



The effect of sleep continuity disruption on multimodal emotion processing and regulation: a laboratory-based, randomized, controlled experiment in good sleepers

Journal:	<i>Journal of Sleep Research</i>
Manuscript ID	JOSR-22-012.R1
Manuscript Type:	Research Article
Date Submitted by the Author:	11-Mar-2022
Complete List of Authors:	Reid, Matthew; University of Oxford, Nuffield Department of Clinical Neurosciences; Johns Hopkins School of Medicine, Psychiatry and Behavioral Sciences Omlin, Ximena Espie, Colin; University of Oxford, Nuffield Department of Clinical Neurosciences/ Sleep & Circadian Neuroscience Institute; Sharman, Rachel; University of Oxford, Nuffield Department of Clinical Neurosciences Tamm, Sandra; Karolinska Institutet, Clinical Neuroscience Kyle, Simon; University of Oxford, Nuffield Department of Clinical Neurosciences/ Sleep & Circadian Neuroscience Institute
Keywords:	sleep deprivation, depression, attentional bias, memory consolidation, emotion regulation, sleep

SCHOLARONE™
Manuscripts

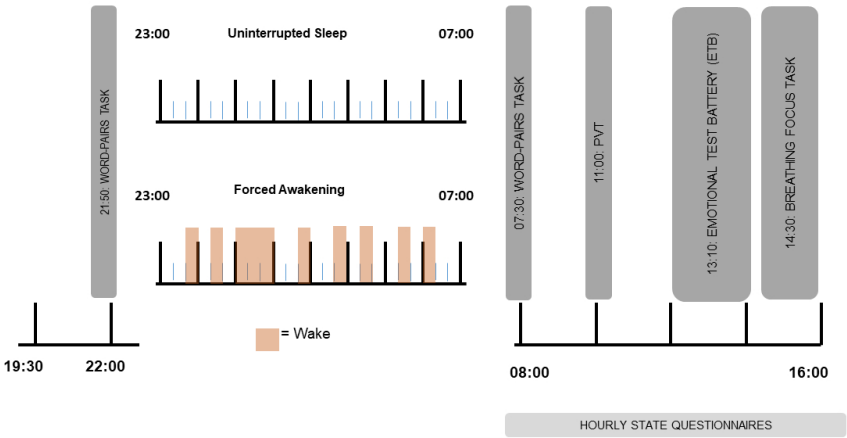


Figure 1

338x190mm (96 x 96 DPI)

The effect of sleep continuity disruption on multimodal emotion processing and regulation: a laboratory-based, randomized, controlled experiment in good sleepers

Running head: Sleep Continuity Disruption and Emotion Processing

Reid, MJ^{1,2}, Omlin, X¹., Espie, CA¹., Sharman, R¹., Tamm, S^{3,4}

& Kyle, SD¹.

¹Sleep and Circadian Neuroscience Institute, The University of Oxford, Oxford, UK

²Johns Hopkins School of Medicine, Baltimore, MD, USA

³Department of Psychiatry, The University of Oxford, Oxford, UK

⁴Department of Clinical Neuroscience, Karolinska Institutet, Stockholm, Sweden

Corresponding Author:

Dr Matthew J Reid

Department of Psychiatry and Behavioral Sciences

Johns Hopkins School of Medicine,

5510 Nathan Shock Drive,

Baltimore MD

Email: mreid27@jhmi.edu

Word Count: 4964

Number of references: 40

Conflict of Interest Statement: The authors of this manuscript declare no financial, or non-financial conflicts of interest

Disclosure Statement: Financial Disclosure: none. Non-financial Disclosure: none

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

This research study was supported financially by the National Institute for Health Research (NIHR) Oxford Biomedical Research Centre (BRC). The research was also supported through a DPhil (PhD) Scholarship (to M.J.R) from the Dr Mortimer and Theresa Sackler Foundation.

Author Contributions: M.J.R designed, conducted the research and wrote the manuscript, X.O assisted in collection of the data and study experiment procedures, C.A.E and S.D.K supervised the study design and conduct, and assisted in writing the manuscript. S.T assisted in writing and editing the manuscript, R.S assisted in data collection and EEG scoring. All authors provided feedback and contributed to the final version.

Abstract

Previous research shows that experimental sleep deprivation alters emotion processing, suggesting a potential mechanism linking sleep disruption to mental ill-health. Extending previous work, we experimentally disrupted sleep continuity in good sleepers and assessed next-day emotion processing and regulation using tasks with established sensitivity to depression. In a laboratory-based study, 51 good sleepers (37 female; mean age = 24 years, SD= 3.63) were randomized to one night of uninterrupted sleep (n=24) or sleep continuity disruption (n=27). We assessed emotion perception, attention, and memory the following day. Participants also completed an emotion regulation task and measures of self-reported

1
2
3 affect, anxiety, sleepiness, overnight declarative memory consolidation, and psychomotor
4
5
6
7 vigilance. Confirming the effects of the manipulation, sleep continuity disruption led to a
8
9
10 marked decrease in polysomnography-defined total sleep time (229.98 mins vs 434.57 mins),
11
12
13 increased wake-time after sleep onset (260.66 mins vs 23.84 mins) and increased sleepiness
14
15
16 (d=0.81). Sleep continuity disruption led to increased anxiety (d=0.68), decreased positive
17
18
19 affect (d=-0.62), reduced overnight declarative memory consolidation (d=-1.08) and reduced
20
21
22 psychomotor vigilance [longer reaction times (d=0.64) and more lapses (d=0.74)], relative to
23
24
25 control. However, contrary to our hypotheses, experimental sleep disruption had no effect on
26
27
28 perception of, or bias for, emotional facial expressions, emotional memory for words, or
29
30
31 emotion regulation following worry induction. In conclusion, one night of sleep continuity
32
33
34 disruption had no appreciable effect on objective measures of emotion processing or emotion
35
36
37 regulation in response to worry induction, despite clear effects on memory consolidation,
38
39
40 vigilance, and self-reported affect and anxiety.
41
42
43
44
45
46
47
48
49

50 **Keywords:** Sleep Deprivation; Depression; Attentional Bias; Memory Consolidation;
51
52
53 Emotional Regulation; Sleep; Emotion;
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review

Introduction

Previous research indicates a link between sleep and emotional functioning (Baglioni, Spiegelhalder et al. 2010, Krause, Simon et al. 2017). Dysfunctional emotional processing has been suggested as a potential mechanism underlying the association between sleep disruption and psychiatric disorders (Hertenstein, Feige et al. 2019). In support of this proposition, several early studies reported that total sleep deprivation (TSD) negatively affected processing of emotional stimuli, including facial expressions (Van Der Helm, Gujar et al. 2010), as well as memory for emotional words and images (Phelps 2004). However, recent studies have failed to show an effect of sleep deprivation (or restriction) on emotional processing (Holding, Laukka et al. 2017, Gerhardsson, Åkerstedt et al. 2019, Tamm, Schwarz et al. 2020).

TSD and chronic sleep restriction protocols do not adequately reflect the type of sleep disruption experienced by patients with mental health problems, where the chief defining feature is sleep discontinuity and self-reported insomnia. Case-control studies, comparing participants with and without insomnia, have also found behavioural impairments in emotional tasks, such as reduced intensity ratings of emotional faces (Kyle, Beattie et al. 2014), and

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

reduced recognition of positive emotional images (Chunhua, Jiاعي et al. 2019). However, similar to the TSD literature, inconsistent findings are observed (Baglioni, Spiegelhalder et al. 2010, Crönlein, Langguth et al. 2016), sample sizes have typically been small, and a broad range of tasks have been used across studies, which vary in both their demands and sensitivity to specific cognitive processes. It is clear that the field needs to causally test the effects of sleep manipulation protocols that map onto sleep disturbance experienced by clinical populations. Moreover, there is a need to investigate different facets of emotional functioning within the same study (using standardized tasks), including processing of emotional stimuli across multiple cognitive domains, regulation of emotion in response to challenge, and self-reported mood state.

We designed a study to address these needs and to assess the effects of sleep continuity disruption on emotional functioning. We selected a forced awakenings protocol (Finan, Quartana et al. 2017) in order to simulate sleep continuity disruption and architectural impairment characteristic of a severe insomnia phenotype (Finan, Quartana et al. 2017). Previous work implementing this protocol has demonstrated attenuation of positive affective systems in healthy participants without influencing negative affect, resulting in an overall

negativity bias (Finan, Quartana et al. 2017). Advancing previous research, we focussed on cognitive-affective tasks with established sensitivity to depression risk, diagnosis, and treatment (Harmer, Cowen et al. 2011), and investigated emotion regulation as well as mood state. We hypothesized that sleep continuity disruption would lead to enhanced processing of negative emotional stimuli and reduced processing of positive emotional stimuli in the following domains: 1) recognition of facial emotions, 2) attention towards emotional faces, 3) categorization of emotional words, and 4) memory for emotional words (see supplemental table 3 for detailed hypotheses). We used a worry induction task to assess effects on goal-oriented attention and positive/negative thought intrusions, hypothesizing impairment in the sleep continuity disruption group versus control. In order to confirm the effects of the sleep manipulation, and to provide context in terms of magnitude of group effects, we assessed affect, sleepiness, vigilance and overnight memory consolidation; domains that are known to be sensitive to the effects of sleep loss.

Methods

Design

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

We performed a between-subjects randomized controlled experiment to assess the effects of sleep continuity disruption (delivered via forced awakenings (Finan, Quartana et al. 2017)) on emotion processing and emotion regulation in a laboratory setting (see figure 1 for schematic of tasks). Our primary outcomes were emotional perception (facial emotion recognition test), emotional attention (faces dot probe task), and emotional memory (emotional recall and recognition memory tasks) measured using the Oxford Emotional Test Battery [ETB (P1Vital Product Ltd, Oxford UK)], and emotion regulation measured using an established worry induction (Adams, Pounder et al. 2016). A between-group design was employed because our primary outcome measure tasks may be susceptible to practice effects (Adams, Pounder et al. 2016). The study was given approval from The Medical Sciences Interdivisional Research Ethics Committee (MS IDREC), University of Oxford Central University Research Ethics Committee (CUREC).

We recruited healthy participants (aged 18-30 years, 38 female; mean age = 24 years, SD= 3.63) who were habitual good sleepers, free from any current or pre-existing sleep, neurological or psychiatric disorders, and were free of any centrally acting central nervous system medications (see inclusion criteria in table 1).

[Insert table 1 here]

Procedures

Recruitment

Participants were recruited through several channels, including online, print, and email. Online and written consent was obtained prior to any procedures being undertaken. Participants first completed an online screening questionnaire followed by a study screening visit at the University of Oxford to assess eligibility according to inclusion and exclusion criteria. The following questionnaires were used during the screening procedure: Pittsburgh Sleep Quality Index (Buysse, Reynolds et al. 1989) (PSQI), Morningness Eveningness Questionnaire (Adan and Almirall 1991) (MEQ), Hospital Anxiety and Depression Rating Scale (Bjelland, Dahl et al. 2002) (HADS), Alcohol Use Disorders Identification Test (Babor, Higgins-Biddle et al. 2001) (AUDIT) and Brief Sleep Disorders Screen (Espie 2006) (BSDS). Baseline measures of neuroticism (Eysenck Personality Questionnaire – Revised Short Form (EPQ-RS) (Eysenck, Eysenck et al. 1985) and rumination (Ruminative Responses Scale (Treynor, Gonzalez et al. 2003) (RRS)) were also obtained during this phase in order to characterize the sample at baseline. Participants received reimbursement for participation (£100 in total).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Sleep monitoring phase

To further determine eligibility, participants underwent an at-home monitoring phase consisting of seven days of actigraphy concurrent with sleep diaries (to index total sleep time [TST] and sleep efficiency [SE] parameters). During this phase, participants were advised to maintain their regular habitual sleep schedule. Participants wore actiwatches (MotionWatch 8, CamnTech Ltd, Cambridge, UK) 24 hours per day on their non-dominant wrist. Data from the night-time periods were used to calculate average TST and SE using validated algorithms (Elbaz, Yaury et al. 2012) embedded in the actigraphy software (MotionWare 1.2.5, CamnTech, Cambridge, UK). Consistent with previous studies, participants indicated bedtime and risetime using the actigraphy event marker, completed the consensus sleep diary (Carney, Harris et al. 2010) upon waking each morning. Diaries were used to verify bed and rise times of actigraphy measures and gather self-report data on perceived TST and SE. In the instance of missing event marker data, sleep diaries were used to substitute bedtime and rise time values in the actigraphy software.

Experimental protocol

1
2
3
4
5
6
7 Immediately after completion of the seven-day screening phase, participants arrived at the
8
9
10 sleep laboratory at 19:30. In the daytime hours prior to coming to the lab, we requested
11
12
13 participants abstain from all alcohol, caffeine and stimulants, and to not engage in intense
14
15
16 exercise. Participants were set up for polysomnographic (PSG) recording (SomnoMedics
17
18
19 GmbH, Germany) and subsequently completed the first session of the computerized memory
20
21
22 assessment (word-pairs task (Marshall, Helgadottir et al. 2006) consisting of encoding and
23
24
25 recall). Participants were randomized at 22:30 and, following completion of the memory task,
26
27
28 were informed about which sleep protocol they were to undergo. At this point, both
29
30
31 experimenter and participant were necessarily un-blinded. Commencement of sleep
32
33
34 opportunity for both groups began at 23:00. Access to smartphones or handheld electronic
35
36
37 devices was restricted to before 22:30 on the first night and between the hours of 07:00-07:30
38
39
40 the following morning. For the duration of the protocol (19:30 to 16:00 the next day)
41
42
43 participants remained in the laboratory. Questionnaires assessing state affect (Positive and
44
45
46 Negative Affective Schedule: PANAS (Crawford and Henry 2004), emotion regulation (State
47
48
49 Difficulties in Regulation Scale: S-DERS (Lavender, Tull et al. 2015), anxiety (State-Trait
50
51
52 Anxiety Inventory: STAI (Spielberger 1970), and sleepiness (Karolinska Sleepiness Scale:
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

KSS (Kaida, Takahashi et al. 2006)) were collected pre-randomization to compare groups at baseline, and completed hourly the following day commencing at 08:00 (Post sleep disruption). During the time in the sleep lab, participants did not consume any caffeinated drinks. Standardized meals were consumed at fixed times (09:00, 12:00).

PSG was conducted according to the American Academy of Sleep Medicine (AASM) standards (Berry, Brooks et al. 2017). A standardized PSG montage consisting of 8 EEG electrodes (F3, F4, F7, F8, C3, C4, O1, O2), 2 electrooculography (EOG) electrodes (EOG1, EOG2), 2 submental electromyography (EMG) electrodes and 2 electrocardiogram (ECG) electrodes (to facilitate artefact detection) were used to record objective sleep using a SOMNO HD device (SomnoMedics GmbH, Germany) between 23:00 and 07:00. We opted not to include further EMG and respiratory channels required to perform sleep apnoea or limb movement disorder screening since we judged the probability of detecting occult sleep disorders (in our highly selected healthy sample) would be low. Electrode sites were measured using the international 10-20 EEG system and positioned according to AASM guidelines. EEG channels were recorded with a sampling rate of 256hz (hardware filter: high pass = 0.3hz, low

pass = 128.0hz), using Cz as reference and FpZ as the ground electrode. For analysis signals were re-referenced to the contra-lateral mastoid (M1 and M2). PSG records were scored by a trained scorer according to current AASM guidelines (Scoring Manual Version 2.5 (Berry, Brooks et al. 2012)). A concordance check was carried out on 15% of records by a European Sleep Research Society (ESRS) Somnologist, achieving a concordance rate of >90%.

Randomization procedures

Participants were randomly allocated 1:1 to the forced awakenings group (experimental) group or the uninterrupted sleep group (control), stratified according to sex to minimise influence on baseline differences in sleep architecture and emotion. Randomisation schedules were created off-site by a member of the research team with no direct involvement in the study using randomly assigned permuted blocks ranging in size between 4-8. Allocations were stored in sealed opaque envelopes until after the pre-sleep tasks and questionnaires had been completed (22:30). When two participants were present in the laboratory on the same night, participants were randomized as a dyad to prevent forced awakenings from disrupting unrestricted sleep conditions. Given the nature of the manipulation, neither participants nor researchers could be blinded. Nevertheless, both participants and researchers were blinded until commencement of

1
2
3
4 the sleep protocol, including during assessments and tasks conducted pre-sleep. Researchers
5
6
7 did not have access to future allocation sequences, which was handled by a study member with
8
9
10 no participant contact.
11
12
13
14
15
16

17 **Sleep manipulations**
18
19
20

21
22 Between the hours of 23:00-07:00 participants underwent their assigned sleep group whilst
23
24
25 ambulatory PSG recordings were obtained. During this time participants in both groups
26
27
28 remained in the bedrooms and access to watches, clocks, mobile phones and other handheld
29
30
31 electronic devices was restricted. Participants were permitted to leave the room only to use the
32
33
34
35 bathroom.
36
37
38
39
40
41

42 *Forced awakening (Experimental)*
43
44
45
46
47
48

49 Participants underwent sleep continuity disruption via a standardized forced awakening
50
51
52 protocol (Finan, Quartana et al. 2017). The night (23:00-07:00) was divided into eight 1-hr
53
54
55 intervals. According to a previous study procedure one of these intervals is randomly allocated
56
57
58 as a 60-minute awakening. The remaining seven 1-h intervals are then subdivided into thirds
59
60

(20-min intervals), and one 20-min interval was selected within each hour as a forced awakening period. In the present experiment, we purposefully fixed the timing of awakenings and sleep times between participants, and allocated the third interval as a 60-min awakening, to promote interruption of slow wave sleep. This adaptation was made as previous forced awakening studies showed reductions in SWS mediated impairment in positive affect (PANAS +ve scores) observed in participants undergoing sleep continuity disruption (Finan, Quartana et al. 2015, Finan, Quartana et al. 2017). The maximum possible sleep time was 280mins (WASO = 200 mins) divided across eight awakenings. To wake participants up, a researcher entered the room to wake participants and remained in the room to ensure continuity of wakefulness.

Uninterrupted sleep (Control)

Participants were given an eight-hour sleep opportunity between 23:00 and 07:00 and instructed to sleep as normal during this period.

Outcome measures

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Participants completed a series of assessments in the evening before sleep, and throughout the subsequent daytime period according to a standardized schedule (+/-5 mins). Testing ceased 30 minutes before bed and commenced 30 minutes post rise-time. Emotion processing tasks were selected on the basis of having a prior demonstration of sensitivity to depression (Harmer, Cowen et al. 2011) and to capture key cognitive-emotional processes (emotional perception, attention and memory). The emotion regulation task (Hirsch, Hayes et al. 2009) was selected on the basis of providing an ecologically valid assessment of trans-diagnostic processes (decreased attentional capacity and increased intrusive thoughts) relevant to psychiatric disorder, including depression and insomnia.

The Oxford Emotional Test Battery (ETB)

The Oxford Emotional Test Battery (ETB) is a cognitive test battery used to provide a multimodal assessment of emotional biases in the domains of memory, attention and perception (Adams, Pounder et al. 2016). Constituent tasks include the facial expression recognition task (FERT), the emotional categorisation task (ECAT), the faces dot-probe task (FDOT), the emotional recall task (EREC), and the emotional recognition memory task (EMEM). The

1
2
3
4 battery takes approximately 60 mins to complete. The battery was administered after lunch,
5
6
7 around 13:00 on the day following sleep manipulation, minimizing the risk that the circadian
8
9
10 peaks in wakefulness and mood that typically occur mid-morning (McClung 2013) could mask
11
12
13 the effects of the sleep disruption. The battery was delivered using a custom computer monitor
14
15
16 (at 60 cm distance) and a button box (P1Vital Products Ltd). For detailed methods of the
17
18
19 constituent tasks see supplement.
20
21
22
23
24
25
26
27
28
29
30
31

32 **Worry induction challenge**

33
34
35
36

37 A worry induction task was conducted to provide an ecologically valid assessment of emotion
38
39
40 regulation in response to challenge (a worry induction). The worry induction task procedure
41
42
43 followed a protocol derived from previous studies conducted by Hirsch et al (Hirsch, Hayes et
44
45
46 al. 2009), and contained three phases. Participants were required to undertake an initial 5-
47
48
49 minute deep breathing focus period, followed by a 5-minute worry period, and then finally a
50
51
52 second 5-minute deep breathing focus period.
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

During the pre- and post-breathing periods participants were instructed, using a standardized protocol, to focus their attention on their breathing, and if they find their concentration deviating, to redirect it back towards their breathing. Participants were not instructed to keep their eyes closed but were permitted to do so if they chose. During the worry period, participants were asked using a standardized script to identify a current worry, defined as *‘intrusive thoughts or images about potential future events or catastrophes that produce negative feelings when they occur’*. Participants then engaged in continuous worry about this topic for 5 minutes, according to instructions, as previously described (Hirsch, Hayes et al. 2009).

During the pre- and post-worry breathing periods, 12 beeps were presented. The inter-beep interval ranged between 20 and 30s and a random list of intervals was generated to produce a standardized sequence of beeps that had varied intervals. On hearing the beep, participants reported if they were a) focused on their breathing (referred to as ‘breathing focuses’ henceforth) OR b) if their attention had diverted to a negative, positive or neutral thought (‘thought intrusions’). Using dedicated response sheets, the researcher documented the number

of 'breathing focuses' and the valence (positive, negative, neutral) and content of thought intrusions.

The dependent measures for this task were 1) number of 'breathing focuses' pre- and post-worry (assessing maintenance of attention on task goal) and 2) number of negative, neutral and positive thought intrusions pre- and post-worry. Our primary hypotheses focused on the number of 'breathing focuses' as well as the number of negative and positive thought intrusions. We hypothesized a reduction in the number of 'breathing focuses' and positive thought intrusions, as well as an increase in negative thought intrusions, in the forced awakening group post-worry, compared with controls.

Overnight declarative memory consolidation: word-pairs task

A word-pairs task was used to measure overnight declarative memory consolidation (Plihal and Born 1997). During encoding in the evening, participants were presented with 54 semantically related word-pairs on-screen for 4 seconds in a randomized order, with an inter-stimulus interval of one second. Participants were informed that recall would be tested immediately after the task and again the following morning. Four dummy pairs were added at

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

the beginning and end of the list to control for primacy and recency effects (see supplementary table 1 for word list). Immediately following encoding, participants were presented with the first word of each of the pairs and required to type in the paired associate. Accuracy feedback was given followed by the correct word-pair displayed for two seconds to facilitate further encoding. In order to avoid ceiling effects, no learning criterion was enforced in order for the task to terminate (e.g., >60% accuracy level) as it was anticipated that our young healthy sample would exhibit good levels of performance. The following morning, participants were presented with the first word of the pair, in a newly randomized order, and asked to type the correctly paired associate, after which feedback and the correct word-pair was given. Number of correct word-pairs was recorded, and an overnight retention score was calculated by computing the difference in number of correct words retained between the immediate recall phase and the delayed recall phase, with greater score indicative of enhanced overnight memory consolidation.

State questionnaires

Questionnaires were administered at eight hourly time-points throughout the day (08:00-15:00). The Karolinska Sleepiness Scale (Kaida, Takahashi et al. 2006) (KSS) [1 item, score

1–9 (9 = maximum Sleepiness)] was used to measure subjective sleepiness. The Positive and Negative Affect Schedule (Crawford and Henry 2004) (PANAS) measured both positive and negative affect [10 positive and 10 negative items, scores on a 5-point likert scale with a possible range of 10-50]. The State Trait Anxiety Inventory (Spielberger 1970) (STAI) measured state anxiety [6 items, score 6-24 (24 = maximum anxiety)]. The State Difficulties in Emotion Regulation Scale (Lavender, Tull et al. 2015) (S-DERS) measured generalized state emotion regulation [21 items, scored 1-5, total score = 21-105 (105 = maximum emotion dysregulation)]. The KSS, STAI, and PANAS were administered hourly, whilst the S-DERS was administered every two hours. Mean daily scores were calculated per participant and entered into the analysis. Our analytic plan involved testing for between-group differences in the subjective reports averaged across the day, consistent with previous FA studies, in order to minimize the number of statistical comparisons, and also to account for circadian fluctuations in measures throughout the day.

Psychomotor vigilance task

Participants performed the psychomotor vigilance task (PVT) (Basner and Dinges 2011) at 11:20am post-sleep manipulation to assess vigilant attention. Participants were instructed to

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

press the left mousepad button as quickly as possible when an asterisk (*) was presented on-screen. 110 trials were completed, and the inter-stimulus-interval (ISI) for each trial varied in duration between 1-10s. ISIs were selected from a randomized list of pre-defined ISIs ranging 1-10s, therefore the overall duration of the task remained consistent between participants (lasting approximately 12 minutes). Five practice trials preceded the experimental trials. The number of lapses (RTs > 500ms) were recorded and the mean reaction time for responses (including lapses and excluding responses <100ms), were calculated in accordance with previous guidelines (Basner and Dinges 2011) for each participant, with higher RTs indicating slower responses.

Statistics and Analysis

Sample size

Our primary outcomes of interest were emotional perception, attention, and memory from the emotional test battery. Based on findings from previous between-group intervention studies utilizing the battery in healthy participants (Thomas, Dourish et al. 2014), we powered the study to detect moderate-to-large effects, should they exist. Assuming a minimum between-

group effect size of 0.8, at 5% level of significance and 80% power, the required sample size was estimated at 50 participants (25 in each group).

Data handling and inspection

Prior to analysis, data cleaning was performed on the emotional test battery data to remove trials with RTs $>3SDs$ from the mean or $<200ms$. Next, visual inspection was performed using histograms and box plots to assess the distribution of outcome data for all tasks. Skewness and Kurtosis values as well as statistical tests of normality (Shapiro Wilk's Test), equality of variance (Levene's Test), and sphericity (Mauchly's Test) were used to interpret data assumptions. Several variables were non-normally distributed and were not corrected following square root or logarithmic transformations. Therefore, in the absence of a suitable non-parametric equivalent, testing proceeded using ANOVA, which is sufficiently robust to handle data with slight deviations from normality (Feir-Walsh and Toothaker 1974).

Statistical analyses

Primary data analysis was performed using ANOVA to test for between-group differences in emotion processing measures (dependent variables from the FERT, ECAT, EMEM, FDOT,

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

EREC) and measures from the worry induction task (breathing focuses, negative intrusions, positive intrusions). Pre-to post change score on the word-pairs task and vigilance performance (RTs and number of lapses from the PVT) were analysed using independent *t*-tests. Normally distributed questionnaire data were analyzed using independent *t*-tests while non-normally distributed questionnaire data (STAI and S-DERS scores) were analyzed using non-parametric *t*-test equivalents (Mann-Whitney U test). Statistical significance was defined as $p \leq 0.05$ in all instances. Cohen's *d* effect sizes were calculated using mean differences and pooled standard deviations.

Results

Screening and baseline characteristics

5272 participants were assessed for eligibility using the online screening questionnaire, of which 516 provided complete screening questionnaires. 51 met criteria and took part in the study (38 females; mean age = 24 years, SD=3.64). A summary of baseline characteristics can be found in table 2.

[Insert table 2 about here]

Manipulation checks

Sleep

Consistent with the aims of the manipulation, participants in the experimental group had significantly greater WASO and significantly lower TST, time spent in N2, N3, and REM sleep stages (Cohen's d for all ≥ 1.56). There were no group differences in N1 or SOL. Sleep variables for both groups are displayed in table 3. Participants in the uninterrupted sleep condition obtained a mean of 434 mins of sleep time defined by PSG, consistent with normal habitual sleep times obtained during the baseline sleep monitoring phase [426mins (Actigraphy) and 412 (Sleep Diary)].

[Insert table 3 here]

Effects on emotion processing and task-related emotion regulation

Facial expression recognition task (FERT)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

In terms of accuracy for identifying facial expressions there was no significant group x emotion interaction effect [$F(6, 50) = .305, p = .93$]. Effect sizes for accuracy values for each type of expression ranged from $d = -0.34$ to 0.27 (See table 4). For reaction times there was similarly no significant emotion x group interaction effect [$F(6, 50) = .974, p = .44$], Effect sizes ranged from $d = -0.31$ to 0.55 . Further unplanned exploratory analyses were conducted on the number of misclassifications of each facial emotion, for which there was again no significant group x emotion interaction effect [$F(6, 50) = .331, p = .92$] (See supplementary [table 2](#)).

Faces dot-probe task (FDOT)

In terms of vigilance indices for masked faces there was no significant group x emotion interaction effect [$F(1, 50) = .128, p = .72$]. Similarly, there was no significant group x emotion interaction effect [$F(1, 50) = .009, p = .93$] for unmasked faces. Effect sizes ranged from $d = -0.18$ to 0.27 (see table 4).

Emotional categorization task (ECAT)

In terms of reaction times for positive and negative words, there was no significant valence x group interaction effect [$F(6, 50) = .202, p = .65$]. Effect sizes for positive, and negative words were $d = 0.12$ and 0.34 respectively (see table 4).

Emotional recall task (EREC)

In terms of the number of positive and negative words recalled, there was no significant group x valence interaction effect [$F(1, 50) = .064, p = .80$]. Effect sizes for positive and negative words were $d = -0.14$, and -0.26 respectively (see table 4).

Emotional recognition memory task (EMEM)

In terms of the number of positive and negative words recognised, there was no significant group x valence interaction effect [$F(1, 50) = .256, p = .61$]. Effect sizes for positive and negative words were $d = 0.07$ and -0.13 respectively (see table 4).

[Insert table 4 here]

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Worry induction task

We investigated ‘breathing focuses’ and positive/negative intrusions prior to and following the worry induction. In terms of the number of ‘breathing focuses’, there was no significant effect of group [$F(1, 50) = .500, p = .483, d = 0.18$] or time [$F(1, 50) = .660, p = .420$] and no significant group x time interaction effect [$F(1, 50) = 1.630, p = .208$]. For negative thought intrusions, there was no significant effect of group [$F(1, 50) = 1.847, p = .180, d = 0.38$] and no significant group x time interaction effect [$F(1,50) = .034, p = .855$]. However, there was a significant main effect of time [$F(1,50) = 9.80, p = .003$], with higher negative thought intrusions present in both groups post-worry, confirming the ability of the worry induction to induce negative intrusions. Similarly, there was no significant effect of group [$F(1,50) = 0.72, p = 0.789, d = -0.44$], or group x time interaction [$F(1,50) = 1.647, p = .205$] for positive thought intrusions, but there was a significant effect of time [$F(1,50) = 6.14, p = 0.017$] with fewer positive thought intrusions observed in both groups post-worry (see table 5).

[insert table 5]

Effects on vigilance and memory

Psychomotor vigilance task

Independent *t*-tests indicated significantly slower reaction times in the experimental group (mean RT= 428.79, SD= 57.59) compared with control [(mean RT= 390.03, SD=57.88), $p = 0.023$, $d = 0.67$] as well as increased attentional lapses (mean lapses = 7.63 SD=5.20 in experimental group vs. mean lapses = 4.12, SD=4.20 for the control group; $p = 0.02$, $d = 0.74$). See table 6.

Declarative memory consolidation

The number of correctly recalled word pairs at the evening time-point, pre-sleep, was similar between groups [experimental group [24.50 (SD 12.94)] vs. control group [25.43 (SD 10.12)].

An independent *t*-test of overnight retention scores demonstrated reduced overnight memory consolidation in the experimental group compared to the control group [overnight retention = 6.73 word-pairs (SD 4.13) for experimental group vs. 12.15 word-pairs (SD 5.79) for control group, $p = .001$, $d = -1.08$] (See table 6).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Effects on self-reported affect, anxiety, sleepiness and emotion regulation

There were significantly higher levels of next-day state anxiety (STAI scores), sleepiness (KSS scores) and lower positive affect (PANAS) in the experimental vs. control group (medium-to-large effect sizes; see table 6). There was a medium effect size difference for negative affect ($d=0.48$), with the experimental group reporting increased scores, though this was not statistically significant ($p=.097$). No group effect was observed for emotion dysregulation (S-DERS Scores).

[Insert table 6 here]

Discussion

This study investigated the effects of sleep continuity disruption on emotion processing and regulation using a spectrum of measures with demonstrable sensitivity to depression (Harmer, Cowen et al. 2011). We hypothesized that sleep continuity disruption would: 1) engender negative biases across the domains of emotional perception, attention, and memory, and 2) impair emotion regulation in response to worry induction. However, no significant group effects were observed, despite impairments in vigilant attention, overnight memory consolidation, and self-reported affect and anxiety.

Consistent with our manipulation aims, we observed large increases in WASO, alongside marked reduction in total sleep time, N3, REM, and psychomotor vigilance in the experimental group vs. control. Self-report data further indicated that participants in the experimental group were significantly sleepier, and had increased anxiety and reduced positive affect with moderate effect sizes. Finally, a large group effect was observed for overnight memory consolidation, with participants in the experimental group exhibiting poorer overnight retention of (non-emotional) word-pairs. Together these results suggest that sleep discontinuity had a

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

significant impact on daytime functioning measures known to be sensitive to sleep disruption (Plihal and Born 1997, Finan, Quartana et al. 2017).

Tests of difference in emotion processing variables yielded no significant findings for facial emotion recognition, categorization, recall or recognition of emotional words, nor attentional biases towards emotional faces. While difficult to directly compare with previous studies due to their small sample sizes and paradigm differences, our findings are largely contrary to historical reports indicating large effects of sleep disruption on emotion processing, particularly with regards to facial emotion processing (Van Der Helm, Gujar et al. 2010). Nevertheless, a recent meta-analysis (Tomaso, Johnson et al. 2020) found small effects of sleep deprivation on emotion processing ($g = -0.11$) and adaptive emotion regulation ($g=-0.32$), whereas effects for self-report positive ($g = -0.94$) and negative mood ($g=0.45$) were greater, consistent with our study, indicating the effects of insufficient sleep on objective measures of emotion might not be as strong as previously believed. Moreover, recent large-scale studies ($n=291$ (Holding, Laukka et al. 2017), $n=201$ (Brand, Schilling et al. 2019)) also showed no effect of sleep disruption (Holding, Laukka et al. 2017, Gerhardsson, Åkerstedt et al. 2019, Tamm, Schwarz et al. 2020), total sleep time (Holding, Laukka et al. 2017), subjective sleep quality (Holding,

Laukka et al. 2017), nor insomnia symptom severity (Brand, Schilling et al. 2019) (ISI scores) on emotional processing. Our findings suggest that experimentally induced sleep fragmentation over one night also has limited effect on emotional processing.

For the worry induction task, we found a main effect of time, reflecting an increase in negative and a decrease in positive thought intrusions (supporting task validity), yet no group effect of sleep disruption. While further examination of this task in the context of sleep is necessary, our findings suggest that one night of sleep fragmentation does not influence the ability to regulate intrusive thoughts under emotion challenge (worry). Supporting our findings, recent work also confirmed the absence of a causal effect of sleep deprivation on emotion regulation, demonstrating no effect on a cognitive re-appraisal task following 24h of total sleep deprivation (Shermohammed, Kordyban et al. 2020).

Nevertheless, our findings should be considered in the context of the strengths and limitations of the study design. We disrupted sleep continuity for just one night; multiple nights of sleep disruption may be required to create negative bias in emotional processing. Additional sleep manipulation protocols, which subtly fragment sleep and/or modify the perception of sleep

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

quality over several days, could be investigated in future work. Second, our sample was predominately female (74.5%), reasonably small, a between-subject design was used, and the study was only powered to detect effects anticipated within the medium to large range. Effect sizes for group differences on the emotional tasks were chiefly in the range of $d=0.1-0.3$, which aligns with recent meta-analytic data (Tomaso, Johnson et al. 2020) demonstrating an effect size of $g = 0.1$ on emotion processing. However, in our study there was no consistency to the direction of these effects across variables. For example, although effects in the $d=0.1-0.2$ range were observed for RT to fearful faces, and accuracy for happy faces, these were in the opposite direction from our hypotheses, which does not support the argument that effects were simply too discrete to be detected. Furthermore, this raises methodological issues as detection of such discrete effects would require sample sizes between $n=350-1200$ in each arm (assuming a between-subjects design where $d = 0.1-0.3$ and one-tailed power of 80%). Our study also has several strengths. Objective measurements of sleep were obtained using PSG, and participants were rigorously screened. Timing of the key emotional variables (emotional test battery) was standardized. Central hypotheses surrounding emotion processing and emotion regulation were tested across various domains and emotional constructs using valid probes with documented sensitivity to depression pathophysiology and manipulations in healthy volunteers.

To conclude, the present study observed that one night of sleep continuity disruption, using an experimental model of insomnia was not associated with effects across multiple domains of emotion processing, despite impairments in declarative memory consolidation, vigilance, positive affect and anxiety. This study therefore suggests that, although one night of sleep continuity disruption has clear cognitive and affective consequences, it does not impair emotion processing or regulation. Such findings may develop existing knowledge of how sleep disruption leverages mechanistic processes that promote risk for depression. Future studies may wish to utilize within-subject paradigms that may address effect size considerations by optimising statistical power within obtainable sample sizes, however caution should be exercised to ensure suitability of outcome measures for repeated measures designs. Future studies may also wish to extend this work by considering the use of alternative populations, such as those with underlying personality traits (e.g. neuroticism), or habitually poor sleep, which may confer a greater risk profile for emotional perturbation, consistent with stress-diathesis models (Slavik and Croake 2006, Gellman 2020) of mental illness. Finally, our work may be extended by probing the potential role of specific sleep stages in mediating mood and emotion processing responses.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Conflict of Interest Statement: The authors of this manuscript declare no financial, or non-financial conflicts of interest

Disclosure Statement: Financial Disclosure: none. Non-financial Disclosure: none

This research study was supported financially by the National Institute for Health Research (NIHR) Oxford Biomedical Research Centre (BRC). The research was also supported through a DPhil Scholarship (to M.J.R) from the Dr Mortimer and Theresa Sackler Foundation.

References

- Adams, T., Z. Pounder, S. Preston, A. Hanson, P. Gallagher, C. J. Harmer and R. H. McAllister-Williams (2016). "Test–retest reliability and task order effects of emotional cognitive tests in healthy subjects." Cognition and Emotion **30**(7): 1247-1259.
- Adan, A. and H. Almirall (1991). "Horne & Östberg morningness-eveningness questionnaire: A reduced scale." Personality and Individual differences **12**(3): 241-253.
- Babor, T. F., J. C. Higgins-Biddle, J. B. Saunders and M. G. Monteiro (2001). The alcohol use disorders identification test, World Health Organization Geneva.
- Baglioni, C., K. Spiegelhalder, C. Lombardo and D. Riemann (2010). "Sleep and emotions: a focus on insomnia." Sleep Med Rev **14**(4): 227-238.
- Basner, M. and D. F. Dinges (2011). "Maximizing sensitivity of the psychomotor vigilance test (PVT) to sleep loss." Sleep **34**(5): 581-591.
- Berry, R. B., R. Brooks, C. Gamaldo, S. M. Harding, R. M. Lloyd, S. F. Quan, M. T. Troester and B. V. Vaughn (2017). AASM scoring manual updates for 2017 (version 2.4), American Academy of Sleep Medicine.
- Berry, R. B., R. Brooks, C. E. Gamaldo, S. M. Harding, C. Marcus and B. V. Vaughn (2012). "The AASM manual for the scoring of sleep and associated events." Rules, Terminology and Technical Specifications, Darien, Illinois, American Academy of Sleep Medicine **176**.
- Bjelland, I., A. A. Dahl, T. T. Haug and D. Neckelmann (2002). "The validity of the Hospital Anxiety and Depression Scale: an updated literature review." Journal of psychosomatic research **52**(2): 69-77.
- Brand, S., R. Schilling, S. Ludyga, F. Colledge, D. Sadeghi Bahmani, E. Holsboer-Trachsler, U. Pühse and M. Gerber (2019). "Further Evidence of the Zero-Association Between Symptoms of Insomnia and Facial Emotion Recognition—Results From a Sample of Adults in Their Late 30s." Frontiers in psychiatry **9**: 754.

- 1
2
3
4 Buysse, D. J., C. F. Reynolds, T. H. Monk, S. R. Berman and D. J. Kupfer (1989). "The
5 Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research."
6 Psychiatry research **28**(2): 193-213.
7
8 Carney, C. E., A. L. Harris, T. G. Moss and J. D. Edinger (2010). "Distinguishing rumination
9 from worry in clinical insomnia." Behaviour research and therapy **48**(6): 540-546.
10
11 Chunhua, X., D. Jiacy, L. Xue and W. Kai (2019). "Impaired emotional memory and decision-
12 making following primary insomnia." Medicine **98**(29): e16512.
13
14 Crawford, J. R. and J. D. Henry (2004). "The Positive and Negative Affect Schedule (PANAS):
15 Construct validity, measurement properties and normative data in a large non-clinical sample."
16 British Journal of Clinical Psychology **43**(3): 245-265.
17
18 Crönlein, T., B. Langguth, P. Eichhammer and V. Busch (2016). "Impaired Recognition of
19 Facially Expressed Emotions in Different Groups of Patients with Sleep Disorders." PLOS
20 ONE **11**(4): e0152754.
21
22 Elbaz, M., K. Yauy, A. Metlaine, M. Martoni and D. Leger (2012). "Validation of a new
23 actigraph motion watch versus polysomnography on 70 healthy and suspected sleep-disordered
24 subjects." J Sleep Res **21**(Suppl 1): 218.
25
26 Espie, C. A. (2006). "Overcoming insomnia and sleep problems." London: Robinson.
27
28 Eysenck, S. B., H. J. Eysenck and P. Barrett (1985). "A revised version of the psychoticism
29 scale." Personality and individual differences **6**(1): 21-29.
30
31 Feir-Walsh, B. J. and L. E. Toothaker (1974). "An empirical comparison of the ANOVA F-
32 test, normal scores test and Kruskal-Wallis test under violation of assumptions." Educational
33 and Psychological Measurement **34**(4): 789-799.
34
35 Finan, P. H., P. J. Quartana, B. Remeniuk, E. L. Garland, J. L. Rhudy, M. Hand, M. R. Irwin
36 and M. T. Smith (2017). "Partial Sleep Deprivation Attenuates the Positive Affective System:
37 Effects Across Multiple Measurement Modalities." Sleep **40**(1).
38
39 Finan, P. H., P. J. Quartana and M. T. Smith (2015). "The Effects of Sleep Continuity
40 Disruption on Positive Mood and Sleep Architecture in Healthy Adults." Sleep **38**(11): 1735-
41 1742.
42
43 Gellman, M. D. (2020). Behavioral medicine. Encyclopedia of Behavioral Medicine, Springer:
44 223-226.
45
46 Gerhardsson, A., T. Åkerstedt, J. Axelsson, H. Fischer, M. Lekander and J. Schwarz (2019).
47 "Effect of sleep deprivation on emotional working memory." Journal of sleep research **28**(1):
48 e12744.
49
50
51
52
53
54
55
56
57
58
59
60

- Harmer, C. J., P. J. Cowen and G. M. Goodwin (2011). "Efficacy markers in depression." Journal of Psychopharmacology **25**(9): 1148-1158.
- Hertenstein, E., B. Feige, T. Gmeiner, C. Kienzler, K. Spiegelhalder, A. Johann, M. Jansson-Fröjmark, L. Palagini, G. Rücker and D. Riemann (2019). "Insomnia as a predictor of mental disorders: A systematic review and meta-analysis." Sleep medicine reviews **43**: 96-105.
- Hirsch, C. R., S. Hayes and A. Mathews (2009). "Looking on the bright side: accessing benign meanings reduces worry." J Abnorm Psychol **118**(1): 44-54.
- Holding, B. C., P. Laukka, H. Fischer, T. Bänziger, J. Axelsson and T. Sundelin (2017). "Multimodal emotion recognition is resilient to insufficient sleep: results from cross-sectional and experimental studies." Sleep **40**(11): zsx145.
- Kaida, K., M. Takahashi, T. Åkerstedt, A. Nakata, Y. Otsuka, T. Haratani and K. Fukasawa (2006). "Validation of the Karolinska sleepiness scale against performance and EEG variables." Clinical Neurophysiology **117**(7): 1574-1581.
- Krause, A. J., E. B. Simon, B. A. Mander, S. M. Greer, J. M. Saletin, A. N. Goldstein-Piekarski and M. P. Walker (2017). "The sleep-deprived human brain." Nat Rev Neurosci.
- Kyle, S. D., L. Beattie, K. Spiegelhalder, Z. Rogers and C. A. Espie (2014). "Altered emotion perception in insomnia disorder." Sleep **37**(4): 775-783.
- Lavender, J. M., M. T. Tull, D. DiLillo, T. Messman-Moore and K. L. Gratz (2015). "Development and Validation of a State-Based Measure of Emotion Dysregulation The State Difficulties in Emotion Regulation Scale (S-DERS)." Assessment: 1073191115601218.
- Marshall, L., H. Helgadottir, M. Molle and J. Born (2006). "Boosting slow oscillations during sleep potentiates memory." Nature **444**(7119): 610-613.
- McClung, C. A. (2013). "How might circadian rhythms control mood? Let me count the ways." Biological psychiatry **74**(4): 242-249.
- Phelps, E. A. (2004). "Human emotion and memory: interactions of the amygdala and hippocampal complex." Current opinion in neurobiology **14**(2): 198-202.
- Plihal, W. and J. Born (1997). "Effects of early and late nocturnal sleep on declarative and procedural memory." Journal of Cognitive Neuroscience **9**(4): 534-547.
- Shermohammed, M., L. E. Kordyban and L. H. Somerville (2020). "Examining the causal effects of sleep deprivation on emotion regulation and its neural mechanisms." Journal of cognitive neuroscience **32**(7): 1289-1300.
- Slavik, S. and J. Croake (2006). "The Individual Psychology Conception of Depression as a Stress-Diathesis Model." Journal of Individual Psychology **62**(4).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Spielberger, C. D. (1970). "STAI manual for the state-trait anxiety inventory." Self-Evaluation Questionnaire: 1-24.

Tamm, S., J. Schwarz, H. Thuné, G. Kecklund, P. Petrovic, T. Åkerstedt, H. Fischer, M. Lekander and G. Nilsson (2020). "A combined fMRI and EMG study of emotional contagion following partial sleep deprivation in young and older humans." Scientific reports **10**(1): 1-13.

Thomas, J., C. Dourish, J. Tomlinson, Z. Hassan-Smith and S. Higgs (2014). "Effects of the 5-HT2C receptor agonist meta-chlorophenylpiperazine on appetite, food intake and emotional processing in healthy volunteers." Psychopharmacology **231**(12): 2449-2459.

Tomaso, C. C., A. B. Johnson and T. D. Nelson (2020). "The Effect of Sleep Deprivation and Restriction on Mood, Emotion, and Emotion Regulation: Three Meta-Analyses in One." Sleep.

Treynor, W., R. Gonzalez and S. Nolen-Hoeksema (2003). "Rumination reconsidered: A psychometric analysis." Cognitive therapy and research **27**(3): 247-259.

Van Der Helm, E., N. Gujar and M. P. Walker (2010). "Sleep deprivation impairs the accurate recognition of human emotions." Sleep **33**(3): 335-342.

For Peer Review

Detailed Hypotheses

Domain	Task	Outcome	Hypotheses
Experimental Hypotheses			
Emotion Perception	Facial Emotion Recognition Task (FERT)	Accuracy (%) for happy, sad, neutral, disgust, fear, surprise, anger	Higher accuracy and in response to: Anger, Disgust, Sadness, Fear, Surprise* Lower accuracy in response to happiness*.
		Reaction Times (RT) (ms) for happy, sad, neutral, disgust, fear, surprise, anger	Shorter reaction time in response to: Anger, Disgust, Sadness, Fear, Surprise* Longer reaction time in response to happiness*
	Emotional Categorisation Task (ECAT)	Reaction times for negative emotional words Reaction times for positive emotional words	Shorter reaction times for negative emotional words* Longer reaction times for positive emotional words*
Emotional Attention	Faces Dot Probe Task (FDOT)	Vigilance score (ms) for happy and fearful faces <i>Difference in RT between emotional and neutral faces</i>	Higher vigilance index for fearful faces* Lower vigilance index for happy faces*
Emotional Memory	Emotional Recognition Memory Task (EMEM)	Percentage of correctly recognized positive and negative emotional words	Lower recognition accuracy for positive emotional words* Higher recognition accuracy for negative emotional words*
	Emotional Recall Task (ECAT)	Number of recalled positive and negative emotional words	Higher recall of negative emotional words* Lower recall of positive emotional words*
Emotion Regulation	Breathing Focus Task	Between-groups	
		Number of Breathing Focuses	Higher number of breathing focuses*
		Number of positive thought intrusions	Lower number of positive thought intrusions*
		Number of negative thought intrusions	Higher number of negative thought intrusions*
		Change following worry induction	
	State-Difficulties in Emotion Regulation Questionnaire (S-DERS)	Number of Breathing Focuses	Larger decrease in breathing focuses*
		Number of positive thought intrusions	Larger decrease in positive thought intrusions*
		Number of negative thought intrusions	Larger increase in negative thought intrusions*
		Total Score	Lower Total Score*
State Affect	Positive and Negative Affective Schedule (PANAS)	Positive Sub-Scale Negative Sub-Scale	Lower Positive sub-scale scores* Higher negative sub-scale score*
State Anxiety	State-Trait Anxiety Inventory (STAI): State Sub-scale	Total score	Higher total score*
Manipulation Checks			
State-Sleepiness	Karolinska Sleepiness Scale (KSS)	Total Score	Higher total score*
Psychomotor Vigilance	(Psychomotor Vigilance Task)	Reaction times Lapses	Longer reaction times* Higher number of lapses*
Overnight Declarative Memory	Word-Pairs Task	Overnight retention scores	Lower overnight retention scores*
*in the forced awakening group than the Uninterrupted Sleep group			

Emotional Test Battery Methods

The Emotional Test Battery was delivered by administering the following tasks in a standardized fixed order:

Facial emotion recognition: facial emotion recognition test (FERT)

In the facial emotion recognition test (FERT) participants categorize faces (500ms presentation time) with seven different facial expressions (happiness, sadness, fear, anger, disgust, surprise or neutral) displayed at morphed intensity levels from 0% (neutral) to 100% (full expression) (6 emotions \times 10 intensities \times 4 examples = 240 trials)⁵⁰. Our a priori hypotheses were that the experimental group, relative to control, would perform with higher percentage accuracy and shorter reaction times for anger, disgust, sadness, fear, as well as lower accuracy and longer reaction times for surprise and happiness. Further unplanned analyses were also conducted on the number of times a facial stimulus was incorrectly classified as an emotion (misclassifications).

Perception of emotional words: Emotion categorisation task (ECAT)

The emotion categorisation task (ECAT)^{47,49} assesses the speed of response towards positive and negative self-referent personality descriptors. Sixty personality characteristics selected to be disagreeable (e.g. “domineering”) or agreeable (e.g. “cheerful”), matched for frequency, length, and meaningfulness were presented for 500ms in a random order. Participants then expressed whether they would ‘like’ or ‘dislike’ to be referred to by each characteristic word. **participants were not instructed to memorize the words.** The outcome measure was reaction time for correct responses to positive and negative words. We hypothesized shorter reaction times for negative words, and longer reaction times for positive words in the experimental vs control group.

Attentional bias for emotional faces: faces dot probe task (FDOT)

The faces dot probe task⁵¹ (FDOT) provides an assessment of relative attention to positive and negative emotional faces. Following a fixation cross, two faces were simultaneously presented on the computer screen, one above the other. Faces displayed either positive (happy), negative (fear) or neutral facial expressions (either a positive-neutral pair or a negative-neutral pair) and were then replaced by a pair of white dots (:), which appeared behind the top or the bottom face, with equal frequency. Probes appeared behind the emotional (congruent trials) or neutral (incongruent trials) faces. Participants then responded by indicating the orientation of the probe. 96 trials were completed (48 happiness, 48 fear). On 50% of trials, faces were presented for 500ms (unmasked). On the remaining 50% of trials, the faces were presented for 14ms followed immediately by a mask consisting of special characters (masked). The dependent variables were relative vigilance scores^a (: (calculated as *mean RT emotion-congruent trials* – *mean RT emotion-incongruent trials*, measured in milliseconds)) for each emotion (masked and unmasked). Higher vigilance score reflected a greater attentional bias towards the relevant emotional valence and thus we hypothesized higher vigilance indices for fearful faces and lower vigilance indices for happy faces in the experimental vs control group.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Emotional recall memory: emotional recall task (EREC)

Participants were asked to write down (on paper) as many of the words previously presented in the emotional categorisation task (ECAT), in a 2-minute interval. Participants were not informed of this task prior to commencing the ETB, and thus was a surprise recall. The recall of emotional words gives a measure of bias for both positive and negative words. The outcome measure was the number of positive and negative self-referent words correctly recalled, thus we hypothesized higher recall of negative words and lower recall of positive words in the experimental vs control group.

Emotional recognition memory: emotional recognition memory Task (EMEM)

Participants were presented with 60 positive and 60 negative self-referent personality descriptors for 500ms in a random order. Some were previously seen in the ECAT, some were unseen distracter words. Participants reported if they had previously seen the word during the ECAT. Outcome measures were the percentage of correct responses for positive and negative words. We hypothesized lower recognition accuracy for positive words and higher recognition accuracy for negative words in the experimental vs control group.

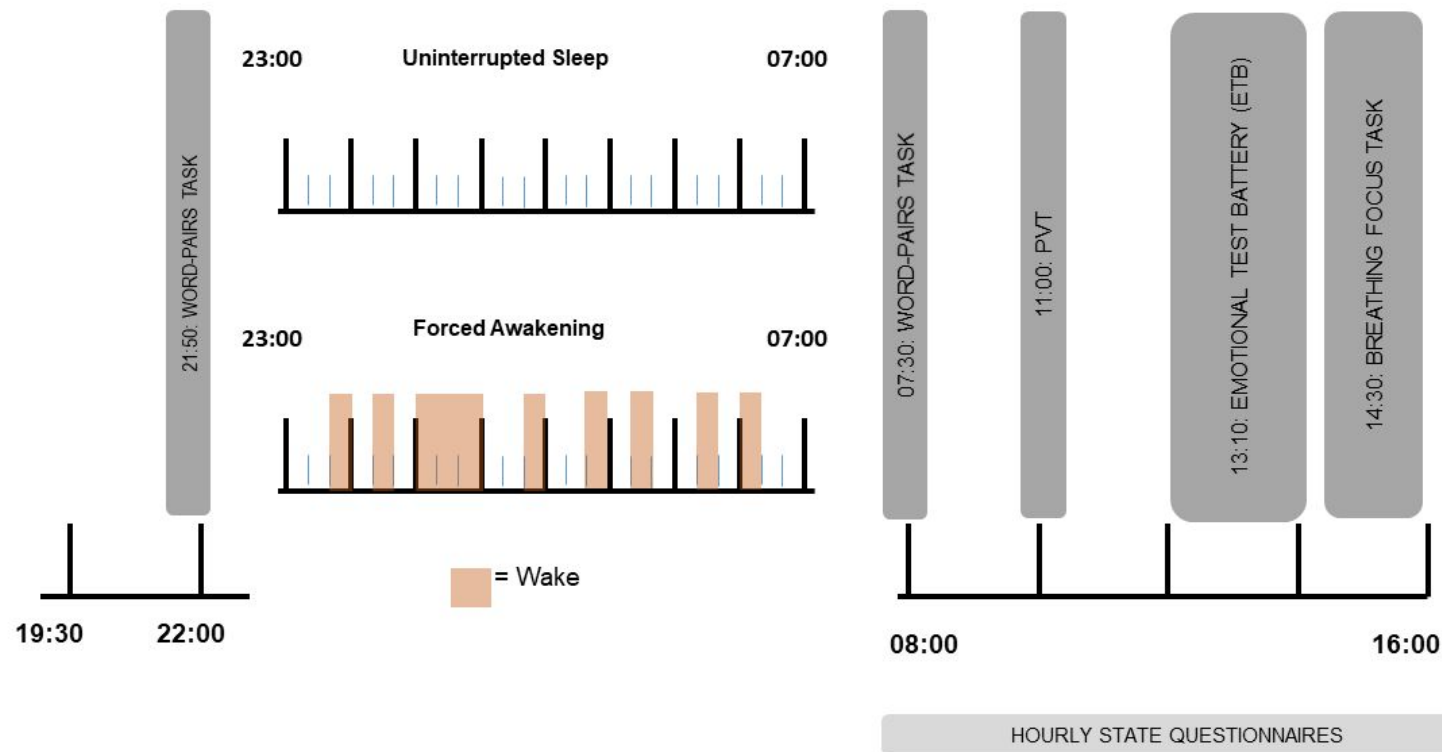
References

47. Harmer CJ, de Bodinat C, Dawson GR, et al. Agomelatine facilitates positive versus negative affective processing in healthy volunteer models. *J Psychopharmacol.* 2011;25(9):1159-1167.

49. Adams T, Pounder Z, Preston S, et al. Test-retest reliability and task order effects of emotional cognitive tests in healthy subjects. *Cogn Emot.* 2016;30(7):1247-1259.

48. Huneke NT, Walsh AE, Brown R, Browning M, Harmer CJ. No evidence for an acute placebo effect on emotional processing in healthy volunteers. *J Psychopharmacol.* 2017;31(12):1578-1587.

Figure 1. Timing of evening and daytime tasks. Task timings are standardized across participants and tasks were completed a minimum of 30 mins pre and post sleep. The timing of sleep protocols and forced awakening periods were also fixed across participants.



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

Table 1 : *Inclusion and exclusion criteria*

Inclusion	Exclusion
<ul style="list-style-type: none">• 18-30 years• Low caffeine users ($\leq 400\text{mg}/4$ cups of coffee per day)• Non-smoker• Low-moderate drinker (≤ 2 drinks/ 4 units daily)• PSQI Total Score ≤ 5.• PSQI Item 6 = ‘Very Good’ or ‘Fairly Good’• Usual sleep onset latency ≤ 30 mins, defined by PSQI items (2 & 5a)• Endorsed good habitual sleep quality• MEQ score 42-58.• Usual total sleep time between 7-9 h/ night defined by PSQI measure item 5.• HADS-Depression ≤ 7 Score & HADS-Anxiety scores ≤ 7	<ul style="list-style-type: none">• Report being troubled by sleep• Report current or previous diagnosis of mental health, or substance abuse disorder• Alcohol dependence (AUDIT score > 8)• Report current or lifetime history of neurological disorders or traumatic brain injury/ significant loss of consciousness• Report current or lifetime history of sleep disorders: Insomnia, Narcolepsy, Sleep Apnea, Nightmare Disorder, Night Terrors, Circadian Rhythm Disorders, Restless Leg Syndrome• Report current or lifetime history of medical or cardiovascular disorders• Learning difficulties or intellectual disabilities• Report insufficient understanding of English• Reported use of prescription or recreational drugs• Currently engaged in nocturnal or rotating shift-work• Trans-meridian travel ≥ 4 hours within the past month or planned within the next month• Report of pregnancy, or planned pregnancy within 2 months

Abbreviations: MEQ = Morningness Eveningness Questionnaire, HADS =Hospital Anxiety and Depression Rating Scale, PSQI = Pittsburgh Sleep Quality Index, AUDIT = Alcohol Use Disorders Identification Test BSDS: Brief Sleep Disorders Screen.

Table 2: *Participant demographics*

Variable	Forced Awakening (FA)		Uninterrupted Sleep (US)	
	Mean	SD	Mean	SD
N, count	27		24	
Sex, count	20F:7M		18F:6M	
Age, mean	24.28	3.84	23.08	3.34
PSQI, mean total	2.20	1.18	1.71	1.04
TST, mins (1-week actigraphy)	421.22	43.13	426.31	43.02
SE, % (1-week actigraphy)	91.19	4.31	92.18	4.25
TST, mins (1-week sleep diaries)	420.86	50.23	421.34	55.64
SE, % (1-week sleep diaries)	89.65	5.63	88.17	5.03
DERS, mean total	61.68	11.47	58.21	9.59
RRS, mean total	35.12	11.45	31.75	8.61
STAI, mean total	38.96	5.35	38.38	5.68
EPQ-RS, mean total	1.52	1.69	1.54	1.86
HADS-Anxiety, mean total	2.75	2.16	2.64	2.06
HADS-Depression, mean total	0.90	1.11	1.10	1.23

Data are means (standard deviation) unless stated otherwise. Abbreviations: PSQI= Pittsburgh Sleep Quality Index, TST = Total Sleep Time, SEI = Sleep Efficiency, DERS = Difficulty in Emotion Regulation Scale, RRS= Ruminative Responses Scale, STAI = State Trait Anxiety Inventory, EQP-RS = Eysenck Personality Questionnaire – Revised Short Form, HADS= Hospital Anxiety and Depression Scale.

Table 3: *Sleep variables by group*

Variable	Forced Awakening (FA)		Uninterrupted Sleep (US)		<i>t</i> value	<i>p</i> value	Cohen's <i>d</i>
	Mean	SD	Mean	SD			
SOL, mins	16.58	19.52	17.92	15.57	-.253	0.80	-0.08
WASO, mins	260.66	84.01	23.84	9.47	-9.83	<0.001	3.96
TST mins	229.98	83.74	434.57	39.04	-10.80	<0.001	-3.14
N1, mins	45.63	26.99	35.65	45.53	.96	0.34	0.27
N2, mins	98.59	57.90	216.25	45.69	-7.88	<0.001	-2.26
N3, mins	47.87	26.37	97.37	36.19	-5.58	<0.001	-1.56
REM, mins	30.76	27.69	83.39	28.49	-6.60	<0.001	-1.87

Data are means (standard deviation) unless stated otherwise. Abbreviations: SOL = Sleep Onset Latency, WASO = Wake After Sleep Onset, TST = Total Sleep Time, SEI = Sleep Efficiency Index, SWS = Slow Wave Sleep, REM = Rapid Eye Movement, N1 = stage 1 sleep, N2 = stage 2 sleep, FA = Forced Awakening, US = Uninterrupted Sleep.

Table 4: *Emotional Test Battery (ETB) values*

Task	Emotion/valence	Group		Effect Size		
Facial Emotion Recognition Task (FERT) (Percentage accuracy)		Forced Awakening,		Uninterrupted Sleep,		Cohen's <i>d</i> 95% CI
		Mean	SD	Mean	SD	
	Anger	62.96	6.20	60.52	11.08	0.27 -0.27 0.82
	Disgust	68.89	7.85	65.00	15.98	0.31 -0.23 0.86
	Sadness	67.41	7.02	65.63	10.08	0.21 -0.34 0.75
	Fear	54.72	16.16	54.06	16.15	0.04 -0.50 0.58
	Surprise	69.81	5.14	71.56	4.98	-0.34 -0.89 0.20
	Neutral	81.11	12.50	79.58	17.81	0.10 -0.44 0.64
	Happy	80.46	5.42	79.79	6.42	0.11 -0.43 0.66
FERT (Reaction Times)	Anger	1564.52	328.77	1497.12	226.58	0.24 -0.33 0.80
	Disgust	1578.85	442.58	1587.92	316.51	-0.02 -0.59 0.54
	Sadness	1370.89	234.43	1332.71	197.30	0.18 -0.39 0.74
	Fear	1943.26	463.61	1857.79	348.66	0.21 -0.36 0.77
	Surprise	1501.59	361.43	1329.59	243.70	0.55 -0.02 1.13
	Neutral	1290.89	323.80	1391.04	314.68	-0.31 -0.88 0.25
	Happy	1375.67	250.81	1266.17	198.64	0.48 -0.09 1.05
Faces Dot Probe Task (FDOT) (Vigilance Scores (ms))	Fear (Masked)	-2.38	37.18	3.33	26.56	-0.18 -0.73 0.38
	Fear (Unmasked)	2.58	28.61	-.46	28.75	0.11 -0.44 0.65
	Happy (Masked)	-7.96	55.81	-3.75	32.19	-0.09 -0.64 0.45
	Happy (Unmasked)	1.31	30.57	-6.29	25.94	0.27 -0.29 0.81
Emotional Categorization Task (ECAT) (Reaction time (ms))	Positive	789.63	168.39	770.50	148.86	0.12 -0.41 0.65
	Negative	852.59	194.38	796.91	124.17	0.34 -0.22 0.89
Emotional Recall Task (EREC) (Number of correctly recalled words)	Positive	4.67	3.17	5.08	2.57	-0.14 -0.69 0.40
	Negative	3.59	2.96	4.29	2.39	-0.26 -0.81 0.29
Emotional Recognition Memory Task (EMEM) (Percentage Accuracy)	Positive	85.18	10.05	84.44	11.95	0.07 -0.48 0.61
	Negative	67.90	11.62	69.58	14.56	-0.13 -0.67 0.42

Table 5: *Breathing focus tasks data*

	Timepoint	Forced Awakening		Uninterrupted Sleep					Time effect	Group*Time effect
		Mean	SD	Mean	SD	Cohen's <i>d</i>	95% CI		(<i>F</i> , <i>p</i>)	(<i>F</i> , <i>p</i>)
Breathing Focuses*	Pre-Worry	8.11	1.97	8.83	2.08	-0.36	-0.90	0.20	$F^{\dagger} = .660$	$F^{\dagger} = 1.630$
									$p = .420$	$p = .208$
	Post-Worry	8.22	2.21	8.33	2.78	-0.04	-0.90	0.59		
	Pre-Worry	8.22	2.21	8.33	2.78	-0.04	-0.90	0.59		
Negative Thought Intrusions	Pre-Worry	1.00	1.33	0.50	0.98	0.42	0.14	0.97	$F^{\dagger} = 9.80$	$F^{\dagger} = .034$
	Post-Worry	1.44	1.74	1.00	1.18	0.29	-0.26	0.84	$p = .003$	$p = .855$
Positive Thought Intrusions	Pre-Worry	1.26	1.16	1.54	1.56	-0.21	-0.21	0.75	$F^{\dagger} = 6.14$	$F^{\dagger} = 1.647$
									$p = .017$	$p = .205$
	Post-Worry	1.07	1.14	0.96	1.04	0.10	0.10	0.45		

Group means and variables. Data are mean (SD) *number of times a participant-maintained focus on their breathing during timed breathing focus period. Time and group*time effects for repeated measures ANOVA are presented [†]Degrees of freedom = 1, 50.

For Peer Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

Table 6: *Effects on vigilance, memory and self-report questionnaires*

	Forced Awakenings (FA)		Uninterrupted Sleep (US)				Cohen's <i>d</i> (95% CI)		
	Mean	SD	Mean	SD	t-value/u value*	<i>p</i> -value			
PANAS +ve	20.90	8.26	25.94	7.91	2.21	0.031	-0.62	-1.15	-0.05
PANAS -ve	11.27	1.41	10.68	0.98	-1.69	0.097	0.54	-0.08	1.03
STAI	7.96	1.99	6.76	1.50	-2.40*	0.024	0.68	0.11	1.23
S-DERS	31.54	3.32	32.54	5.08	0.85*	0.406	-0.24	-0.78	0.31
KSS	5.54	2.01	4.09	1.49	-2.70	0.009	0.81	0.25	1.38
PVT RT (<i>ms</i>)	428.79	57.59	390.03	57.88	2.31	0.023	0.67	0.11	1.23
PVT lapses	7.63	5.20	4.12	4.20	2.65	0.015	0.74	0.18	1.30
Word Pairs	6.73	4.13	12.15	5.79	3.63	0.001	-1.08	-1.67	-0.50
Memory task (Overnight improvement)									

Data are mean (SD), effect sizes are *d* (95% CI) PANAS= Positive and Negative Affect Schedule, +ve = positive, -ve = negative, STAI = State Trait Anxiety Inventory, SDERS = State Difficulties with Emotion Regulation Scale, KSS=Karolinska Sleepiness Scale, PVT = Psychomotor Vigilance Task.