the actual source and the so-called *phantom sources* caused by sidelobes of the beampattern. Acceptable values of the MSL are $-10\,\mathrm{dB}$ to $-6\,\mathrm{dB}$.

Half-Power Beamwidth (HPBW): The HPBW is a measure of the spatial resolution, usually measured in degrees. It is defined as the width between the points where the beampattern drops to $-3\,\mathrm{dB}$ relative to the maximum. Sources that are more than the HPBW apart can typically be separated.

Beamwidth Null-to-Null (BWNN): Another parameter related to the spatial resolution is the BWNN, which is the width between the first minima measured from the mainlobe. It is less important than the HPBW and seldom used.

Directivity Index (DI): A single-value parameter that gives an indication of the spatial selectivity of an array steered in a specific direction is the Directivity Index in dB. This relates the power of the beampattern in the steering direction (usually the maximum value) to the average power:

$$DI = 10 \cdot \log_{10} \left(\frac{A_{j,j}}{\frac{1}{N_i} \sum_i A_{i,j}} \right) . \tag{2.5}$$

2.1.3. Cross-Spectral Matrix

To capture the essential spectral information – including the correlation between microphones – from the recorded pressure signals, the so-called *Cross-Spectral Matrix* $\mathbf{C}(k)$ can be calculated according to

$$\mathbf{C}(k) = < \mathbf{p}(k)\, \mathbf{p}(k)^H > , \tag{2.6}$$

where $\mathbf{p}(k)$ is the vector of pressure signals at the array microphones and $()^H$ is the complex conjugate transpose. The operation $< x >$ represents the spectral estimation, which involves averaging the Cross-Spectral Matrix across many signal blocks.

In real-time systems, the averaging for spectral estimation is not feasible, and hence a running estimate of the Cross-Spectral Matrix has to be obtained. This is achieved by exponential smoothing, where the Cross-Spectral Matrix in the current audio block with index i is given by

$$\mathbf{C}_i(k) = (1 - \alpha) \cdot \mathbf{C}_{i-1}(k) + \alpha \cdot \mathbf{p}_i(k)\, \mathbf{p}_i(k)^H , \tag{2.7}$$

where the result in the previous block is $\mathbf{C}_{i-1}(k)$ and the exponential smoothing factor is α. The smoothing factor can be related to the time constant τ of this filter as

$$\alpha = 1 - e^{-\frac{(n_{\text{block}} - n_{\text{overlap}})/f_s}{\tau}} , \tag{2.8}$$

where f_s is the sampling rate in Hz, n_{block} and n_{overlap} are the block size and number of overlap samples, respectively. The smoothing factor determines how the weight is distributed between current data and the result from previous blocks.

In all subsequent equations, the dependence on the wavenumber k will be dropped to improve readability.

2.2. Classical and Adaptive Beamforming

The most basic algorithm is the Delay-and-Sum beamformer, which compensates for the phase differences of the signal across the array of microphones by using the steering vector:

$$\underline{B} = \mathbf{w}^H \mathbf{p}\,, \tag{2.9}$$

or, using the Cross-Spectral Matrix and computing the average output power,

$$|\underline{B}|^2 = \mathbf{w}^H \mathbf{C}\, \mathbf{w}\,. \tag{2.10}$$

If the correlation information of the Cross-Spectral Matrix is not used, computation power and memory can be saved by applying the averaging to the beamforming output power calculated according to Eq. (2.9):

$$|\underline{B}|^2 =< \left|\mathbf{w}^H \mathbf{p}\right|^2 > \ . \tag{2.11}$$

The advantage of the Delay-and-Sum algorithm is that it is very robust, however it only has limited spatial resolution capabilities.

Knowledge about the spectral information contained in the Cross-Spectral Matrix can be exploited to adapt the beamformer to the signal content and thus increase the spatial discrimination. The most popular adaptive algorithm is the Minimum-Variance Distortionless Response (MVDR) beamformer [3], which involves the inverted Cross-Spectral Matrix:

$$|\underline{B}|^2 = \frac{1}{\mathbf{w}^H \mathbf{C}^{-1}\, \mathbf{w}}\,. \tag{2.12}$$

Since the matrix inversion can become unstable, robust variations of the MVDR algorithm have been developed. The one used here applies diagonal loading to overcome the instability problem [4, 5].

2.3. Algorithms based on the Decomposition of the Cross-Spectral Matrix

Another group of beamforming algorithms employs the eigenvalue decomposition of the Cross-Spectral Matrix, yielding a diagonal matrix of eigenvalues λ and a matrix of eigenvectors $\mathbf{U}$:

$$\mathbf{C} = \mathbf{U}\lambda\mathbf{U}^H \tag{2.13}$$

In real scenarios, only a limited number of uncorrelated sources will be active at the same time. This means that there are fewer significant eigenvalues than microphones, i. e. $\mathrm{rank}(\mathbf{C}) = L \ll M$, so that after ordering the eigenvalues,

$$\mathrm{diag}(\lambda) = [\lambda_{S,1},\, \lambda_{S,2},\, \ldots,\, \lambda_{S,L},\, \lambda_{N,1},\, \ldots,\, \lambda_{N,M-L}]\,, \tag{2.14}$$

the Cross-Spectral Matrix can be split into a signal part $\mathbf{C}_S$ and a noise part $\mathbf{C}_N$:

$$\mathbf{C}_S = \mathbf{U}_S \lambda_S \mathbf{U}_S \tag{2.15}$$

$$\mathbf{C}_N = \mathbf{U}_N \lambda_N \mathbf{U}_N \tag{2.16}$$

This decomposition can then be used in some more advanced beamforming algorithms described in the following sections.

2.3.1. Multiple Signal Classification (MUSIC)

The MUSIC algorithm makes use of the previously described decomposition of the Cross-Spectral Matrix into a signal and a noise subspace. MUSIC projects the steering vectors onto the noise subspace and then searches for the direction of minimum power (or rather a maximum of the inverse) [6]

$$|\underline{B}|^2 = \frac{1}{\mathbf{w}^H (\mathbf{I} - \mathbf{U}_s \, \mathbf{U}_s^H) \, \mathbf{w}} \,, \tag{2.17}$$

where instead of the actual noise subspace the complement to the signal subspace is used as this usually involves fewer computations. It can be seen that the actual level information is lost in the process so that MUSIC is mainly used to estimate the direction-of-arrival (DOA) rather than actual source contributions.

2.3.2. Functional Beamforming

A different approach has been presented recently by Dougherty [7], where the beamforming result is raised to the power ν in order to increase the spatial resolution:

$$|\underline{B}|^2 = (\mathbf{w}^H \mathbf{U} \, \lambda^{\frac{1}{\nu}} \, \mathbf{U}^H \, \mathbf{w})^\nu \,. \tag{2.18}$$

Here, the eigenvalues are first raised to the power $1/\nu$ (the ν-th root) to compensate for the change in levels. In practice, however, this does not work perfectly so that accurate level information is usually lost. A modified version of the algorithm can be implemented to improve the level estimation, leading to

$$|\underline{B}|^2 = (\mathbf{w}^H \mathbf{U} \, \lambda^{\frac{1}{\nu}} \, \mathbf{U}^H \, \mathbf{w})^\nu \cdot \|\mathbf{w}\|^{1-\nu} \,. \tag{2.19}$$

This approach is based on the fact that the sound pressure recorded by the microphones can be approximated by the steering vector. Eq. (2.19) improves the ability to estimate levels with the functional beamformer.

2.3.3. Subspace Beamforming

Another algorithm that makes use of the eigenvalue decomposition of the Cross-Spectral Matrix is the subspace approach suggested by Sarradj [8]. Here the contributions to the Cross-Spectral Matrix by the individual eigenvalues

$$\mathbf{C}_{s,i} = \mathbf{U}_{s,i}\,\lambda_{s,i}\,\mathbf{U}_{s,i}^H \quad i = 1 \ldots n_s \tag{2.20}$$

lead to separate beamforming results and the maximum value of each is taken as the source contribution

$$|\underline{B}_i|^2 = \max(\mathbf{w}^H \mathbf{C}_{s,i}\,\mathbf{w})\,. \tag{2.21}$$

This algorithm is very good at separating sources and estimating their levels, the only drawback being the use of the eigenvalue decomposition, which makes it slower than the algorithms described in the next section, which are based on (iterative) deconvolution.

2.4. Deconvolution Approaches

The response of the beamforming processing can be considered as a spatial convolution of the beampattern $\mathbf{A}$ for all scan positions with the source distribution $\mathbf{x}$. Using the definition of the beampattern in Eq. (2.4) the output power of the beamformer can be expressed as

$$|\underline{B}|^2 = \mathbf{w}^H \mathbf{C}\,\mathbf{w} = \mathbf{A}\,\mathbf{x}\,. \tag{2.22}$$

It is the goal of deconvolution algorithms to estimate the source vector $\mathbf{x}$. This can be achieved either iteratively (CLEAN and CLEAN-SC) or with a matrix inversion (DAMAS). In all cases, a first estimate of the beamforming output is obtained with the Delay-and-Sum algorithm. An advantage is that the matrix $\mathbf{A}$ can be pre-computed, as it does not depend on the data. This can lead to considerably reduced calculation times.

2.4.1. CLEAN and CLEAN-SC

The CLEAN algorithm determines an iterative solution to the problem in Eq. (2.22) [9]. In each step of the iteration, the following steps are carried out:

1. determine the maximum power and the location of the previous iteration result as a source estimate:

$$x_{i-1} = |\underline{B}|^2_{i-1,\max} \tag{2.23}$$

$$\mathbf{g}_{i-1,\max} = \frac{\mathbf{w}_{i-1,\max}}{\left\|\mathbf{w}_{i-1,\max}\right\|^2} \tag{2.24}$$

2. subtract the contribution by that source estimate to update the Cross-Spectral Matrix:
$$\mathbf{C}_i = \mathbf{C}_{i-1} - x_{i-1}\,\mathbf{g}_{i-1,\max}\,\mathbf{g}_{i-1,\max}^H \tag{2.25}$$

3. calculate the *cleaner* beamforming result with the updated Cross-Spectral Matrix:
$$|\underline{B}|_i^2 = \mathbf{w}^H \mathbf{C}_i\,\mathbf{w} \tag{2.26}$$

4. repeat steps 1–3 until only noise is left

This algorithm is only slightly slower than the simple Delay-and-Sum beamformer but gives a much sparser source map. As the CLEAN algorithm does not actually use the information in the Cross-Spectral Matrix, the entry of the pre-calculated matrix in Eq. (2.4) corresponding to the location of the maximum in each map can be used in a faster CLEAN version by combining steps 2. and 3. above:

$$|B|_i^2 = |B|_{i-1}^2 - x_{i-1} \cdot \mathbf{A}_{i-1,\max}\,. \tag{2.27}$$

A comparison of the speed of the different implementations will be given in Chapter 6.

The CLEAN algorithm treats all sources as being uncorrelated and lists them as separate sources. However, it may be beneficial to combine the correlated contributions. This is achieved by the CLEAN-SC approach, which replaces the update equation (step 2) in Eq. (2.25) to determine the contribution of correlated sources [10]:

$$\mathbf{h}_i = \mathbf{C}_{i-1}\frac{\mathbf{w}_{i-1,\max}}{x_{i-1}} \tag{2.28}$$
$$\mathbf{C}_i = \mathbf{C}_{i-1} - x_{i-1}\mathbf{h}_i\mathbf{h}_i^H \tag{2.29}$$

2.4.2. DAMAS

Instead of the iterative solution to the deconvolution problem of CLEAN and CLEAN-SC, another set of algorithms solves Eq. (2.22) directly. The DAMAS approach uses the Gauss-Seidel algorithm with the assumption of $x_i \geq 0$ to obtain the source vector [11].

The original DAMAS algorithm provides a best estimate of the source vector in a least-square sense. A better solution can be recovered under the assumption that only few sources are active. This means that the solution is sparse and several approaches exist for the problem. Here the FOCUSS algorithm is used [12].

2.5. Comparison of Algorithms

To get a better impression on the performance of the presented algorithms, a simulation of the sound propagation from three acoustic sources in the free-field towards a 16-channel microphone array was carried out. The sources were emitting pink noise signals and had

approximate A-weighted levels at a distance of 1 m of 90 dB(A), 87 dB(A) and 85 dB(A), respectively. The geometrical setup is depicted in Figure 2.2.

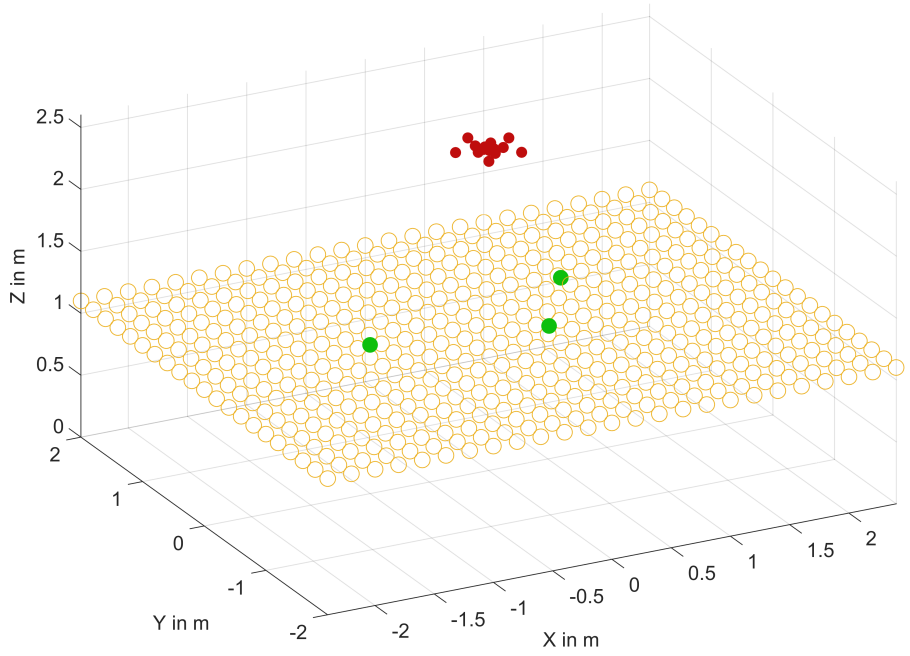


Figure 2.2.: Setup for the simulation to compare beamforming algorithms: array microphones in red, sources in green and scan points in yellow

In Figure 2.3 the broadband beamforming result in dB(A) is plotted for all of the algorithms described in this chapter. The time it took to calculate the result is shown in the title of each sub-figure. The dynamic range of the plots is 20 dB. For the first plot in the upper left corner (Delay-and-Sum), the location of the sources in the map is indicated by white crosses.

It can be seen that although the Delay-and-Sum beamformer can achieve some spatial discrimination, it is outperformed by all other algorithms. It is, however, the fastest algorithm by at least 50 %. As mentioned before, the MVDR (center in the top row) and MUSIC (top right corner) algorithm are not capable of estimating the source level. Nevertheless they achieve very good localization, especially the MUSIC algorithm.

The Functional beamformer (left in the center row, here with $\nu = 20$) has a slightly reduced resolution compared to MUSIC, however with an additional term in the calculation the levels can be recovered in this case. The calculation of the eigenvalue decomposition obviously makes the adaptive algorithms considerably slower than the Delay-and-Sum beamformer.

This is also true for the Subspace approach (center). However, this algorithm provides a much better spatial selectivity, which is due to the source separation with the eigenvalue decomposition. In comparison, the CLEAN algorithm (right in the center row) yields essentially the same result taking only 60 % of the time, as it uses an iterative approach and hence the eigenvalue decomposition is not needed.

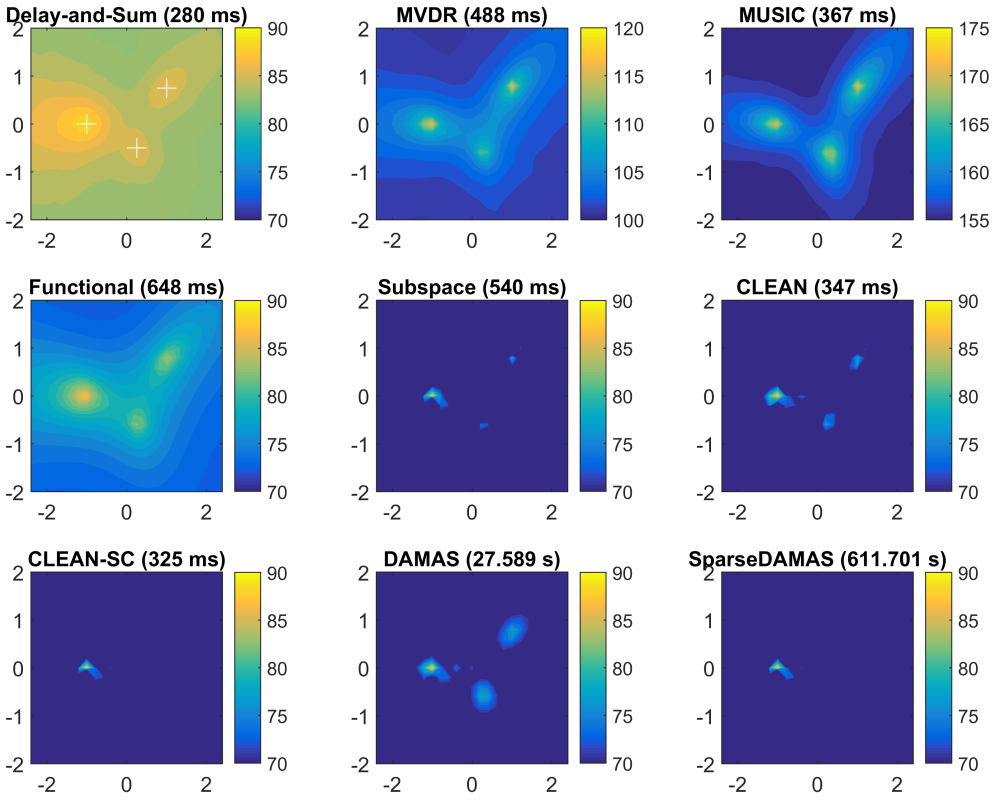


Figure 2.3.: Comparison of beamforming algorithms for the setup depicted in Figure 2.2

In the example shown here, CLEAN-SC (lower left corner) only shows the strongest source contribution. This may stem from the fact that the algorithm incorrectly identifies the sources to be coherent. The same result is returned by the sparse version of the DAMAS algorithm (lower right corner), albeit after 2000 times the computation time of CLEAN-SC. The original, iterative version of DAMAS (center in the bottom row) yields a result very similar to the Subspace approach and CLEAN, however it is also considerably slower, by a factor of almost 60.

2.6. Conclusions

With respect to the performance of beamforming algorithms, the classical Delay-and-Sum (DAS) beamformer is both the most robust and fastest, but it has only limited resolution and dynamic range. Better resolution capabilities can be achieved with adaptive algorithms, such as MVDR, MUSIC and Functional Beamforming, of which the latter offers the best overall performance. All of these three algorithms, however, are not always capable of estimating source levels.

The remaining algorithms essentially give the same result as they are all based on using the information in the Cross-Spectral Matrix to separate the contributions from different sources. Among these approaches, subspace beamforming and CLEAN / CLEAN-SC have similar calculation times, whereas DAMAS is slower by about two to three orders of

magnitude. Depending on the levels of the sources, CLEAN-SC and SparseDAMAS may not always show all source contributions.

For a fast and robust source identification, the approach taken in this project is hence to use a combination of the DAS and either CLEAN or CLEAN-SC.

3. Array Design

The performance of array processing is mainly affected by the sensor arrangement. A major part of this project hence has consisted of optimizing the microphone locations. To fully take advantage of the hardware possibilities, 64 channels were used for the arrays, and these channels were distributed between four clusters of 16 microphones each in order to provide full coverage of the full acoustic space. The optimization of the individual cluster design will be described in this chapter, while the placement of the clusters will be discussed in the following chapters.

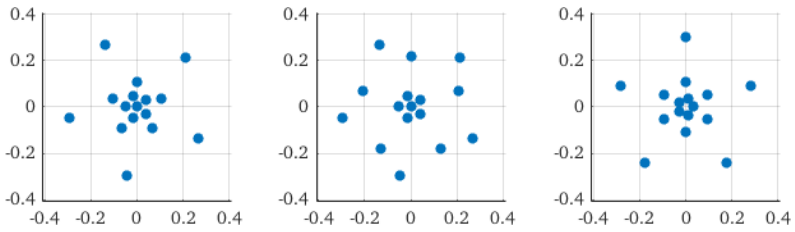
3.1. Array Geometries

To find the best configuration of the microphone arrays a number of different geometries were investigated and compared. Figure 3.1 shows nine common layouts of 16 microphones with similar outer dimensions of $0.6\,\mathrm{m} \times 0.6\,\mathrm{m}$, which takes into account the fact that the arrays had to be installed in the ceiling tiles of the ICU. The cross and square layouts in Figure 3.1c are slightly smaller due to the underlying design process.

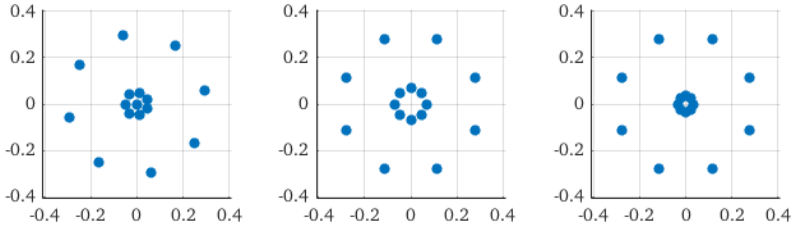
The first three layouts (Figure 3.1a) are variations of the so-called logarithmic spiral, which consists of three concentric circles of five microphones each, rotated around the center microphone to cover all directions and with increasing diameter of each circle towards the outer ring. The circles of the first version (left) have diameters that increase approximately logarithmically, whereas the second version (center) has two circles with larger diameter to concentrate more sensors away from the array center. The third variant of the logarithmic spiral array (right) has no center microphone but is otherwise the same as the first version.

The circular arrays in the second row (Figure 3.1b) consist of two concentric circles either with or without a center microphone. The last row, which is given for completeness, represents the cross and square types of arrays, with sensors distributed along two specific directions. These variants have a smaller diameter, especially the grid array (right) to shift the aliasing frequency towards the upper end of the operating range.

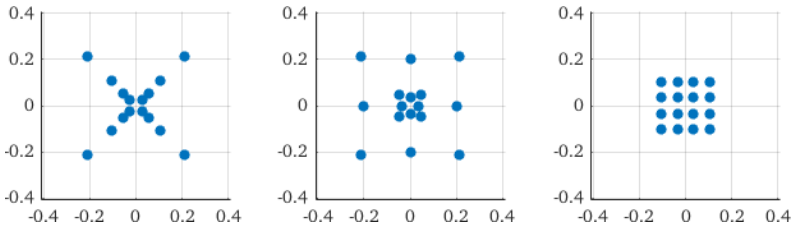
In the following, the performance parameters introduced in Section 2.1.2 are evaluated for all variants in Figure 3.1. As the beampattern, and hence the performance, is strongly dependent on frequency, the parameters will be evaluated in the considered operating frequency range between 500 Hz and 10 kHz.



(a) Spiral Arrays



(b) Circular Arrays



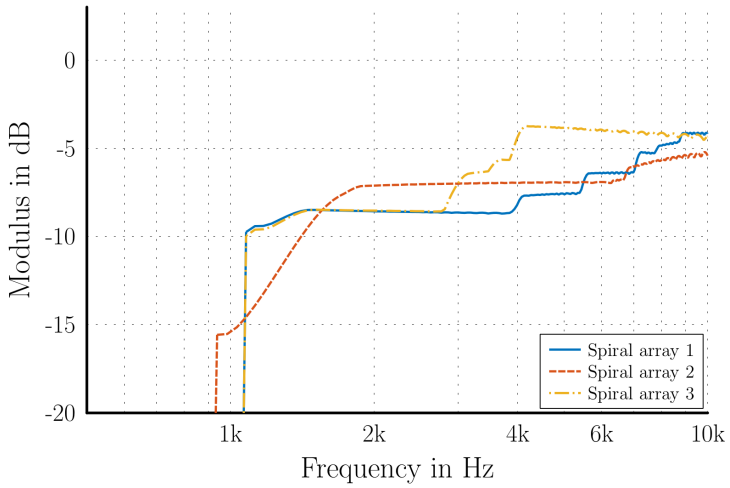
(c) Cross and Square Arrays

Figure 3.1.: Variants of different array layouts with 16 microphones

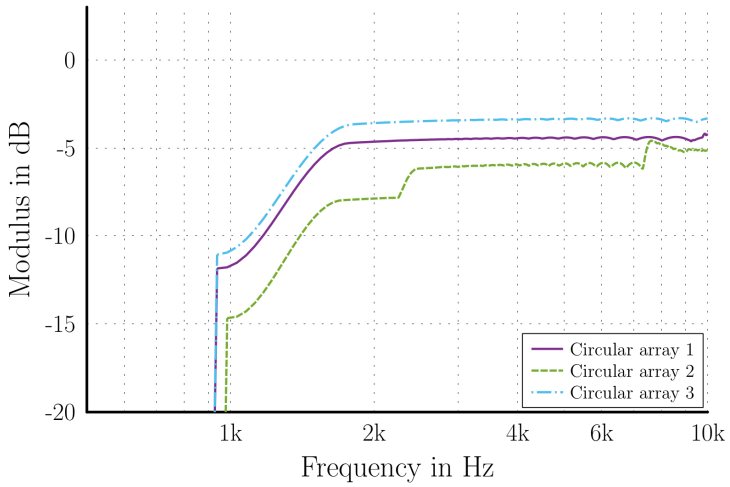
Figure 3.2 shows the Maximum Sidelobe Level (MSL) in dB for all arrays, sorted in the same way as Figure 3.1. Here, lower levels are better. The trade-off that always has to be taken into account for the array design can be seen in these graphs. In the lower frequency range (below 2 kHz) a larger number of sensors on the outer rings (as in the case of the circular arrays, Figure 3.1b) gives a lower MSL (Figure 3.2b). However, for higher frequencies, it is favourable to condense the sensors in the center of the array (see blue curve in Figure 3.2a), as is done in the first spiral array in Figure 3.1a. A special case is the regular square array (on the right in Figure 3.1c), which yields by far the lowest MSL in the low and medium frequency range. However, it has a specific spatial aliasing frequency, determined by the microphone spacing, above which the MSL is 0 dB and thus so-called *phantom sources* appear in the beamforming map.

Comparing all of the MSL values for the arrays, the first and second spiral array in Figure 3.1a and the second circular array in Figure 3.1b seem to offer the best broadband performance according to this metric.

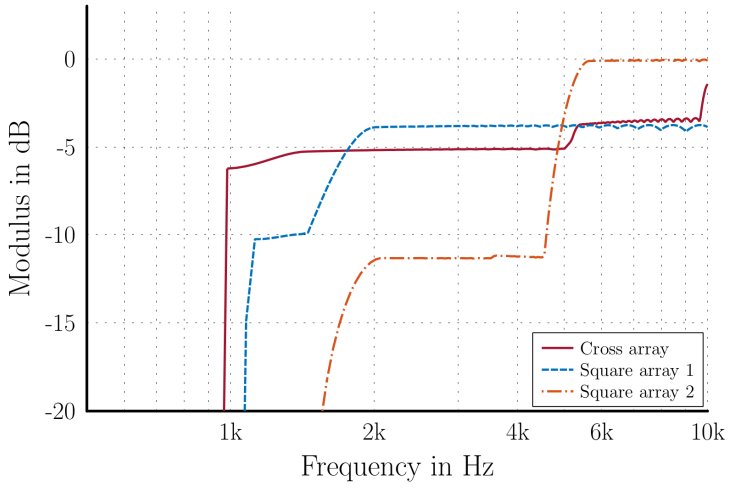
With respect to the spatial resolution, represented by the Half-Power Beamwidth (HPBW), a general trend can be observed in the data in Figure 3.3: the resolution of the arrays is always proportional to frequency, giving lower values of the HPBW, i. e. better resolution, at higher frequencies. A difference in the design is then only a factor in the slope of the curves.



(a) Spiral Arrays

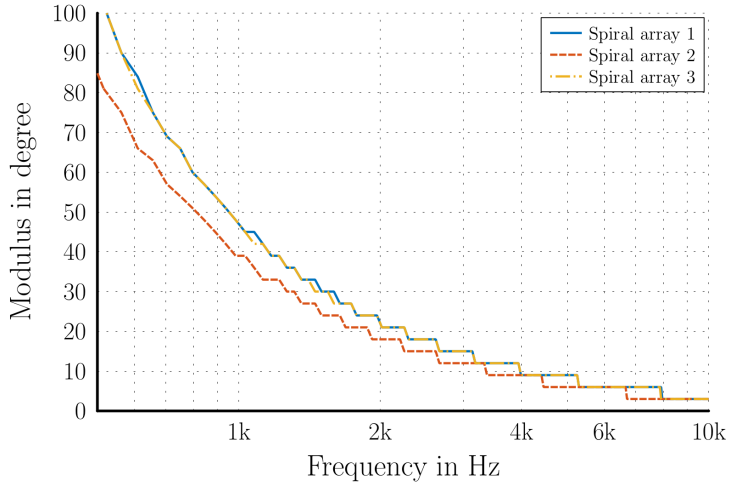


(b) Circular Arrays

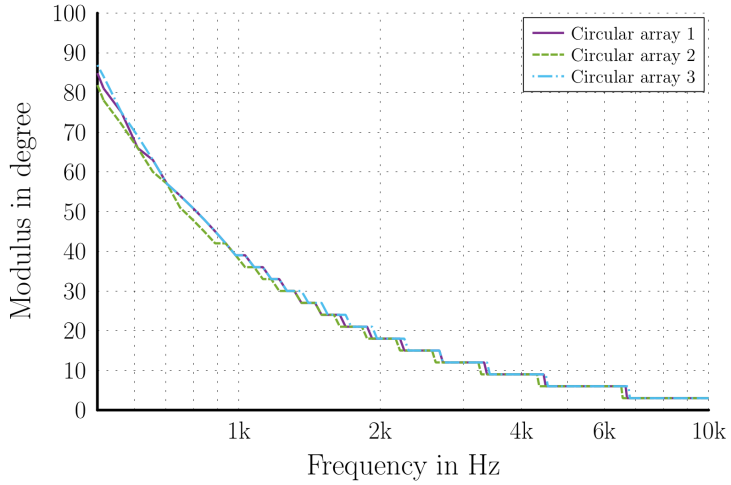


(c) Cross and Square Arrays

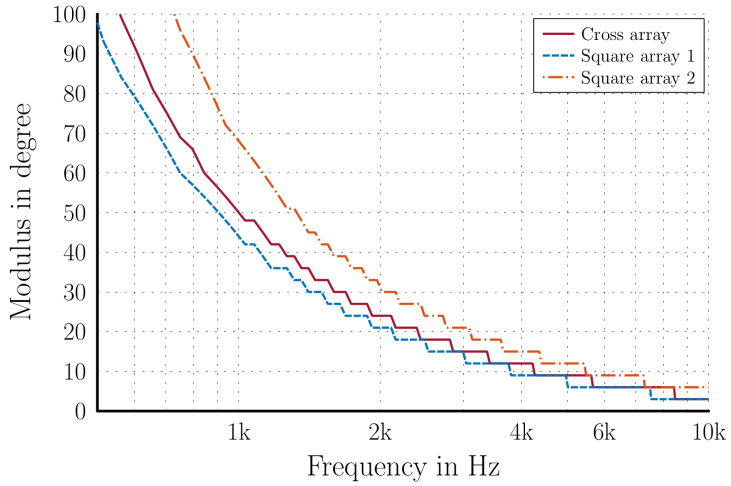
Figure 3.2.: Maximum Sidelobe Level in dB across frequency for all array variants



(a) Spiral Arrays



(b) Circular Arrays



(c) Cross and Square Arrays

Figure 3.3.: Half-Power Beam Width in degree across frequency for all array variants

In general, it can be said that a larger diameter, or more sensors on the outer rings, leads to a better resolution, which is why the worst performance (orange curve in Figure 3.3c) is given by the second square array in Figure 3.1c, which has the smallest outer diameter. Considering the HPBW, the second spiral array in Figure 3.1a and the circular arrays (Figure 3.1b) provide the best resolution.

For a more abstract evaluation of the directivity of an array, the Directivity Index (DI) in dB is a good measure to compare different designs. For the nine array variants shown in Figure 3.1, the DI is depicted in Figure 3.4. Here, higher values without abrupt changes across frequency are desirable.

Again, the first spiral array (blue line in Figure 3.4a) performs very well with high values that are almost constant in the high frequency range. The second spiral array has a similar or better performance for high and low ($< 1.6\,\mathrm{kHz}$) frequencies but slightly worse performance in the mid frequency range. Other arrays that perform well regarding the DI are the second circular array (green line in Figure 3.4b) and the first square array (blue line in Figure 3.4c).

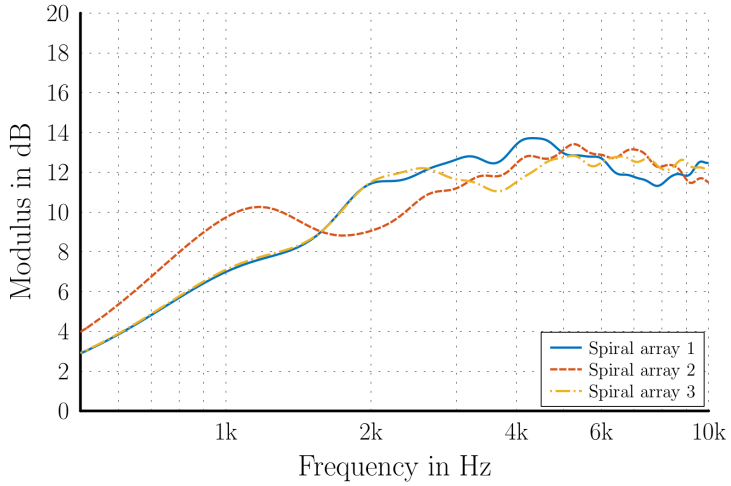
From the evaluation of the array performance parameters in this section, three array designs stand out and will be the subject of further analysis in the next section: the first and second spiral arrays and the second circular array.

3.2. Array Shading Weights

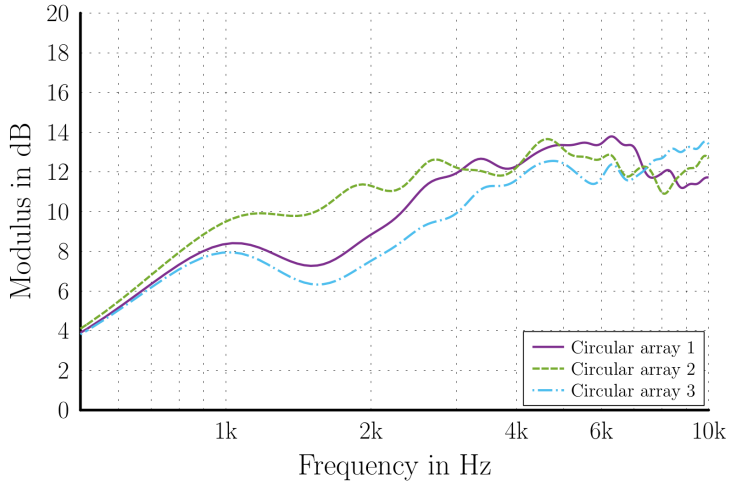
While the array performance is mainly determined by the distribution of the sensors in space, some improvements can be achieved electronically by assigning shading weights to each of the microphones. This allows the effective outer diameter to be controlled, for example, to allow a trade-off between resolution and MSL. The shading is usually applied to each circle of microphones, so the number of degrees of freedom is determined by the number of concentric circles in the array.

The arrays selected in the previous section (shown again in Figure 3.5) are analyzed with respect to their suitability for shading across frequency in this section. The goal is to achieve the best trade-off between the MSL and spatial resolution.

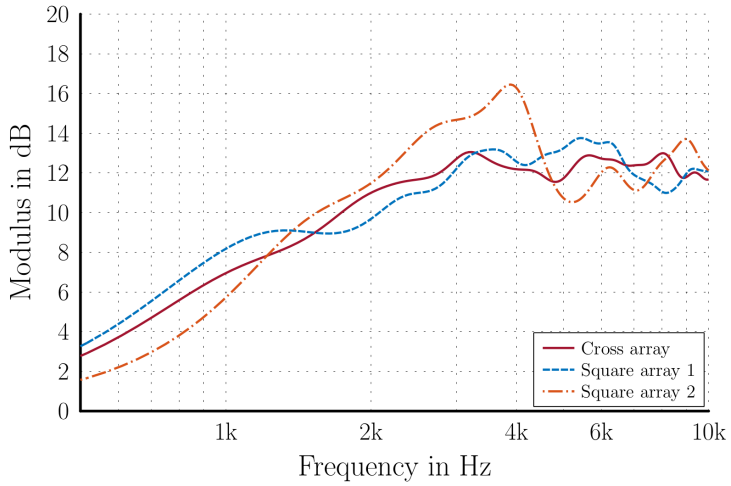
In the following subsections, each of the three arrays will be investigated in terms of the performance parameters, first without any shading and then with different variants of shading weights. For a smooth transition across frequency, the band edges of the shading weights are chosen to coincide with the third-octave band edge frequencies, so that the same number of sensors are always active within the same third-octave band. The frequencies reported here are the center frequencies of the respective third-octave band.



(a) Spiral Arrays



(b) Circular Arrays



(c) Cross and Square Arrays

Figure 3.4.: Directivity Index in dB across frequency for all array variants

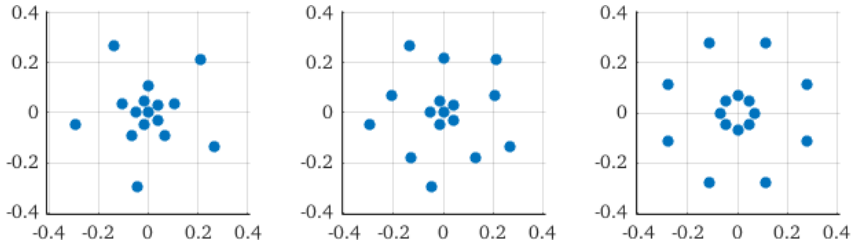


Figure 3.5.: Three array designs from Figure 3.1 with best broadband performance

3.2.1. Spiral Array 1

In Figure 3.6, the performance parameters for the first spiral array are presented without any shading weights. It can be seen that the MSL is always above 10 dB and the HPBW drops below 10 degrees at high frequencies. These values can be optimized, as such a high resolution is usually not required, but a lower MSL would be desirable.

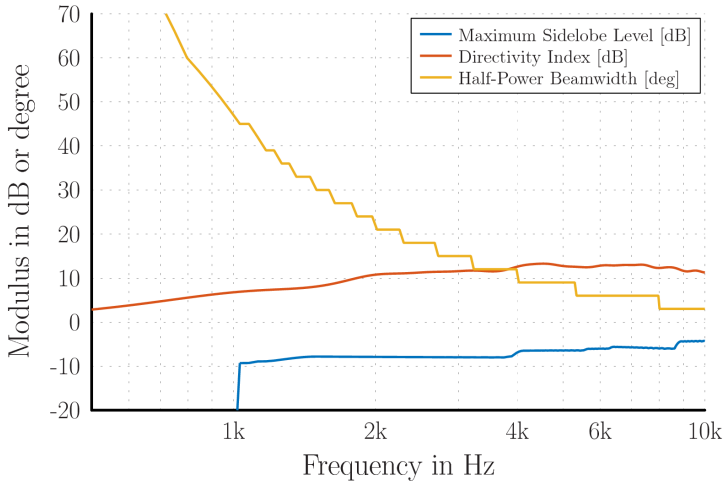
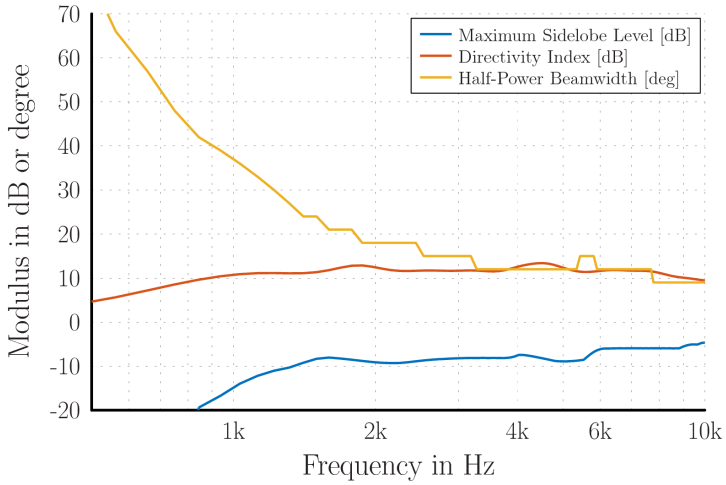


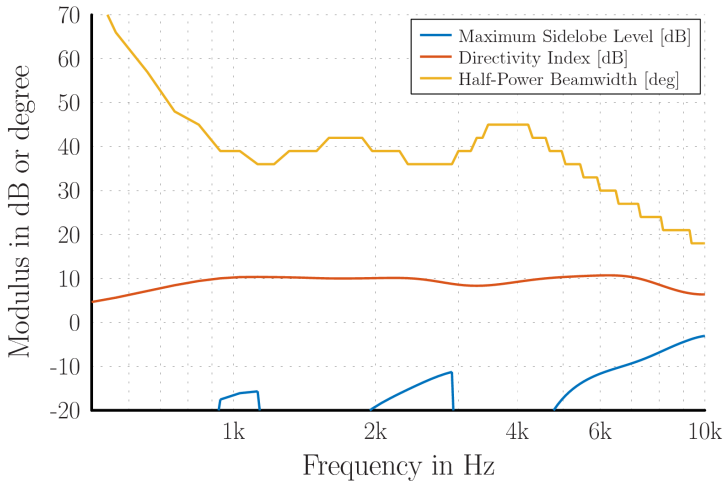
Figure 3.6.: Performance parameters of the first spiral array in Figure 3.5 without shading

Figure 3.7 shows three different versions of shading weights across frequency. In Figure 3.7a, the two inner circles of microphones are not used below 2 kHz and the outermost circle is not used above 4 kHz. This effectively reduces the diameter at high frequencies, which leads to slightly reduced resolution with improved MSL. Omitting the center microphones at low frequencies helps to improve the numerical stability and thus leads to better resolution.

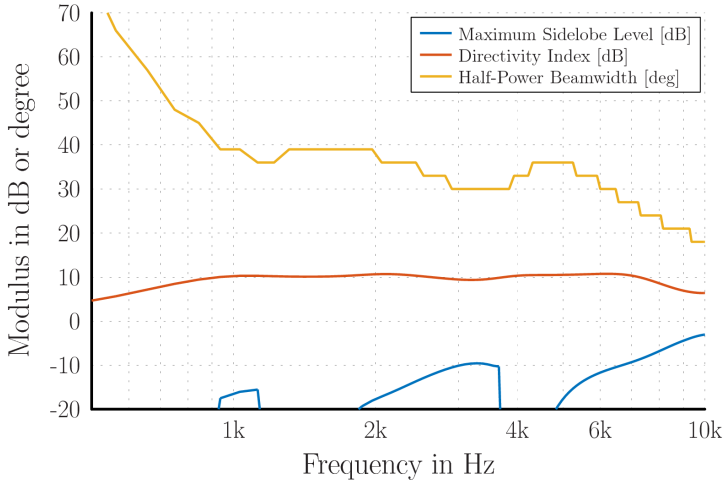
The MSL can be improved by further reducing the diameter at high frequencies. For the data in Figure 3.7b, the cut-off frequency for the outermost circle is set to 1 kHz and for the next circle towards the center it is 2.5 kHz. At the same time, the cut-on for the center microphone is also at 2.5 kHz and the inner circle has a cut-on frequency of 1.6 kHz. This results in an improved MSL with much lower values especially up to 5 kHz. However, the resolution is severely degraded, which can be seen in the curve for the HPBW.



(a) Shading version 1



(b) Shading version 2



(c) Shading version 3

Figure 3.7.: Performance parameters of the first spiral array in Figure 3.5 with different shading weights

A different trade-off with slightly better resolution is achieved for another set of cut-on and cut-off frequencies: for the data shown in Figure 3.7c, the cut-off frequencies for the two outer circles of sensors are 3.15 kHz and 1 kHz, respectively. The cut-on frequencies for the center microphone and the inner circle are 1.25 kHz and 2 kHz, respectively. This produces a slightly better resolution at high frequencies.

Although a low MSL is desirable, the spatial resolution is probably the more significant performance factor. The preferred combination of shading weights is thus version 1 (Figure 3.7a). This will serve as a reference for the next evaluations.

3.2.2. Spiral Array 2

The second spiral array chosen for the shading analysis has two outer circles of sensors with larger radii. This slightly reduces the degrees of freedom for shading, as the distribution according to the radius is not ideal. That is why only two versions of shading can be presented here, both leading to non-ideal results.

The performance parameters for the array without any shading (Figure 3.8a) show the high resolution at high frequencies, while at the same time the MSL is also relatively high which may result in poor source separation. The data in Figure 3.8b has been obtained for cut-on frequencies for the center microphone of 5 kHz and for the inner sensor ring of 800 Hz. The cut-off frequencies for the two outer sensor rings are 5 kHz and 3.15 kHz, respectively. It can be seen that only minor improvements can be obtained for the MSL while a relatively sharp increase in the HPBW occurs. This is due to the aforementioned distribution of the circle radii.

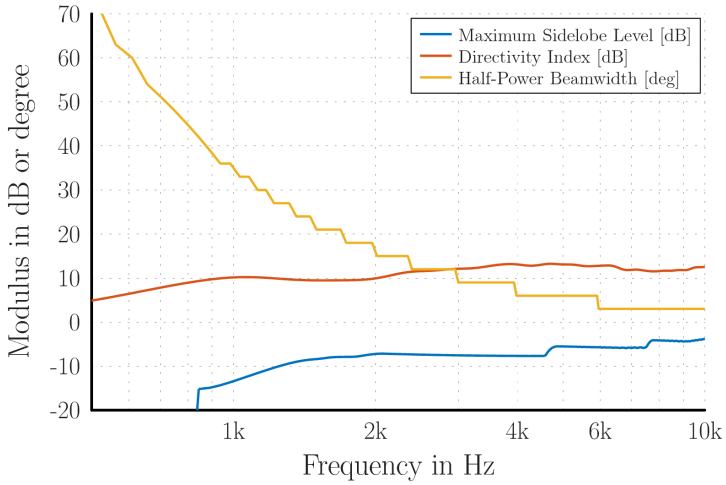
The result for another set of shading weights is presented in Figure 3.8c. In this case, the cut-off frequencies for the two outer circles are 3.15 kHz and 800 Hz, respectively, and the cut-on frequencies for the inner microphones are 1.25 kHz and 800 Hz. The lower cut-off at high frequencies leads to an improved MSL and degraded resolution. However, because the radii of the outer sensor rings are very similar, there is an abrupt change in the values across frequency, which is undesirable.

Hence, compared to the data for the first spiral array in Figure 3.7a, none of the modified shading weightings for the second spiral array achieve a useful increase in performance.

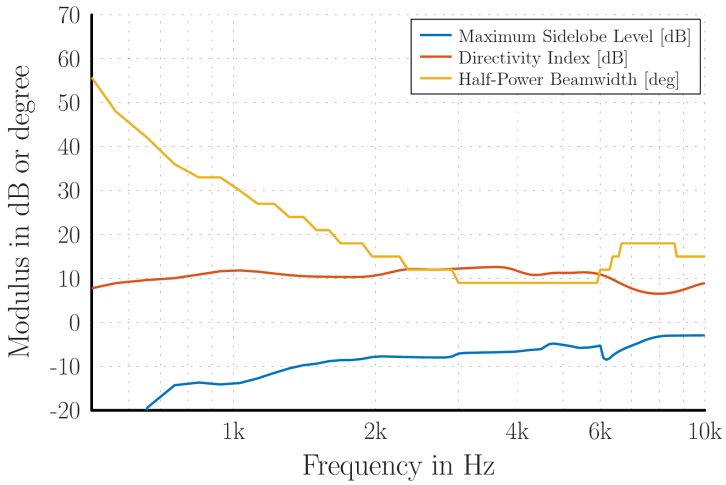
3.2.3. Circular Array

Similar to the second spiral array, the circular array in Figure 3.5 with only two separate rings of microphones provides little opportunity for choosing the shading weights. In Figure 3.9, the performance parameters are shown for the unweighted array (Figure 3.9a) as well as for shading weights with a cut-off frequency for the outer ring of 2.5 kHz and a cut-on frequency for the inner ring of 800 Hz.

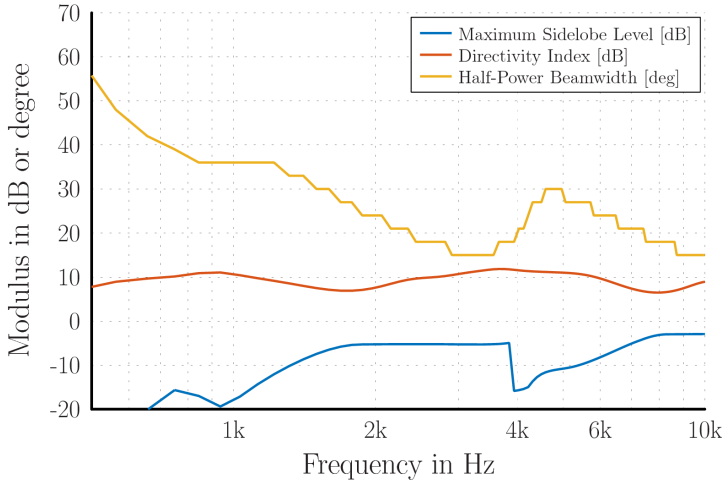
Due to the limited degrees of freedom, no significant improvement can be achieved with the shading weights.



(a) No shading

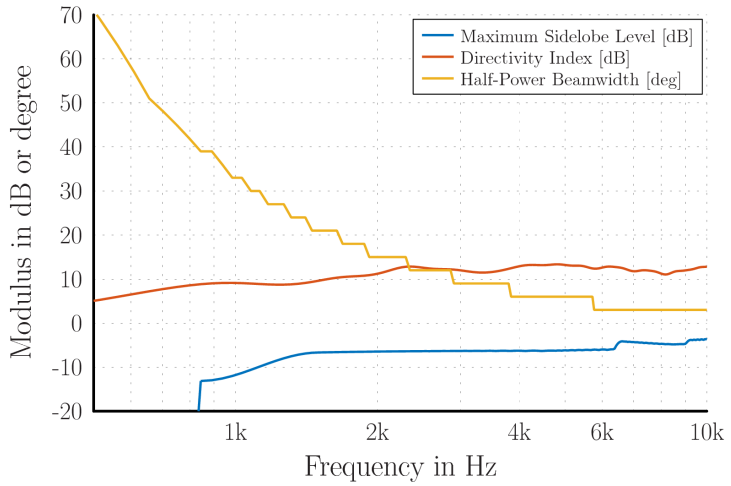


(b) Shading version 1

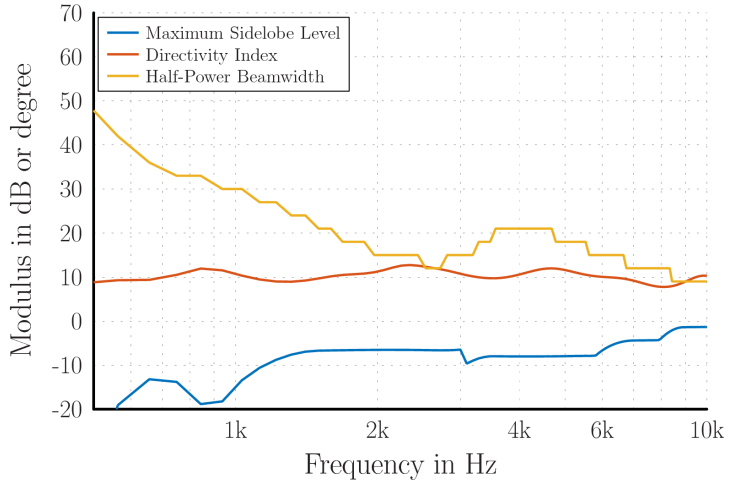


(c) Shading version 2

Figure 3.8.: Performance parameters of the second spiral array in Figure 3.5 with different shading weights



(a) No shading



(b) Shading version 1

Figure 3.9.: Performance parameters of the circular array in Figure 3.5 with different shading weights

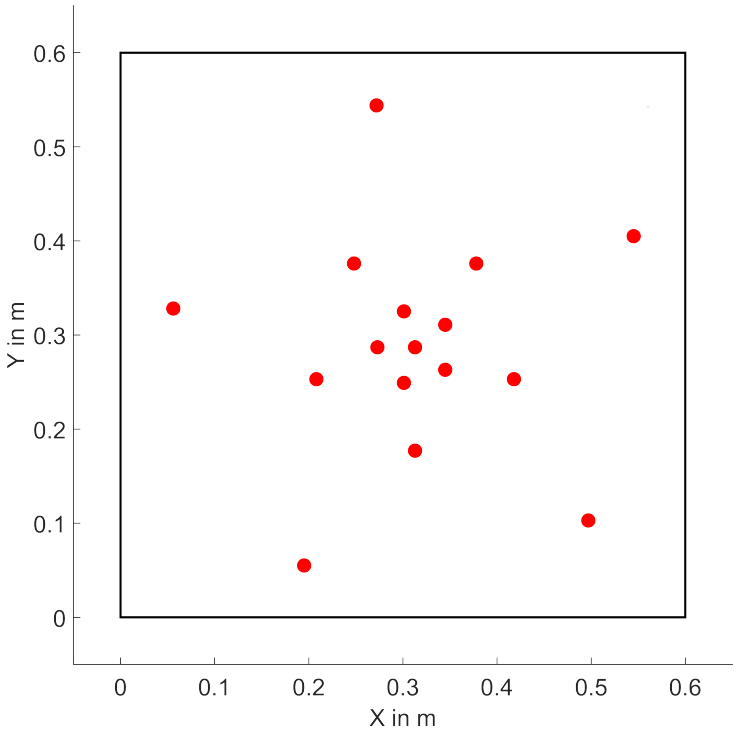
3.3. Conclusion

To conclude this section, the first version of the shading weights for the first spiral array in Figure 3.5 offers the best performance and will be chosen for the array processing. The corner frequencies are listed in Table 3.1 and the effective filters as they are implemented in the software are shown in Figure 3.10.

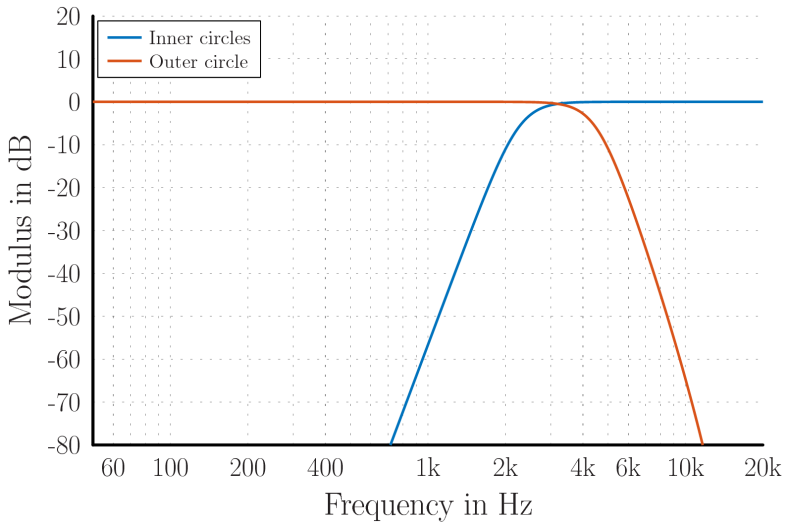
A total of 4 replicas of the spiral array will be used, resulting in a total of 64 array microphones. Additionally, 8 individual microphones will be distributed in the room for additional level monitoring at key locations.

Table 3.1.: Microphone ring radii and corner frequencies for the shading weights

Radius of Microphone Ring (in m)	**Cut-on Frequency (in kHz)**	**Cut-off Frequency (in kHz)**
0.0	2 kHz	—
0.04	2 kHz	—
0.11	—	—
0.26	—	4 kHz



(a) Geometry with respect to ceiling tile (rectangle)



(b) Shading weights

Figure 3.10.: Final array geometry and shading weights for the spiral array

4. Simulations of the ICU Environment

To predict the performance of the array design and beamforming algorithms in a more realistic acoustic scenario, a simulation environment was set up in MATLAB based on the geometry of the ICU at John Radcliffe Hospital. This chapter describes the measurements used to characterise the ICU and the different sources of noise in the ICU, and provides details of the simulation model.

4.1. Acoustic Measurements in the ICU

In order to obtain an acoustic impression of the ICU environment, the impulse response (IR) was measured for five representative source-receiver combinations. The source was a Mackie HR824 two-way studio monitor. The IRs were measured with a sinusoidal sweep excitation signal [13] and all processing was done with the ITA-Toolbox for MATLAB [14].

The average reverberation time T_{60}, as the most important room-acoustic parameter, has been evaluated from the IRs and is plotted in seconds as a function of frequency in Figure 4.1. It can be seen that the reverberation time is below 0.3 s for most of the frequency range, which means that the ICU is not too reverberant.

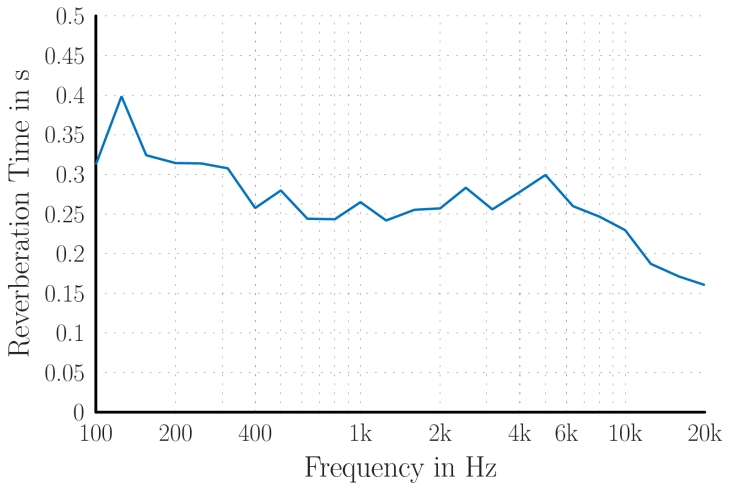


Figure 4.1.: Average reverberation time of the ICU

Knowing the surface area S_{room} and volume V_{room} of the ICU, the average absorption coefficient can be calculated from the reverberation time using Sabine's equation [15]:

$$\overline{\alpha} = \frac{24\,\log(10) V_{\text{room}}}{S_{\text{room}}\, c\, T_{60}}\,, \tag{4.1}$$

where $c \approx 343\,\text{m/s}$ is the speed of sound.

The result in Eq. (4.1) is an average across all individual surfaces of the room. However, it is safe to assume that the floor is less absorptive, as it is a hard reflective surface, and that the ceiling is more absorptive than average, since it is constructed using acoustic ceiling tiles. With this assumption, the absorption coefficient was split between the separate surfaces to fulfill

$$\overline{\alpha}\, S_{\text{room}} = \alpha_{\text{floor}}\, S_{\text{floor}} + \alpha_{\text{ceiling}}\, S_{\text{ceiling}} + \alpha_{\text{wall}}\, S_{\text{wall}}\,. \tag{4.2}$$

For the ICU, the following values were chosen (frequency-average): $\alpha_{\text{floor}} = 0.2$ and $\alpha_{\text{ceiling}} = 0.6$, resulting in $\alpha_{\text{wall}} \approx 0.375$. The absorption coefficients of the different surfaces are shown in Figure 4.2 as a function of frequency.

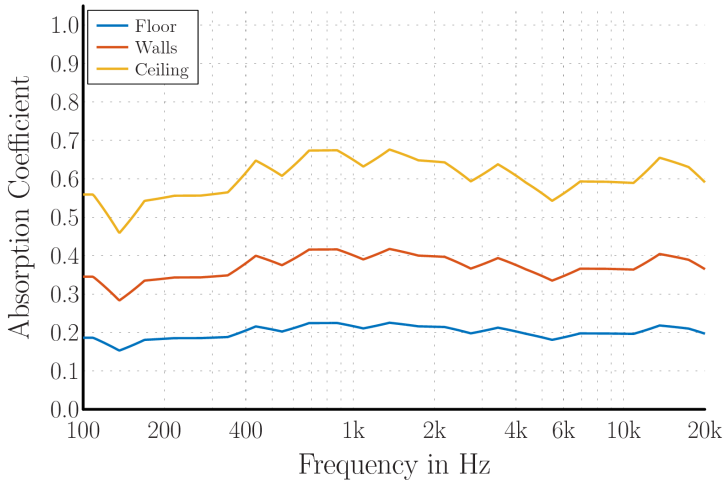


Figure 4.2.: Absorption coefficients of the room surfaces as used for the simulations

The information obtained from the acoustic measurements will be used later in the simulations.

4.2. Recordings of ICU Equipment

For a realistic simulation, recordings of the sound produced by various medical equipment used in the ICU were made. The typical sounds of different types of equipment were made close to the source to provide as close an anechoic recording a possible.

The following equipment sounds were recorded:

1. Feed pump alarm
2. Humidifier alarm

3. Pulse alarm
4. Pulse high-level alarm
5. Pulse oximeter (low pitch)
6. Pulse oximeter (high pitch)
7. Pulse oximeter leads disconnect alarm
8. Syringe pump alarm
9. Syringe pump attention alarm
10. Syringe pump button
11. Ventilator

For an additional component, babble speech (speech sounds without meaning) were used to simulate people talking. The A-weighted level as well as the loudness level is plotted in Figure 4.3.

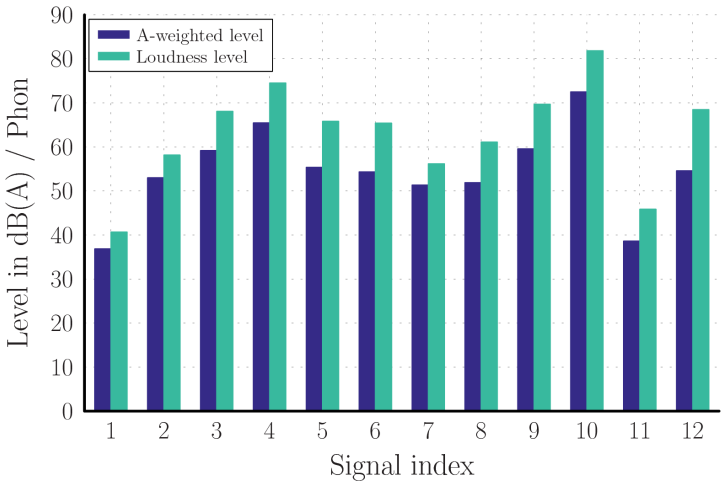


Figure 4.3.: A-weighted levels and loudness levels of all signals used for the simulations

4.3. Simulation Method and Examples

To model sound reflections in rooms, the so-called *image source method* (ISM) can be employed, where specular reflection of sound at each surface is simulated by mirroring the source position at that surface and then calculating the sound propagation from the mirrored source to the receiver [16, 17]. An example of the source model geometry for the model of the ICU with a single source (in green), a receiver (in red) and the first-order image sources (in blue) is depicted in Figure 4.4.

The information about surface absorption from Section 4.1 is used to weight the reflected sound relative to the direct path. In this work, an angle-dependent reflection factor is implemented for a more realistic result [18].

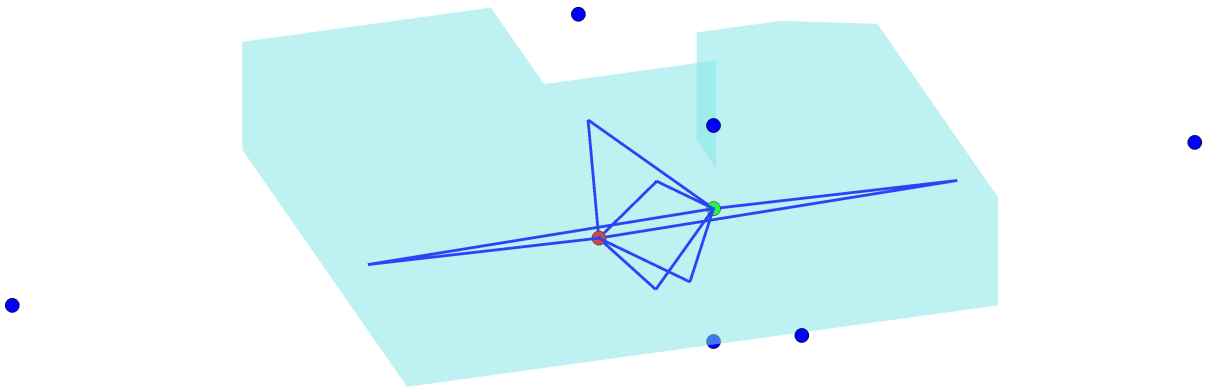


Figure 4.4.: Example of image source setup for one source (green), a receiver (red) and first-order image sources (blue) in the ICU model

The ISM is only accurate and efficient for low reflection orders (typically up to second or third reflection order), so late reverberation is usually modeled with statistical reflections from random directions. This is shaped in such a way that the given reverberation time is obtained [19].

An example of a simulation result is presented in Figure 4.5 as the A-weighted broadband sound pressure level over the ICU. The beamforming result for this data is plotted in Figure 4.6. In Figure 4.6a, the result of the CLEAN algorithm is shown and the result with subsequent data clustering is shown in Figure 4.6b.

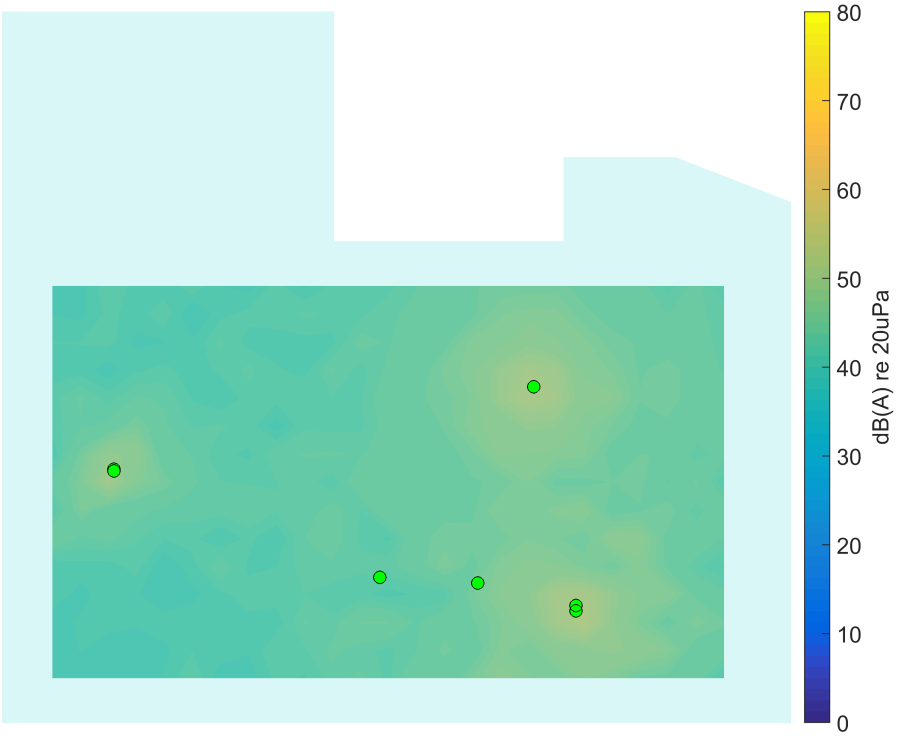
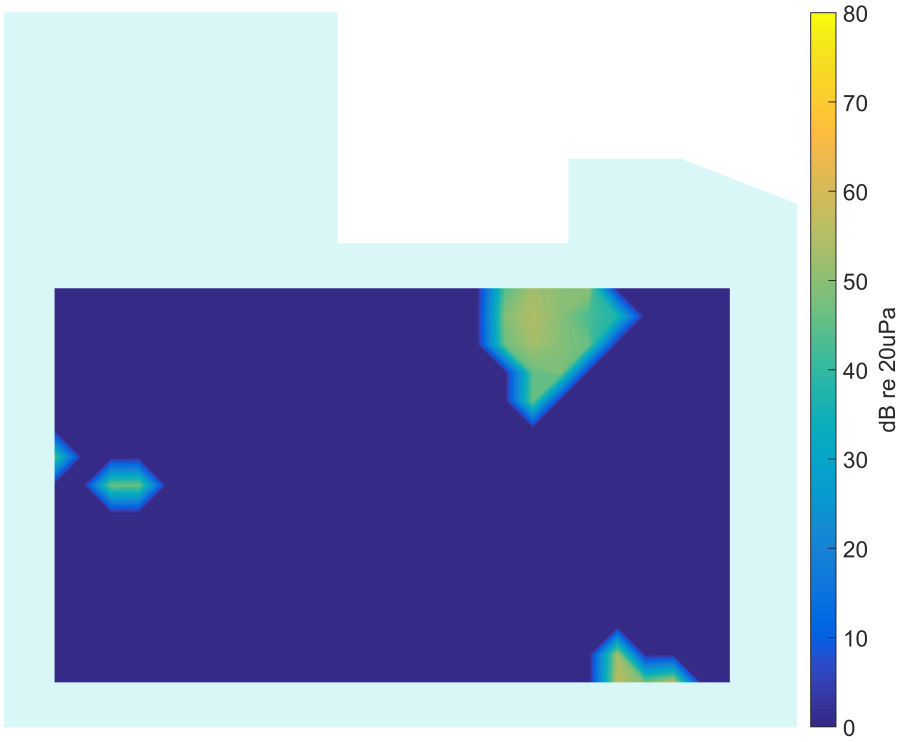
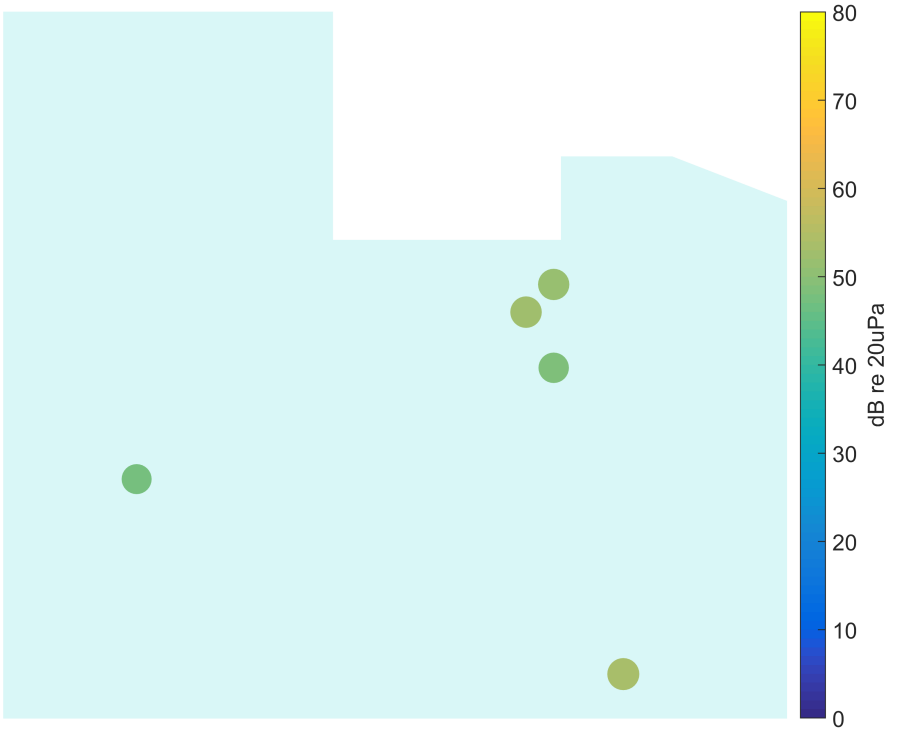


Figure 4.5.: Simulated A-weighted level in the ICU – source positions marked as green circles – for three active sources



(a) CLEAN algorithm



(b) CLEAN algorithm with data clustering

Figure 4.6.: Beamforming results for the simulated data shown in Figure 4.5

The data shown in Figure 4.5 is a snapshot from a 20 s simulation. In this snapshot, three sources (left, top right and bottom right) are active as can be seen from the high levels around these sources. The signals for the active sources were taken from the recorded equipment described above, in this case from the humidifier, the pulse oximeter and babble speech.

The beamforming result of the CLEAN algorithm in Figure 4.6a shows that the designed arrays work well in the simulated ICU environment as the location of the sources is correctly identified. The result is a summed broadband level across the entire frequency range. Since the location of the sources may shift slightly across frequency, this may lead to larger spots in the beamforming source map, as in the case in Figure 4.6a for the source at the top right.

Based on the data of the CLEAN algorithm in Figure 4.6a, the source contributions are combined into five clusters: for this, the largest values are sorted and grouped according to their location with the *k-means* algorithm. The clustering result is shown in Figure 4.6b.

In conclusion, the simulation environment was useful to test different algorithms and array configurations. It was found that the actual location of the four sub-arrays within the ICU did not have a big influence on the result. This means that practical limitations on the microphone placement due to building constraints can be accommodated without affecting the signal processing quality.

5. Hardware Design and Setup

In this chapter, the different hardware components of the system are described. This includes the design considerations and the calibration of the individual components.

5.1. Microphones

The most important part of the array system are the microphones. The best solution that accomplishes a trade-off between quality and cost is to use electret microphones. This type of microphone is manufactured in very large quantities keeping the price low (unit cost is around £ 1). However, compared to higher-quality, and more expensive, condenser measurement microphones, the frequency response is not as well balanced, which makes it essential to calibrate electret microphones across the entire frequency range, both in modulus as well as phase. The latter is particularly important for array signal processing.

5.1.1. Capsules

The capsules chosen for this project are the omni-directional PCB-mount type by OBO.Pro.2 (model no. OBO-04FP-0A-1F0, now no longer in production) and, as a replacement, the same type by RS Pro [20]. Both capsules have a diameter of 9.7 mm. An example of these types of capsules is shown in Figure 5.1. The most important properties are listed in Table 5.1.

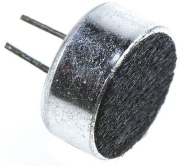


Figure 5.1.: Example of electret microphone capsule

Table 5.1.: Electronic properties of electret microphone capsules

Parameter	Value
Sensitivity	−41 dB re V/Pa or 9 mV/Pa
Directivity	omni-directional
Operating voltage	1.5–10 V
Output impedance	2.2 kOhm
Maximum supply current	0.5 mA
Frequency range	50–16000 Hz

5.1.2. Powering Circuit

To be able to use the microphone capsules, a supply voltage has to be provided. Additionally, when cable lengths of more than 2 m are going to be used, which is the case in the ICU, the electrical impedance has to be adapted to the microphone pre-amplifier. This is achieved by a powering circuit, presented in Figure 5.2.

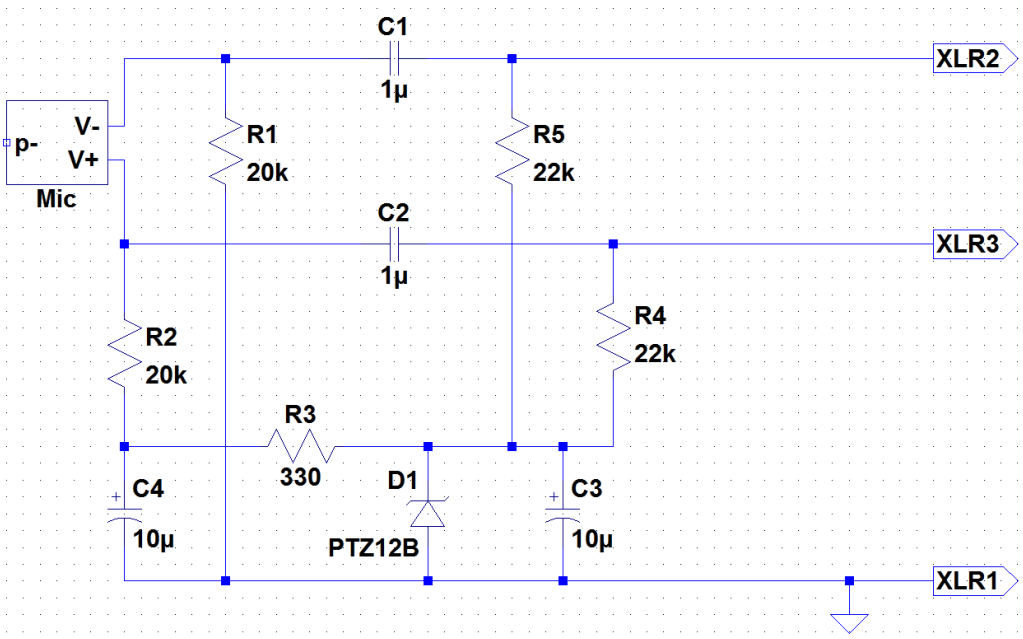


Figure 5.2.: Microphone powering circuit

This circuit takes advantage of the symmetrical layout of the professional XLR connector, which helps to reduce the influence of noise on the microphone signal. When connected to the pre-amplifier, which provides a phantom power voltage of 48 V, the circuit steps down the voltage to the microphone supply voltage of approximately 4 V. Additionally, an electrical high-pass filter is implemented in this circuit to reduce the interference from vibration in the practical installation, due for example to the building plant.

A photo of the microphone with the powering circuit built into the cable and the XLR plug is shown in Figure 5.3.



Figure 5.3.: Microphone with powering circuit and XLR plug

5.1.3. Calibration

As mentioned above, a broadband calibration of the microphone responses is imperative to achieving a good performance from the array processing. The calibration is achieved by comparing the transfer function measured between a loudspeaker and each electret microphone to the result measured using a microphone with a known response, in this case a *Brüel & Kjær* 1/2 inch free-field-equalized microphone. The setup for the calibration measurements in the small anechoic chamber of the ISVR is presented in Figure 5.4a, together with the calibration result of all 72 microphones in Figure 5.4b.

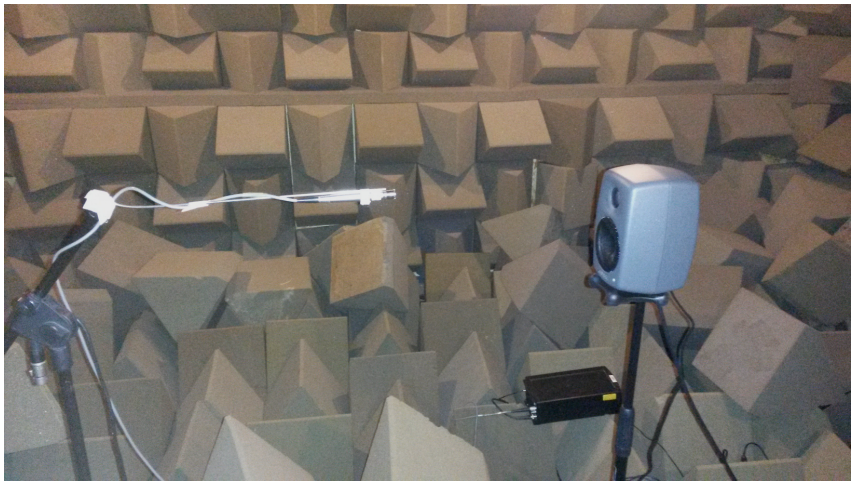
5.1.4. Ceiling Tile Insert

For an easy way of installing and possibly replacing the microphones in the ceiling tiles, an insert piece was designed (Figure 5.5a) and then printed in 3D (Figure 5.5b). A total of 84 of these inserts (including spares) have been printed in white color and have been used to install the microphones into the ceiling in the ICU.

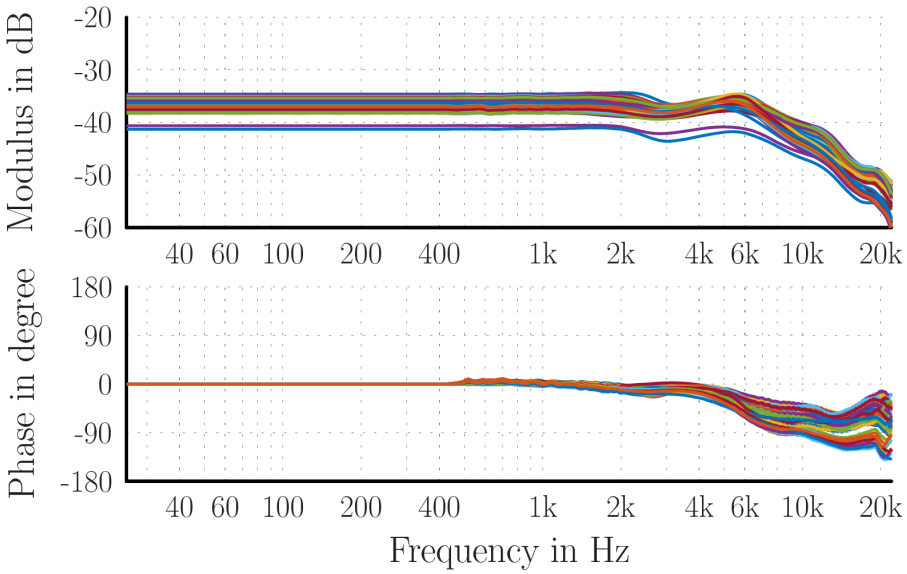
5.2. Microphone Pre-Amplifier

The electrical signal from the microphone has to be conditioned and amplified to line level (approximately 1.23 V_{rms}). This is done by the microphone pre-amplifier. The pre-amplifier also provides a phantom power voltage of 48 V to power the connected microphones. In most modern equipment, the pre-amplifier also converts the signal into digital format with an A/D converter.

The pre-amplifier used in this project is the 8-channel Focusrite OctoPre MKII [21] (see Figure 5.6). The input connections are through XLR sockets and the output is a digital stream of eight channels in the standardized ADAT format via a TosLink cable.



(a) Measurement setup



(b) Microphone sensitivity in dB re V/Pa for all 72 microphones

Figure 5.4.: Microphone calibration setup and results



(a) CAD model **(b)** Printed insert

Figure 5.5.: Insert piece to install microphones into the ceiling tiles



Figure 5.6.: Focusrite OctoPre MKII microphone pre-amplifier [21]

As the OctoPre has adjustable gain settings with a variable potentiometer, the gains have to be calibrated to be able to measure absolute sound pressure. For this, the gain potentiometers are all set to approximately the same value and then the conversion factors from input voltage to digital output are measured. The result for all of the 72 channels are plotted in dB re 1/V in Figure 5.7. It can be seen that the channels are well matched, so that the variation is less than one dB.

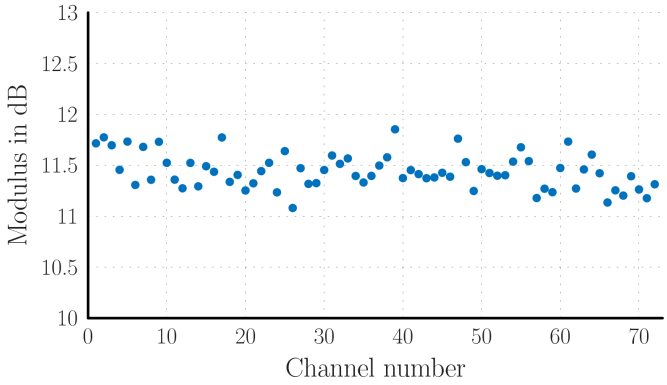


Figure 5.7.: Preamp gains in dB re 1/V

Combining the information of the microphone calibration (Figure 5.4b) and the preamp gains and inverting the result leads to the equalisation filters that can then be applied to the digital measured data to obtain the sound pressure in Pa. The equalisation filters are shown in dB re 20μPa in Figure 5.8.

5.3. ADAT to MADI Digital Converters

In total, nine of the pre-amplifier units described in the last section are used to capture the outputs of all 72 microphones. This means that nine ADAT streams have to be processed.

The digital format with the largest channel count is the MADI format, combining eight ADAT streams. Hence, two separate format converters are needed for the 72 channels of audio input from the pre-amplifiers. Data from the 64 array channels is converted from ADAT to MADI by the RME ADI-648 [22] (Figure 5.9a) and the remaining eight channels from the individual microphones are converted into the second MADI stream by the Ferrofish A16 [23] (Figure 5.9b).

To synchronize the sampling process to convert the analogue microphone signals into digital data, a common sampling clock signal has to be used. This so-called word-clock signal is provided by the RME ADI-648 and distributed by BNC cables to the Ferrofish A16 and all of the Focusrite pre-amplifiers.

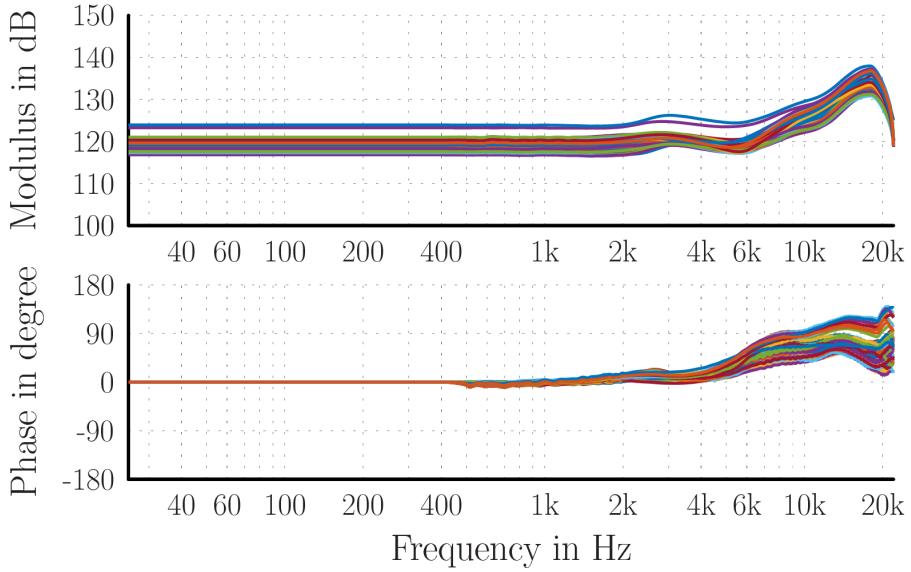


Figure 5.8.: Equalisation filters including pre-amplifier gains in dB re 20μPa



(a) RME ADI-648 [22]



(b) Ferrofish A16 MK-II [23]

Figure 5.9.: ADAT to MADI converters

5.4. MADI Sound Card

To actually record the audio data on a computer, a sound card capable of processing two MADI streams is required. The only card with this capability currently available is the RME MADI FX sound card [24] (Figure 5.10). This card is then installed in the computer.

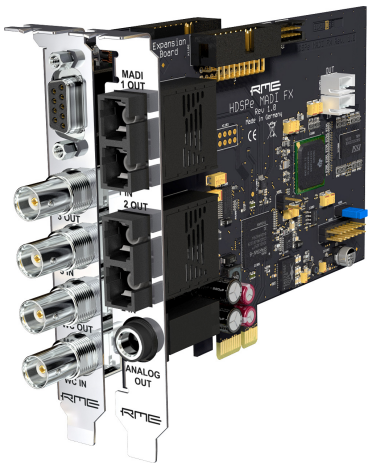


Figure 5.10.: RME MADI FX sound card [24]

5.5. Rack Server Computer

The computer chosen for the project is a DELL PowerEdge R330 rack-mountable server [25] (Figure 5.11). For sufficient computing power and memory, an INTEL XEON quad-core processor and 64 GB of RAM are chosen. A redundant data storage is achieved with two 1 TB hard drives in RAID 1 mode, which means that all data is copied identically to both drives so that in case of the failure of one drive, all data can be restored.



Figure 5.11.: DELL PowerEdge R330 [25]

5.6. Conclusion

Figure 5.12 shows a schematic of the connections of the different parts described in this chapter. A more detailed, practical description of the connections will be given in Chapter A.

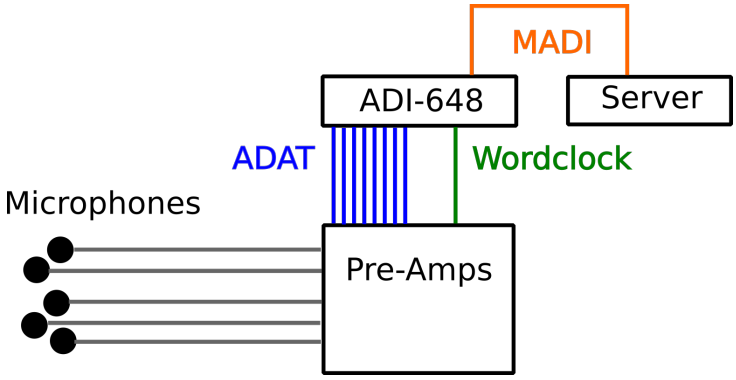


Figure 5.12.: Schematic of hardware connections

6. Software Overview

This chapter will give an overview of the software used for processing the audio data recorded by the hardware described in Chapter 5. The software design as well as the data processing steps will be described.

Initial implementation and prototyping of the algorithms has been done in the MATLAB scientific programming language [26]. The final implementation of the system is carried out in Julia [27], a free and open-source (under MIT license) programming language created in 2012 at MIT. The language is very similar to MATLAB or Python but increases performance by using a so-called *Just-in-Time (JIT) compiler*. The current stable version that has been used for this project is v0.5. All following descriptions of the software concern only the part in Julia.

6.1. Implementation

The functions that are needed for the signal processing and beamforming algorithms are all implemented in separate modules in the Julia language, so that the functionality can be reused in any program. The preparations and processing steps that are taken in the main script of the software – `run_beamforming.jl` – are shown in the schematic in Figure 6.1 and will be described in the following.

6.1.1. Audio preparations and processing

In the script `audio_preparations.jl` the block size and sampling rate are defined (currently 4096 samples at 48 kHz), as well as the signal window and the third-octave band limits for transforming the broadband data into band levels.

The *JACK Audio Connection Kit* [28] is used to connect to the sound card. In Julia the *JACKAudio* package allows the audio data to be read from JACK. The preparation script establishes a JACK client and sets up the audio data buffer.

During processing, the previous block and the current block are concatenated (to effectively achieve a data overlap of half a block), windowed and transformed into the frequency domain. The microphone equalization filters (Figure 5.8) are then applied to convert the digital data into absolute sound pressure values.

To obtain general level information the 72 channels of audio data are directly transformed into third-octave band levels, total A-weighted level and the loudness level in Phon (see Section 6.1.4). Additionally, data from the 64 array microphones is used for the spatial processing.

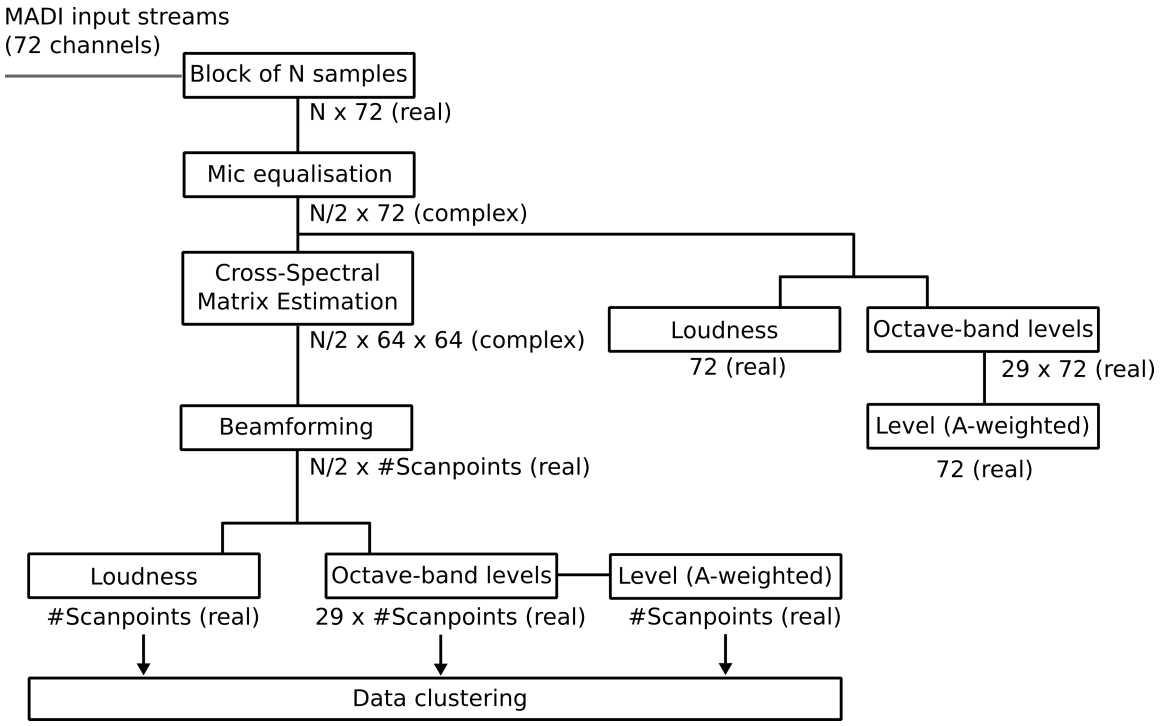


Figure 6.1.: Overview of array processing steps from audio input to exported data (data dimensions and type in brackets)

6.1.2. Array preparations and processing

The setup of all microphones and scan points is carried out in `array_preparations.jl`. In Figure 6.2 the layout with a room model of the ICU at the John Radcliffe Hospital in Oxford is depicted.

The center positions of the four sub-arrays are presented in Table 7.1 and the locations of the individual microphones are listed in 6.1.

Table 6.1.: Individual microphone coordinates

Channel Index	X in m	Y in m
65	2.1	6.3
66	2.1	3.3
67	7.5	2.1
68	10.5	2.1
69	16.3	2.5
70	16.3	6.8
71	8.7	7.5
72	4.5	11.7

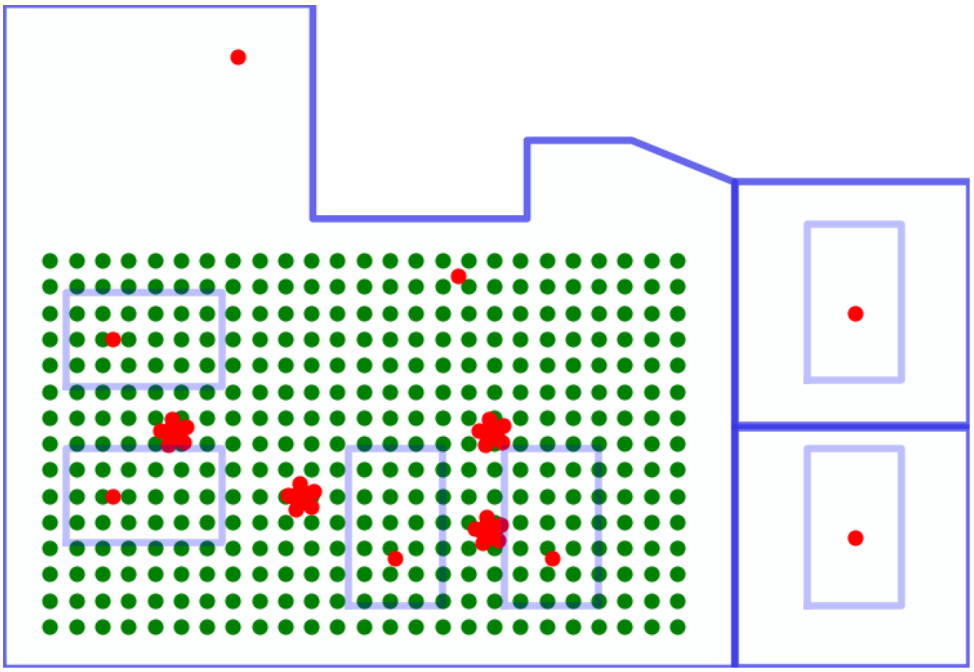


Figure 6.2.: Setup of the microphones (red) and scan positions (green) in the ICU, including the side rooms, with positions of the beds

6.1.3. Beamforming preparations and processing

An advantage of the structure of beamforming calculations is that the steering vectors (Eq. (2.1)) and the **A** matrix (Eq. (2.4)) can be computed in advance to reduce the computation time. This does, however, require more RAM to store all of the data in memory for faster access.

Based on the array and scan positions defined in the previous step (Section 6.1.2), the script `beamforming_preparations.jl` performs the pre-calculation of the steering vectors and the **A** matrix.

With the calibrated audio data from the 64 array microphones, for each block of data the Cross-Spectral Matrix with exponential smoothing according to Eq. (2.7) is computed and then used for the beamforming calculations. The beamforming algorithm can be chosen freely, however the default is set to the fast version of the CLEAN algorithm (Eq. (2.27)).

The broadband beamformer power output per scan point can then either be transformed to third-octave band levels and finally A-weighted levels, or the total loudness level in Phon can be calculated per scan point.

Although the beamforming result, which is calculated for each third-octave band, shows a sparse source distribution, the summation for the broadband result may lead to a slightly blurred map. Hence, for a better representation of the data, the broadband result is combined into five clusters by the *k-means clustering* method. An example will be provided later.

6.1.4. Psychoacoustics

To include perceptual aspects into the evaluation process, the psychoacoustic quantity of loudness is also calculated. Loudness uses a modified weighting across frequency, which, compared to the simple A-weighting curve, provides a better indication of the subjective perception. Loudness also includes the important phenomenon of frequency-masking, taking into account the relationship between different tonal components within a critical band.

Two standards exist that describe the calculation of loudness: ISO 532B [29] follows the model proposed by Zwicker (see [30] for an implementation example) and works on data in third-octave bands, whereas ANSI S3.4 [31] is based on a model developed by Moore, Glasberg, and Baer [32] and uses broadband data. A comparison of the specific loudness in Sone/Bark of a sinusoid signal with a frequency of 1 kHz and varying SPL is presented in Figure 6.3 for both standards.

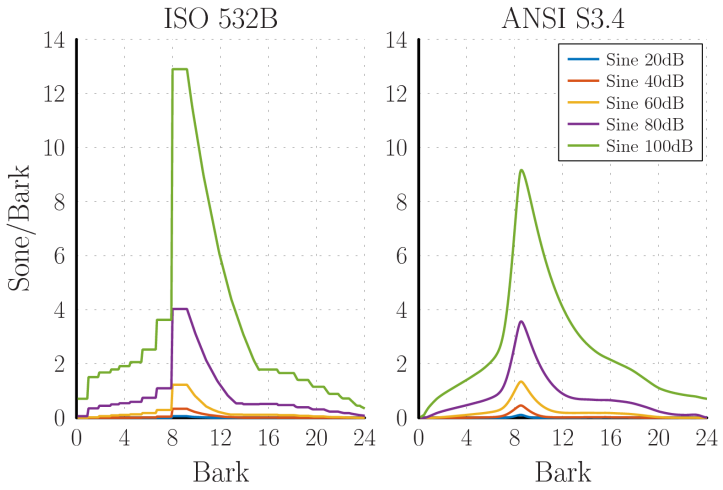


Figure 6.3.: Specific loudness in Sone/Bark for two psychoacoustics standards for an example of a 1 kHz with varying level

In general, both standards result in similar loudness values, especially for lower levels (up to $70 - 80$ dB). However, in terms of performance, ISO 532B can be implemented much more efficiently and is 20 times faster than the ANSI implementation. Hence, in this project, ISO 532B is used for all loudness calculations. For the efficient implementation of ISO 532B, some variables can be pre-calculated. This is done in the script `psychoacoustics_preparations.jl`.

It should be noted that the loudness standards assume binaural listening, so the result is multiplied by a factor of two. This means that the output of the loudness calculations will be at least 6 dB higher than the broadband level.

6.1.5. Data Export

Apart from showing the results of the beamforming process on a display, the data is also exported to hard disk for subsequent statistical evaluation. The format of the exported file is CSV (comma-separated values), which can easily be imported into any spreadsheet program. A new file is created every minute, with a new folder for every calendar day.

Within each file, a new set of data is written each second. The layout of the export file is shown in Table 6.2. The data is written first for all 72 microphones, then for all scan points and the last entries are for the clustering result, specifying the location, overall level and predicted class type for each cluster point. The size of each file is approximately 2 MB.

Table 6.2.: Layout of the CSV file with data dimensions

Index	**1/3-Octave Band Level in dB**	**Overall Level in dB(A)**	**Loudness Level in Phon**
1 ... 72	72 × 29	72 × 1	72 × 1
73 ... 447	375 × 29	375 × 1	375 × 1
Index	**X-/Y-Coordinates in m**	**Overall Level in dB(A)**	**Source Class**
448 ... 452	5 × 2	5 × 1	5 × 1

6.1.6. Data Display

To present the data gathered from the array system to the nursing staff, a display was created in Julia. For an abstraction between the signal processing and the display, a web server was created on the rack computer in Julia listening on port 2000. This server will accept socket connections on that port and then wait for a request of data in the form of the message `getMessage`. Once this message is received, the data necessary for the display is sent back in the JSON format. The fields of the JSON message are listed in Table 6.3.

An example of the Julia display with data from the simulation in Figure 4.5 is shown in Figure 6.4. The *level* field of the JSON message (Table 6.3) is used to display the level of the individual microphones and the average level across the array microphones in the color bar (right side of the display). If the type of processing is in the form of a contour map (compare Figure 4.6a) all level values for the map are transmitted in the JSON data. If the beamforming data is clustered (Figure 4.6b) then the location and the associated levels of the five clusters are transmitted. The display is updated once a second.

Table 6.3.: Fields of the JSON message for displaying the result

Field	Description
time	Time string (format YYYY-MM-DDThh:mm:ss)
blockSize	Audio block size
beamformingType	Used beamforming algorithm
levels	A-weighted levels of all microphones
plotType	Which data to plot: dB, dBA – (A-weighted) levels loudness – Loudness level in Phon cluster – Source clusters
plotData	Depending on plotType: (data dimensions) cluster: positions and levels (5, 3) otherwise: levels ($N_{\text{scan},x}$, $N_{\text{scan},y}$)

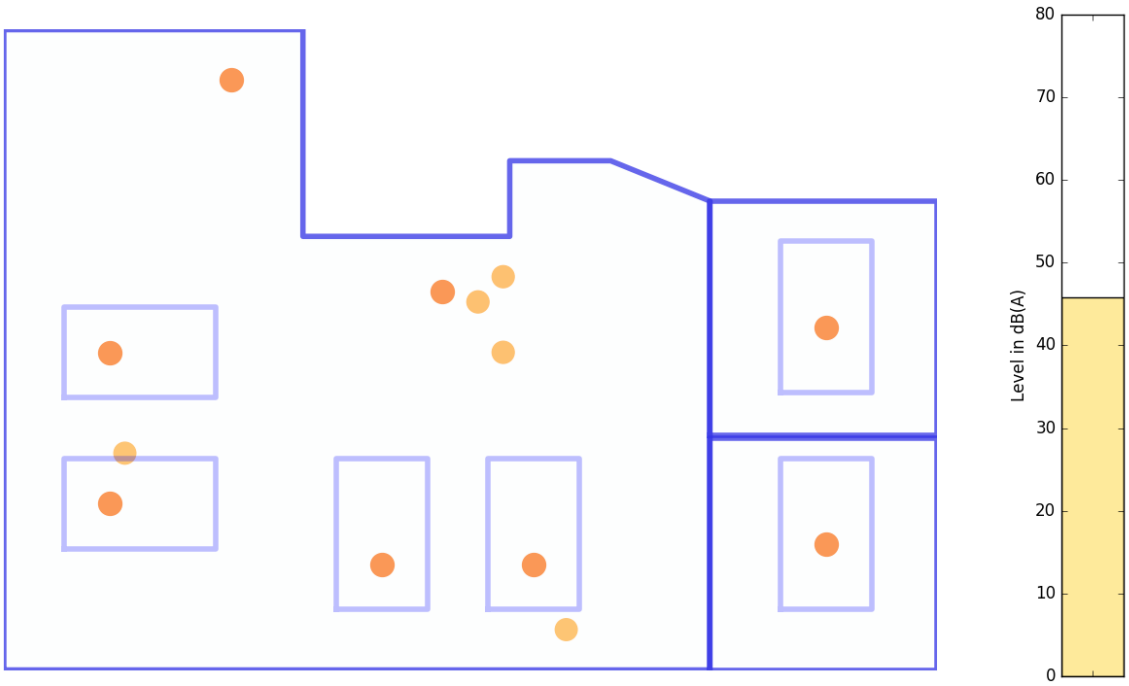


Figure 6.4.: Screenshot of the data display in Julia for plot type *cluster* (compare Figure 4.6b)

6.2. Beamforming Performance

To get an impression of the real-time capability of the beamforming processing, some of the algorithms in Chapter 2 have been compared using simulated data. As a measure of the processing speed, the real-time factor (RTF) has been used, which is the time it takes to process a block of data relative to the length of the block in seconds.

In Table 6.4, the RTF is listed for the most suited algorithms implemented in the software. As expected, the algorithms that do not calculate the Cross-Spectral Matrix perform much better in terms of speed. CLEAN and CLEAN-SC usually do not take much longer than the original Delay-and-Sum beamformer. As mentioned in Chapter 2, the calculation of the eigenvalue decomposition significantly slows down the subspace algorithm.

Table 6.4.: Real-time factor of beamforming algorithms

Algorithm	RTF in s
Delay-and-Sum (w/o CSM Eq. (2.11))	2
CLEAN (w/o CSM)	3
Delay-and-Sum (Eq. (2.10))	9
CLEAN (Eq. (2.27))	12
CLEAN-SC (Eq. (2.29))	11
Subspace (Section 2.3.3)	42

In conclusion, if source coherence is not taken into account, the fast version of CLEAN is the best choice. Otherwise, CLEAN-SC should be used.

6.3. Unit Testing

To make sure that no changes to the code during development break functionality of the software, unit tests have been created for essential module functions. After each major change in the code, these unit tests should be run. For this, a function `run_all_unittests.jl` has been created, which goes through the following tests:

- `steering_vector_unittest.jl`
- `beamforming_unittest.jl`
- `coordinates_unittest.jl`
- `general_unittest.jl`
- `psychoacoustics_unittest.jl`
- `signalprocessing_unittest.jl`
- `simulations_unittest.jl`

6.4. Version Control

To keep track of code changes, the Git version control system is used for all code as well as this documentation [33]. This allows for concurrent programming in two separate branches: one stable branch for the system in Oxford and a development branch for new developments at the ISVR. The Git system provides a history of all code and also enables specific versions to be tagged, as has been done for the version used for the ICU installation.

At the moment, the repository location for this project is

```
https://gitlab.com/Mueller-Trapet/SILENCE.git
```

although this would have to be changed in the future.

7. ICU Installation

In this chapter, the process and results of the installation in the ICU at John Radcliffe Hospital in Oxford on 26–27 October 2016 are described.

7.1. Hardware Installation

As the hardware was too large and heavy to put into the ceiling with the arrays, an office close to the ICU was chosen as the location for the audio hardware (pre-amplifiers and converters), which was assembled into a rack with 12 height units (Figure 7.1).



Figure 7.1.: Assembled hardware rack, from top to bottom: RME MADI converter, 8 pre-amplifiers for the array microphones, Ferrofish MADI converter, pre-amplifier for the individual microphones

The microphone arrays and the individual microphones are connected to the pre-amplifiers with 30 m 16-channel professional multi-core cables (Figure 7.2). For the 72 microphones used, a total of 5 multi-core cables have to be used, leaving eight spare channels for additional sensors.



Figure 7.2.: 16-channel multi-core cable

The computer is placed together with similar equipment into a rack in a separate room. Thus, to connect the computer to the MADI converters, two optical MADI cables of 50 m length are routed between the hardware rack and the server room. The floor plan with the location of the microphones, the hardware rack and the cable routing is shown in Figure 7.3.



Figure 7.3.: ICU installation schematic: microphone arrays (large red circles), individual microphones (small red circles), multi-core cables (black lines) and MADI cable (orange line)

7.2. Calibration Measurement

For optimal performance of the beamforming processing, it is important to know the exact locations of the microphone arrays. The fact that the ceiling is divided into tiles helps with the approximate location of the arrays.

To obtain a more precise estimate of the array positions, a calibration measurement with a small loudspeaker (Genelec 8010) was performed after the installation. The loudspeaker was placed with its back on the floor at approximately $(X, Y) = (6.9\,\mathrm{m}, 4.9\,\mathrm{m})$, relative to the lower left corner in Figure 7.3. The transfer function between the loudspeaker and the array microphones was measured and after compensating for the system latency the acoustic delay was used to determine the four array center positions. The positions before and after the calibration are listed in Table 7.1.

Table 7.1.: Array color codes as well as center positions before (**X**, **Y**) and after (**X'**, **Y'**) calibration, relative to lower left corner in the ICU

Array #	**Channel Index**	**X in m**	**Y in m**	**X' in m**	**Y' in m**
1 (green)	1 . . . 16	3.30 m	4.50 m	3.27 m	4.51 m
2 (blue)	17 . . . 32	5.70 m	3.30 m	5.71 m	3.27 m
3 (red)	33 . . . 48	9.30 m	4.50 m	9.35 m	4.52 m
4 (black)	49 . . . 64	9.30 m	2.70 m	9.29 m	2.63 m

As can be seen, the measured locations differ only slightly from the predicted ones. These more accurate values are used in the software for the beamforming processing.

8. Conclusions

In the course of this project, a microphone array system has been created and installed in the ICU of the John Radcliffe Hospital in Oxford.

After researching the most important beamforming algorithms, the distribution of the array sensors and the shading weights were optimized for the best broadband performance in terms of dynamic range and spatial resolution. A logarithmic spiral array was found to provide the best performance and most degrees of freedom for the shading weights.

The performance of the array was tested in a simulation of the ICU environment. Measurements and recordings of medical equipment were used as input for the simulations to provide a more realistic result. This allowed the most suitable beamforming algorithm to be determined with respect to both processing speed and accuracy, and this was found to be the CLEAN algorithm.

The hardware needed for the project was then developed and assembled, including a powering circuit for the microphones. Given the number of channels, the digital MADI format was chosen and the necessary hardware was included into the system. To provide enough computing power and with the goal of installation into a rack, a server computer was chosen as the data processing unit.

For the software development, the Julia language was ultimately chosen as a free, open-source programming language targeted at scientific computing. The functionality needed for data processing was either taken from publicly available packages or created by writing different modules. The software takes care of reading the audio streams, processing the data as well as exporting and displaying the results. In terms of professional software management, unit testing as well as version control are used for quality control.

The system was installed in the John Radcliffe Hospital in Oxford on November 26–27 2016. A detailed floor plan has been presented in this document. The calibration following the installation ensured accurate microphone positioning information to achieve the best possible array processing result.

Currently, the system is running continuously to collect data and the display is updated accordingly. With that data, hopefully important information can be gathered about the noise sources in the ICU. A short follow-up project will focus on using the system in connection with machine listening to determine the types of noise sources in addition to their location and strength.

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A. Hardware Connections and Settings

This chapter describes the connection of the individual hardware components and the most important settings.

A.1. Electrical Connections

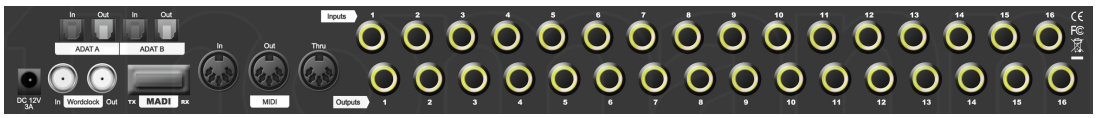
A color coding scheme has been applied to the cables connecting the microphone arrays to the pre-amplifiers. For the color of each array see Table 7.1. Colored cable ties are attached to the cables of each sub-array, each end of the corresponding multi-core as well as the corresponding pre-amplifiers.

Each multi-core is connected to two pre-amplifiers, where channels 1–8 are connected to the upper unit and channels 9–16 to the lower unit. Since the Focusrite OctoPre has two microphone inputs on the front, a total of four channels of each multi-core (channels 1, 2, 9 and 10) have to be routed to the front of the rack.

The digital outputs of the top eight pre-amplifiers are connected via TosLink cables from one of the outputs marked *OPTICAL OUT* on the back of the unit (Figure A.1c) to the inputs on the back of the RME ADI-648 marked *ADAT INPUTS* (Figure A.1a). Each pre-amplifier has a sticker with *UNIT* and the number of the unit on it, to indicate which of the ADAT inputs have to be connected on the RME ADI-648. The last pre-amplifier is connected to the input marked *ADAT A In* on the Ferrofish A-16 (Figure A.1b).



(a) RME ADI-648 [22]



(b) Ferrofish A-16 [23]



(c) Focusrite OctoPre MKII [21]

Figure A.1.: Back panels of the audio equipment

As mentioned in Section 5.3, the sampling process has to be synchronized by a word-clock signal. This is supplied by the RME ADI-648 and distributed from the output terminal marked *WORD CLOCK OUTPUT*. This output is connected via BNC cables in a daisy-chain starting with the first pre-amplifier. At each pre-amplifier the connection is made to the terminal marked *WORD-CLOCK IN*. For the Ferrofish A-16, the BNC cable is connected to the terminal marked *Wordclock In*.

The first of the two duplex MADI cables is connected to the input marked *MADI OPTICAL* on the RME ADI-648. The duplex cables have small fins so that they can only be connected in the correct way. The second MADI cable is connected to the input marked *MADI* on the Ferrofish A-16. On the rear side of the computer, the first MADI cable is connected to the inputs marked *1 IN* and *1 OUT* on the RME MADI FX sound card (see Figure 5.10) and the second MADI cable is connected to the inputs *2 IN* and *2 OUT*.

A.2. Settings

Once all connections are made, the phantom power buttons marked *MIC 48V 1–4* and *5–8* on the front of the pre-amplifiers (Figure 5.6) have to be pressed so that the LEDs underneath light up when the unit is turned on. None of the other buttons (*PAD* or *INST*) should be pressed. On the right side of the front panel, the red LED marked *Wordclock* should be illuminated, otherwise the button marked *Clock Source* has to be pressed until the correct setting is obtained. Out of the green LEDs above the button marked *Sample Rate* the one marked *48* should be lit up, otherwise the button has to be pressed repeatedly until the correct setting is achieved. If all settings and connections are correct, the green LED marked *Locked* should be lit. All of the hardware settings are remembered after the power is turned off, so the settings only have to be made once.

Regarding the RME ADI-648 (Figure 5.9a), the *INPUT* on the left of the front panel should be set to *OPT*, otherwise the button marked *SELECT* underneath can be pressed until the correct setting is achieved. In the section marked *CLOCK*, the LED marked *INPUT* should be lit up and the to the left of it, the one marked *MADI* has to be chosen, otherwise the settings can be changed with the *SELECT* button. On the right side of the front panel, it should be ensured that the LED for the state of the channel matrix marked *ON* is **not** illuminated.

On the front panel of the Ferrofish A-16 (Figure 5.9b), the left screen should show the selection *48k*, otherwise the button marked *SAMPLERATE* can be pressed until the correct setting is obtained. On the right screen, the setting *BNC* should be marked, otherwise the setting can be changed with the button *SYNCHRONIZATION*.

B. Software Setup

This chapter provides the software settings and commands needed to set up the system on a new computer. To have a low-maintenance operating system well suited for audio processing, the *Studio* version of *Ubuntu* was chosen [34]. The user name of the PC used in this project is `silence`, the root password is `noise2016`. The project files are located in the folder `/home/silence/Git/SILENCE`. The following sections describe how the software is set up.

B.1. Git

To be able to checkout the latest version of the software using version control, the Git program has to be installed with the following command:

```
sudo apt-get install git
```

B.2. MADI FX Driver

The linux driver for the RME MADI FX sound card is developed by Adrian Knoth and can be installed from his git repository with the following commands:

```
cd /usr/local/src
sudo git clone git://github.com/adiknoth/madifx.git
cd madifx
sudo make install
```

The install command has to be run everytime the linux kernel is changed during a system update. The MADI FX module and driver have to be loaded on startup to make the sound card available to JACK:

```
sudo modprobe madifx
sudo apt-get install alsa-firmware-loaders
sudo hdsploader
```

After this, the correct functionality of the sound card can be tested by running

```
aplay -l
```

B.3. JACK

As an important part of the audio processing, the JACK program has to be installed. To be able to automatically start JACK when the computer is turned on, a version without the *dbus* system has to be compiled and installed. The following set of commands has to be entered into the terminal to do this:

```
sudo apt-get install build-essential libsamplerate0-dev
sudo apt-get install libasound2-dev libsndfile1-dev

cd /usr/local/src
sudo git clone git://github.com/jackaudio/jack2.git
cd jack2

sudo ./waf configure --alsa --prefix=/usr/local --libdir=/usr/lib/x86_64-linux-gnu
sudo ./waf
sudo ./waf install
```

After this, JACK can be run from `/usr/local/bin/` with the following command:

```
/usr/local/bin/jackd -S -R -d alsa -d hw:MADIFXtest -r 48000 -p 2048
```

B.4. Julia

To download and install Julia from source, the following commands have to be run:

```
sudo apt-get install gfortran
cd /usr/local/src
sudo git clone git://github.com/JuliaLang/julia.git
cd julia
sudo git checkout release-0.5
sudo make
sudo ln -s /usr/local/src/julia/usr/bin/julia /usr/local/bin/julia
```

If there is an error during compilation, some dependencies might not be met. See the Julia website for more information (`http://julialang.org`).

In preparation to add the PyPlot package to the Julia installation, the matplotlib software for Python has to be installed:

```
sudo apt-get install python-matplotlib
```

After this, the necessary packages have to be added in Julia:

```
julia
Pkg.update()
Pkg.build("MbedTLS")
Pkg.add("JACKAudio")
Pkg.add("DSP")
Pkg.add("PyPlot")
Pkg.add("Distances")
Pkg.add("Interpolations")
Pkg.add("Debug")
Pkg.add("NumericExtensions")
Pkg.add("Clustering")
Pkg.add("DataArrays")
Pkg.add("DistributedArrays")
Pkg.update()
push!(LOAD_PATH, "/home/silence/Git/SILENCE/Code/Julia")
push!(LOAD_PATH, "/home/silence/Git/SILENCE/Code/Julia/modules")
```

The last line adds the modules of the SILENCE project to the module path. At this point, the unit tests should be run to ensure the correct functionality:

```
cd /home/silence/Git/SILENCE/Code/Julia
julia run_all_unittests.jl
```

B.5. Autostart: rc.local

To enable the automatic start of the system on startup, the following lines have to be added to `/etc/rc.local`:

```
modprobe madifx
hdsploader
runuser -l silence -c "/usr/local/bin/jackd -S -R -d alsa -d hw:MADIFXtest -r 48000 -p
runuser -l silence -c "/home/silence/Git/SILENCE/Code/Julia/julia_startup_script.sh"
```