Auditory Discrimination in Dyslexia - Differences between University and Non-University educated Individuals



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Abstract

It is still unresolved whether individuals with dyslexia suffer non-verbal auditory processing deficits that may explain their phonological problems. Many studies have shown that dyslexic individuals are poor at discriminating pure tones, and this deficit has been attributed to impaired rapid auditory processing. In order to investigate the temporal properties of auditory processing in dyslexia, I have therefore studied the pure tone discrimination abilities of dyslexics, and then analysed the effects of varying interstimulus interval, the amount of frequency difference, and the effect of adding distractor tones during the interstimulus interval.

In an investigation of dyslexic individuals' ability to remember sequences of tones or digits (tonal and digit recognition memory), Rose and Rosner (2005) found that their results were affected by the education their subjects had received. The university educated dyslexics showed little tone discrimination deficit, whereas the dyslexic participants who never attended university showed greater deficits. Therefore, another aim of this thesis was to further study these findings and to identify any auditory processing compensatory mechanisms used by dyslexics who have received higher education.

In eight different auditory tasks, the majority of which I programmed, I found strong evidence of non-verbal auditory processing deficits in dyslexic individuals. The comparison of university and non-university groups showed that educational differences had clear effects on many of their abilities, and should not be underestimated.

The results showed that:

- In general, dyslexics had poorer auditory frequency discrimination than controls.
- Dyslexics who did not attend university had lower performance on almost all the auditory tests than the university dyslexic or control groups.
- Unexpectedly, university educated dyslexics were less distracted by interrupting tones during frequency discrimination than university educated controls.
- In a tone sequence memory task, the university educated dyslexics compensated in their performance to a level not much below that of the university educated controls, and above the controls who did not go to university.
- The frequency recognition tasks positively correlated with literacy abilities, and were independent of general intelligence. The strongest correlations were in the non-university dyslexic group.

The implications of these results are that not only do dyslexic individuals suffer from a low level, non-linguistic, auditory processing deficit, but those who do not get to university are less able to compensate for these difficulties. It is impossible to say if the higher performance in university educated dyslexics was due to compensation, or if their presence at university was due to a lack of these deficits in the first place. Nevertheless, since university educated dyslexics were better at resisting distractions this may underlie their ability to compensate.

These findings could facilitate the creation of new teaching methods to support the development of dyslexics' compensatory skills and new non-linguistic diagnostic aids. These would help with identifying dyslexia in second languages and enable earlier testing and identification, before reading failure exerts its inevitable negative effects on children's self-confidence, happiness and future academic potential.

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On a more personal note I'd like to thank Dr Gill Hebb, for initiating me into the world of dyslexia and Oxford University. For many years her academic and emotional support have seen this project though to fruition but her friendship has been one of the most fulfilling outcomes. I'd like to thank my family for endless support, understanding, proof reading and distractions. Finally to Chris for waiting, loving and reminding me why it's all worth it.

The first chapters of this thesis outline basic auditory functions in good readers and dyslexics; I then discuss the historical background, research that has been carried out on dyslexia and examine what is known about the compensatory effects of a university education.

This thesis has two major aims: (1) to study the presence and investigate the depth of auditory deficits in dyslexia and (2) to investigate compensatory mechanisms used by university educated dyslexics.

If I can confirm the presence of a non-verbal deficit in dyslexia then we can start to move towards a tool which could help to identify dyslexics without waiting for them to fail at reading. Another reason this is becoming increasingly important, is the rise in numbers of both children and young adults in the UK studying in a second language. It is important to have tools to identify dyslexia reliably, without having to wait until literacy acquisition fails and without the complications of second languages, to give everyone equal opportunity and access to education. Also by looking at the differences between those dyslexics who have stayed in education to university level and those who did not, I hope to identify compensatory strategies which could be taught from a younger age to enable more people to study to a higher level.
When covering the literature in this thesis the terminology for dyslexia or learning difficulties has been taken from each publication. For the sake of clarity the term dyslexia is used in this thesis when discussing my own research.

1 The physiology of audition

Different sounds are characterised by different mixtures of frequency and amplitude changes. Our auditory system is specialised to distinguish and identify different information from these initial sound waves. The following chapter is a review of the auditory system, compiled from a range of textbooks, reviews and papers. For more detailed information see: Huffman and Henson Jr. (1990); Nicholls *et al.*, (1992); Schofield and Cant (1999); Pinel (2000); Gathercole (2001); Moore (2003) and Møller (2006).

1.1 The ear

Sound waves are longitudinal pressure changes that travel from their source to the ear. The waves are collected by the auricle and funnelled, via the external auditory meatus, to the tympanic membrane (ear drum) where the pressure changes are converted into vibrations of the basilar membrane.

This movement is conveyed though the malleus (hammer), incus (anvil) and stapes (styrrup) within the pressure regulated middle ear. The base of the stapes is attached to the oval window's covering membrane. This acts as a window to the inner ear, where the cochlea transforms the vibrations into the electrical signals carried by the auditory nerve.

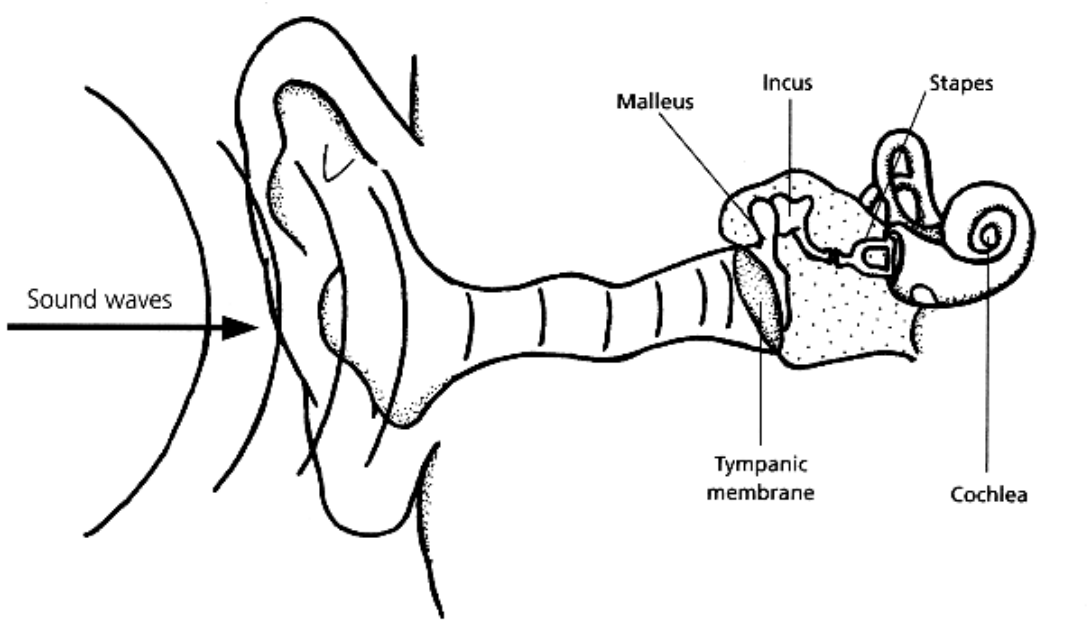


Figure 1-1 Simplified schematic of the outer, middle and inner ear
Diagram with permissions from Stein and Stoodley, Neuroscience an Introduction, p164, (2006)

The human cochlea has three fluid filled tubular components wrapped two and a half turns around a bony core (modiolus). The cochlea has a wide base and tapers to a narrower apex. The upper tube, the scala vestibuli, communicates with the lower tube, the scala tympani, at its apex. The scala tympani then terminates at the round window at the base of the cochlea. Between these two tubes is the sealed scala media which contains the organ of Corti. Membranes isolate the three chambers; the basilar membrane separates the scala media from the scala tympani and Reissner's membrane separates the scala vestibuli from the scala media.

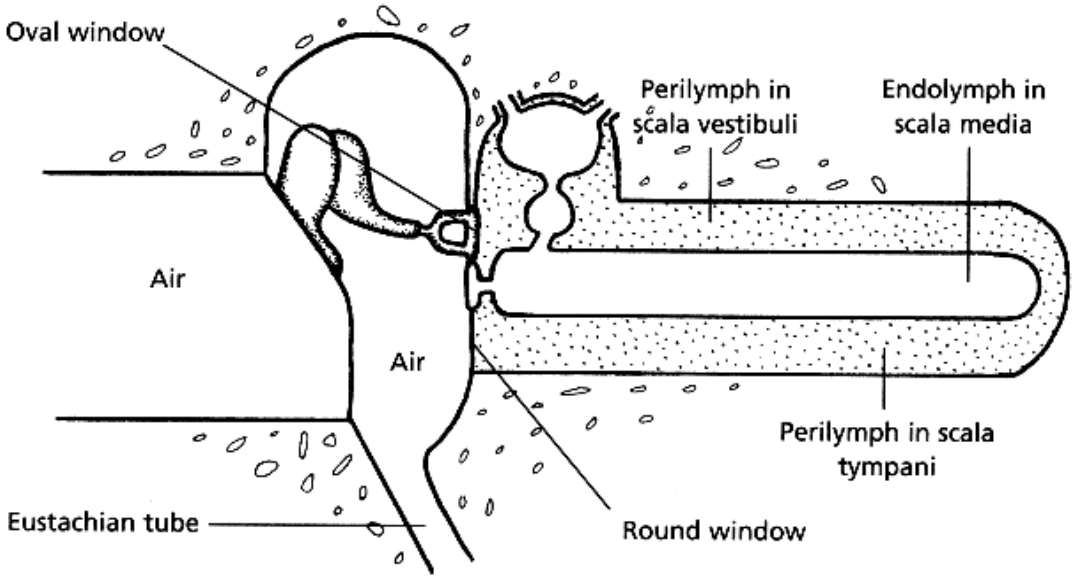


Figure 1-2 Simplified schematic diagram of the cochlea (straightened out)
Diagram with permissions from Stein and Stoodley, Neuroscience an Introduction p166, (2006)

The three chambers also differ in the composition of the fluid filling them. The scala tympani and scala vestibuli are filled with perilymph, which has a high content of sodium in relation to a low level of potassium. The fluid in the scala media, endolymph, is the reverse, with high levels of potassium and low levels of sodium. In this respect they approximate the composition of extracellular and intracellular fluid respectively (Nobili *et al.*, 1998).

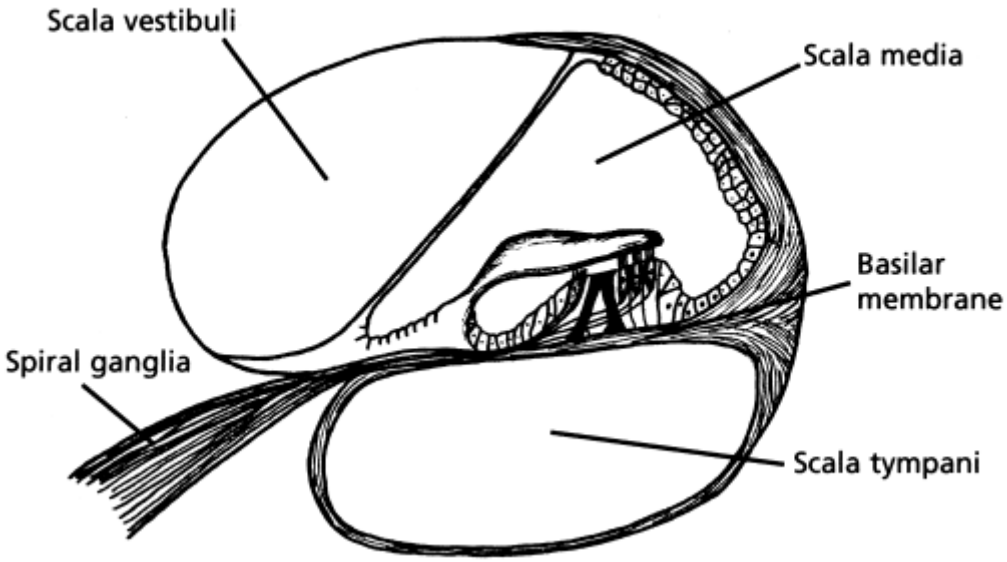


Figure 1-3 Simplified schematic of a cross section of the cochlea
Diagram with permissions from Stein and Stoodley, Neuroscience an Introduction p168, (2006)

The organ of Corti is the delicate hearing apparatus where we start to distinguish between different frequencies. It contains one row of inner hair cells and three to five rows of outer hair cells. Each of these hair cells responds differently to different frequencies. Each hair cell has stereocilia (fine hairs) on its upper surface. At its base each hair cell synapses with the afferent fibres of the auditory nerve. The hair cells of the cochlea differ from vestibular hair cells in that they lack a kinocilium, believed to be important in delineating the anatomical asymmetry of stereocilia or in making some mechanical connections with the hair cells in which they exist (Nolte, 2002).

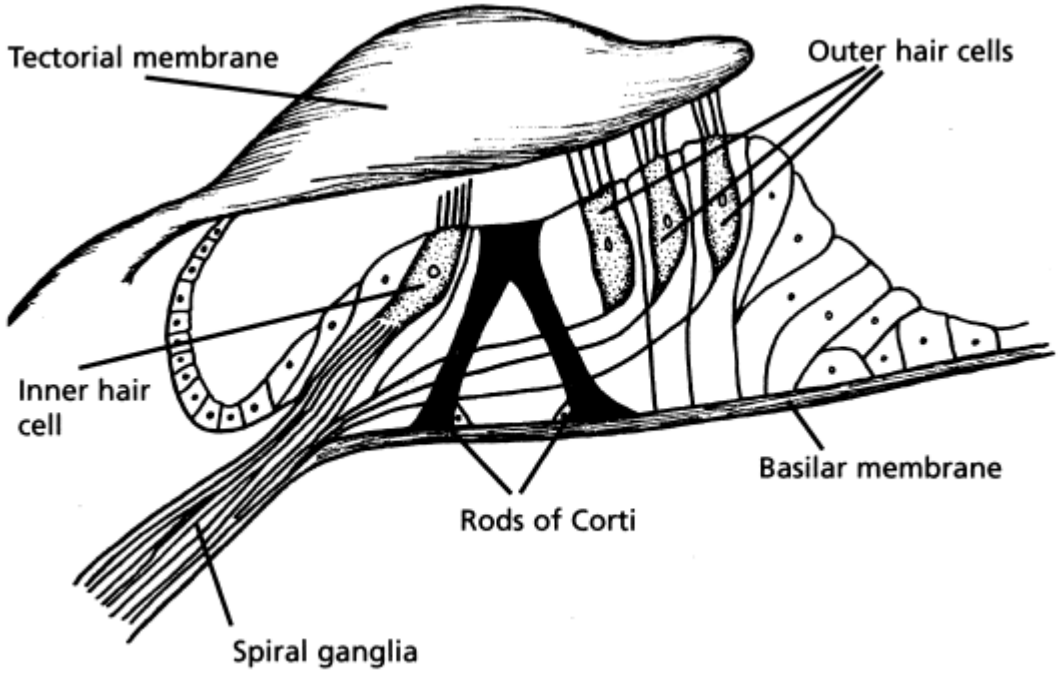


Figure 1-4 Simplified schematic of the organ of Corti
Diagram with permissions from Stein and Stoodley, Neuroscience an Introduction p168, (2006)

1.2 The auditory nervous system

The auditory nervous system has a complex system of ascending and descending pathways. Its pathways are more complex than any of the ascending pathways of other sensory systems such as the somatosensory or visual systems. Two distinct ascending pathways have been identified; the classical, tonotopic system and the non-classical, extraleminiscal system. Descending pathways run parallel to the ascending pathways. Two or three separate systems have been identified; however they are normally regarded as reciprocal to the ascending pathways, conveying messages from the auditory cortex to the relay nuclei and right out to the cochlea hair cells.

1.2.1 Classical ascending auditory pathways

These comprise three main nuclei with several intervening synaptic connections. The cochlear nerve, which is part of the VIIIth cranial nerve, transmits through the central processes of the spiral ganglion to the cochlear nuclei. The dorsal cochlear nucleus then projects through the dorsal acoustic stria to the superior olivary nucleus and then the lateral lemniscus, synapsing in the nuclei of the lateral lemniscus and relaying information bilaterally to the inferior colliculus (Figure 1-5).

Damage to the VIIIth auditory nerve can result in complete deafness on that side. However due to the extensive crossing and re-crossing of so many ascending and descending fibres, lesions to the lateral lemniscus or auditory cortex are very difficult to lateralise.

Afferent axons from the ventral cochlear nuclei pass though the intermediate acoustic stria or trapezoid body to synapse with the nuclei of the trapezoid body before passing via the superior olivary nucleus to the lateral lemniscus. Each axon synapses in the nuclei of the lateral lemniscus and decussates to the contralateral side of the mid pons and ascends with the lateral lemniscus to the inferior colliculus on that side.

The majority of the lateral lemniscus fibres terminate at the inferior colliculi in the mid brain. It is here that many of the low level auditory processes, such as involuntary reflexes, occur. Many axons pass between the two colliculi connecting the two inferior colliculi in the two hemispheres via the commissure of the inferior colliculi. The brachia of the inferior colliculi then project to the medial geniculate body of the thalamus.

From the medial geniculate the auditory radiation terminates in the primary auditory cortex; otherwise known as Herschel’s Gyrus or Area 41.

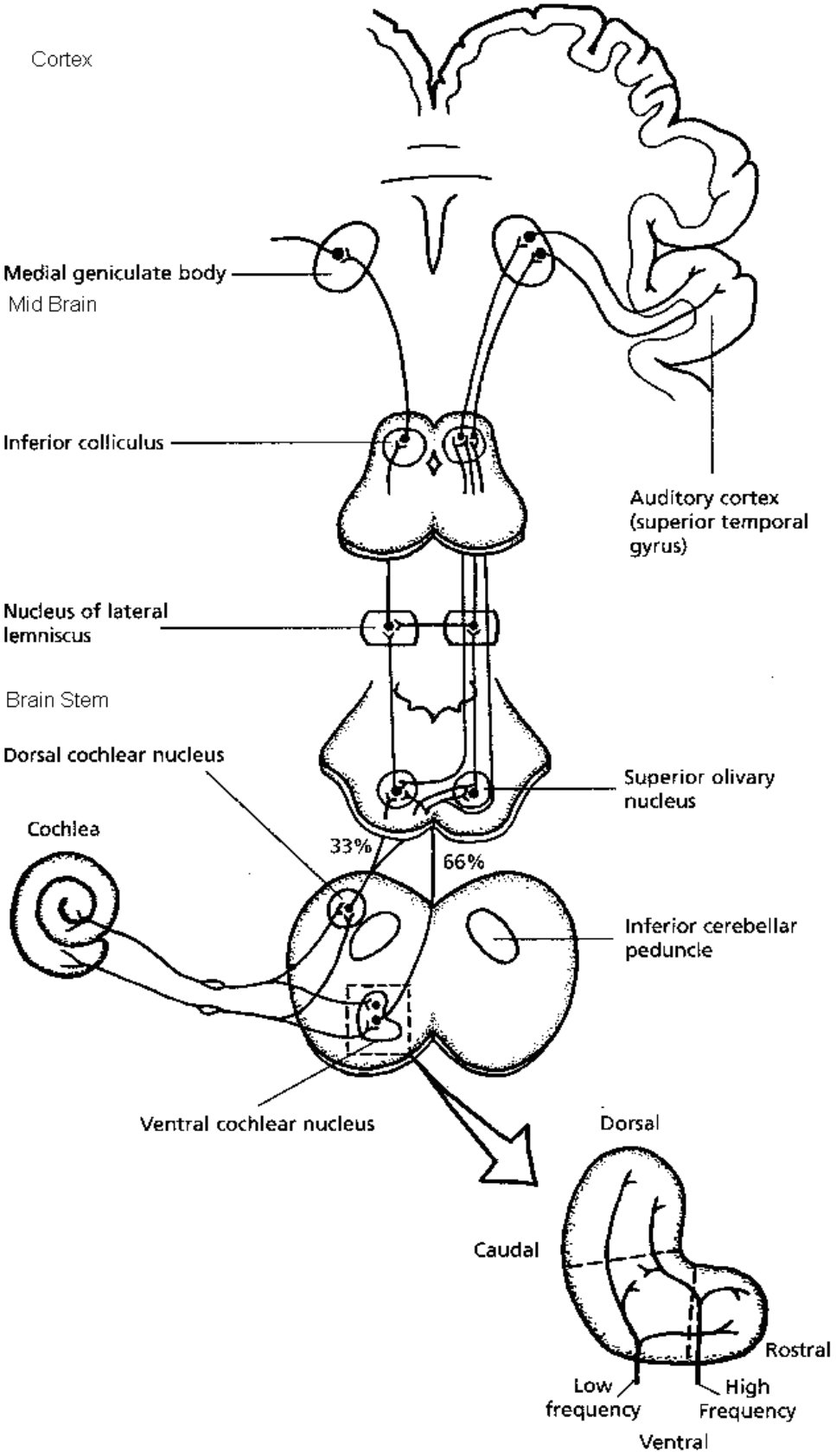


Figure 1-5 Simplified schematic of the main ascending auditory pathways
66% and 33% of synapses project to the contralateral and ipsilateral superior olive; diagram adapted with permissions from Stein and Stoodley, Neuroscience an Introduction, p175 (2006).

1.2.2 Non-classical ascending auditory pathways

The so called ‘non-classical’ ascending system, distinct from the classical pathways, was described anatomically by Graybiel in cats (Graybiel, 1972). This system is otherwise known as the ‘diffuse system’, emphasising the lack of anatomical organisation when compared to the classical. It is also referred to as the ‘polysensory system’ reflecting the input it receives from other sensory systems. Neurons in the non-classical pathway respond to sensory stimuli such as somatosensory (Aitkin *et al.*, 1994) and visual (Blum *et al.*, 1979) as well as auditory.

The classical and non-classical pathways differ in anatomical connectivity. Previously it was believed that the non-classical branched away from the classical pathways at the inferior colliculus (Aitkin, 1986); however more recently it is thought that there are non-classical projections to the cochlear nucleus from the somatosensory system (Shore *et al.*, 2003).

Where the classical pathways pass through the central nucleus of the inferior colliculus the non-classical pathways bypass this nucleus, passing though the external and the dorsal nuclei of the inferior colliculus. The neurons from the dorsal nucleus deliver their signals to the diffuse thalamocortical auditory system and the external nucleus passes inputs from the somatosensory system to the medial portion of the medial geniculate body and acoustic reflex pathways.

It has been suggested that the entirety of the inferior colliculus works as the reflex centre for the auditory system, connecting to the superior colliculus for motor responses in mammals and birds (Agmon-Snir *et al.*, 1998). It was suggested that the non-classical pathways are only important in children, and in normally functioning adults they lie dormant (Møller and Rollins, 2002). However dysfunction has been linked to disorders such as tinnitus (Møller, 2003) and interestingly it is thought to function abnormally in those with developmental disorders such as autism (Møller *et al.*, 2005).

1.2.3 Descending auditory pathways

Descending pathways mediate feedback mechanisms to inhibit auditory input. This helps to block out background noise allowing higher level discrimination resources

for the stimulus being attended to. It is these mechanisms which allow the comprehension of one-on-one conversation when surrounded by other noise; these discoveries went someway to explaining earlier conceived theories such as the 'cocktail party effect' (Cherry, 1953).

The majority of the descending auditory pathways match those of the ascending, with the cochlear nucleus as the main target. There are projections from the auditory cortex direct to the cochlear nucleus but the majority travel via the inferior colliculus. Some tracts project back from the contralateral auditory cortex to the brainstem nuclei, including the nuclei of the superior olivary complex, then down through the olivo-cochlear bundle to the organ of Corti's hair cells.

Three separate pathways run from the auditory cortex in parallel to the medial geniculate body and on to the inferior colliculus. The three sets of connections are mutually exclusive, providing multiple feedback loops, which enable great parallel processing of auditory information (Huffman and Henson Jr., 1990).

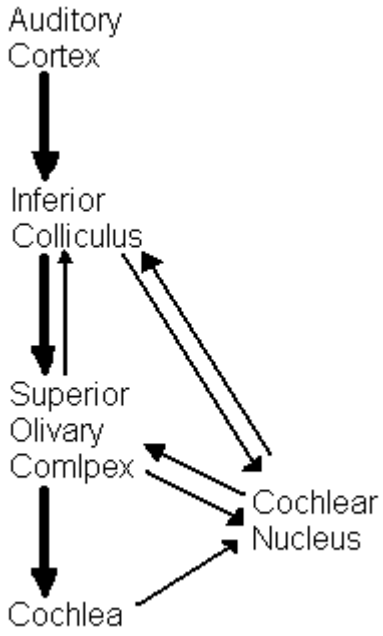


Figure 1-6 Trisynaptic pathway between the auditory cortex and the cochlea (thick arrows) and other descending feedback loops**.** From Huffman and Henson Jr. 1990 (p310)

From the inferior colliculus information is projected bilaterally to the ventral nucleus of the trapezoid body, to the anterio-ventral periolivary nucleus and onto the superior olivary nucleus before terminating at the cochlea nucleus. The inferior colliculus also

directly inputs to the cochlear nucleus, where the synapses terminate in the dorsal central nucleus, in the granule cell area, and connects to the acousticomotor and somatosensory systems.

The different pathways and projections imply that different information is transmitted from different sites. It is thought that the unilateral and bilateral projections serve different purposes too; unilateral projections may be reserved for independent control of activity in the two sides of the brain, possibly useful in the feedback of location orientation (Schofield and Cant, 1999).

1.2.4 Cortical processing

Once the auditory signals reach the cortex, comprehension of the signals begins. The auditory cortex is a combination of the primary auditory cortex (AI) and the outlying belt, referred to as the non-primary areas (AII).

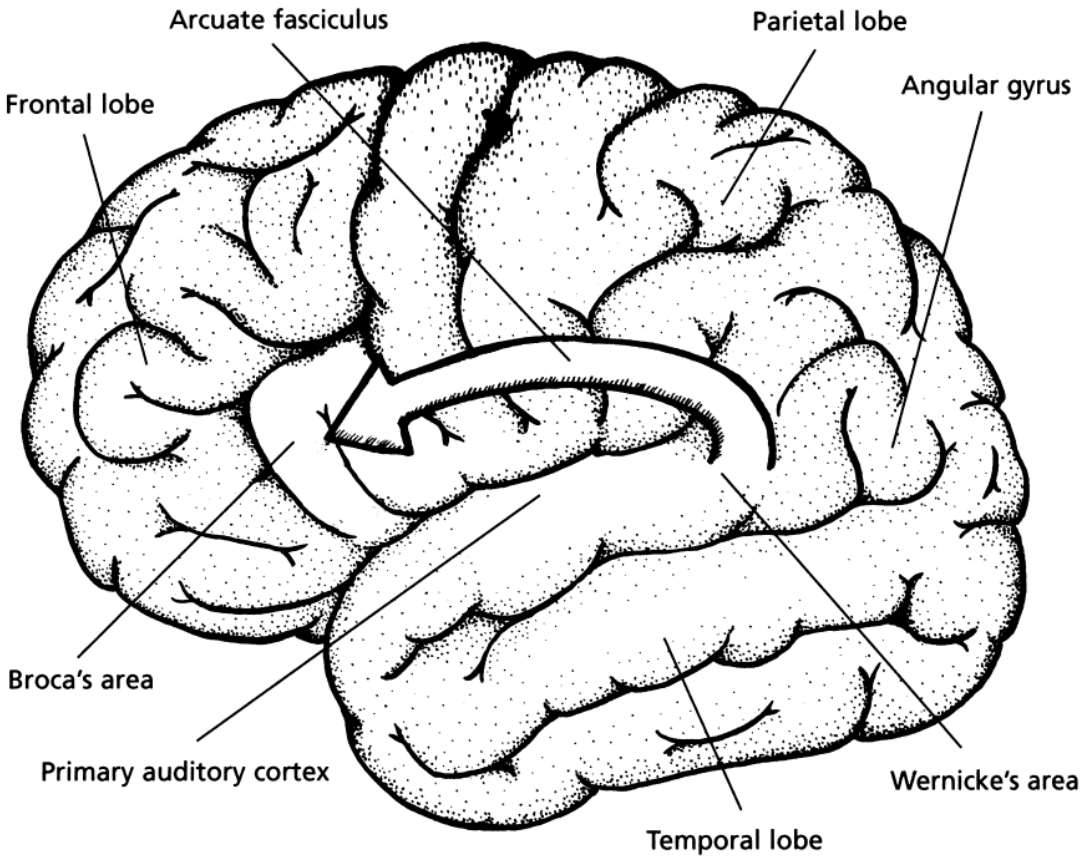


Figure 1-7 Left hemisphere schema depicting auditory areas of the cortex
Arrow indicating arcuate fasiculus. Diagram with permissions from Stein and Stoodley, Neuroscience an Introduction, p176 (2006)

AI is found on the superior (transverse) temporal gyrus, in the temporal lobe, and it receives input from the ventral division of the medial geniculate complex. Just as the primary visual and primary somatosensory cortices have topographical maps of their respective sensory fields, the primary auditory cortex contains a tonotopic map, which corresponds to the organised acoustical signals from the cochlear. The anterior of the superior temporal gyrus represents the apex of the cochlear, hence the lower frequencies (i.e. up to 500Hz), whereas the posterior part of the superior temporal gyrus represents the higher frequencies (i.e. up to 16,000Hz) transmitted from the base of the cochlea. The same tonotopic organisation is retained at all levels of the ascending auditory system, but it is in AI where many of the basic auditory functions take place, including frequency discrimination and sound localisation.

AII has a less strict tonotopic organisation and its processing is more complex. In the parietal area of AII, just posterior to the base of the motor area, is Wernicke's area, critical for language comprehension. Damage to this area does not affect a person's hearing, as such, but damages their ability to comprehend the meaning of spoken or written words. Wernicke's findings gave damage of this sort the name, 'Wernicke's aphasia'.

The location of AI is still a controversial topic. Most describe its location as in Heschl's Gyrus. However Liegeas-Chauvel and colleagues (1991) studied 150 different recordings in the superior transverse gyrus in a clinical population of 15 surgical epileptics. They concluded that only a portion of Heschl's Gyrus, the postero-medial portion, was the primary auditory cortex.

Different sound qualities are processed in different cortical locations. Where Heschl's Gyrus bilaterally responds to temporal non-verbal information, the processing of spectral non-verbal information is localised bilaterally in the superior temporal gyrus and the right superior temporal sulcus (Jamison *et al.*, 2006, Hart *et al.*, 2002). Sensitivity to the human voice is observed in the left inferior prefrontal cortex, pars orbitalis, which is reserved for human speech and non-linguistic vocalisations (Fecteau *et al.*, 2005).

In a study of 12 right handed, normally developed adults, Specht and Rule (2003) investigated differences between the activations caused by different stimuli types: tones, animal sounds, instrumental sounds and words. The tonal stimuli activated the auditory cortex areas the least, whereas words created the highest levels of activation, activating not only the left superior temporal sulcus but also the left inferior frontal gyrus. Non-verbal sounds activated the superior temporal sulcus bilaterally (right dominant). Thus the temporal lobes seem to be functionally segregated into a number of highly differentiated subsystems. The posterior part seems to be more important for sound localisation and movement; whereas the anterior focuses on the perception of speech. Likewise, when looking at dominant right handers, the left hemisphere is more specialised for verbal information, whereas the right specialises in tone recognition and music (Specht and Reul, 2003; Tervaniemi and Hugdahl, 2003).

Ahverninen *et al.* (2006) studied these specialisations further. They used functional Magnetic Resonance Imaging (fMRI) and magnetoencephalography (MEG) to trace two distinct pathways in the non-primary auditory cortex, replicating those in the visual system. They identified a 'what' pathway, used to identify speech sounds, in the parallel anterior regions (anterolateral Heschl's gyrus, anterior superior temporal gyrus, and posterior planum polare). Ahverninen and colleagues identified the 'where' pathway, to locate the sounds, in the posterior cortex areas (planum temporale and posterior superior temporal gyrus). In further support of the theory that the auditory system has the equivalent of the visual system's magnocells, they showed that the 'where' pathway was activated approximately 30ms before the activation of the 'what' pathway.

In a MEG study, Heim *et al.* found that right handed, dyslexic children differed from normally developing 'control' children, in that their left hemispheric auditory cortex showed earlier responses in the anterior locations than the normally literate children (Heim *et al.*, 2000). Paul and colleagues (2006) found that dyslexics had reduced hemispheric asymmetry in the planum temporale during a passive auditory oddball paradigm, where the repetition of one sound is interspersed with a different one and the participant's response to the unexpected different sound is recorded.

McAnally and Stein (1996a) studied event related potentials (ERP) to trace the dyslexics' auditory impairments in the brainstem nuclei. They believed that their two tasks, frequency discrimination and binaural unmasking, relied on the decoding of neural discharges phase-locked onto the stimuli. Using ERP measurements, McAnally and Stein found that the dyslexics' phase-locked discharges were significantly smaller than the normally-reading controls in both the auditory tasks. Reduced cortical sensitivity to acoustic change in those individuals with learning disabilities was thus linked to abnormal brainstem timing. Children with learning disabilities were split into two groups: those with abnormal brainstem timing were more likely to show reduced processing of acoustic change at the cortical level, than those with learning disabilities but normal brainstem timing or a group of normally learning controls (Banai *et al.*, 2005).

1.3 Pure tone perception

1.3.1 Pitch discrimination

How the brain tells one tone from another is the focus of this thesis. As small a difference as 0.1% Hz change can be picked up by the best human listeners, when the comparison tone is 1 kHz. Tone perception may be processed differently from voices or other stimuli (Houde *et al.*, 2002; Zatorre *et al.*, 2002; Zatorre *et al.*, 2007; Kruglikov *et al.*, 2008). Hart, Palmer and Hall (2002) found that Heschl's Gyrus was more sensitive to tone processing than belt areas outside AI. However Price *et al.* (2005) argue that there are no macro-anatomical structures dedicated to speech distinct from non-speech stimuli.

There are two main theories of pitch perception: the 'Place' and 'Temporal' theories:

1.3.1.1 Place theory

The place theory sees pitch perception as if on a piano. Each individual tone has its 'key' which resonates one 'string' and gives rise to tonotopic organisation.

The basilar membrane carries out spectral analysis in the inner ear with each pure tone (sinusoid) exciting a specific individual place along it. Thus stimulus pitch is represented by the location of maximum excitation on the

basilar membrane (Békésy, 1960). Complex tones are therefore represented by complex patterns of basilar membrane vibration with many peaks.

1.3.1.2 Temporal theory

The temporal theory links the stimulus frequency to the time pattern of the neural impulses evoked by that stimulus. Phase-locking causes nerve spikes to occur at a particular phase of the waveform of the stimulus (Ruggero *et al.*, 1986). However temporal phase-locking cannot work accurately at very high frequencies (above 5kHz) (Rose *et al.*, 1968; Palmer and Russell, 1986). It is for this reason that a combination of the two theories appears to be the best fit, as an explanation as to how we hear.

1.4 Auditory memory

1.4.1 Theories of working memory

"Working memory is the system that holds information in temporary storage during the planning and executing of a task, often in face of competing demands." (Roediger *et al.*, 2007, p145)

1.4.1.1 Theories

When defining working memory, cognitive and brain scientists see it differently. Cognitivists view working memory as a short-term memory process where information is worked though before being encoded into long-term memory. Physiologists, on the other hand, regard working memory as a dynamic tool that combines current sensory or mental information with information from long-term memory. In both cases working memory uses both persistence and ephemerality but the cognitivists believe it encodes and forms new memories where the brainists believe it works with retrieval and use of preformed memories.

The most accepted theory of working memory is Baddeley and Hitch's 1974 model (Baddeley and Hitch, 1974). Initially the model consisted of the 'central executive' controlling the two working areas of the 'phonological loop' and the 'visuo-spatial sketch pad'. Their original model was purely verbally expressed. Others emphasised different modelling styles: production system of language (Kieras and Polson, 1999; Young and Lewis, 1999) or more mathematical models (Burgess and Hitch, 2006; O'Reilly and Frank, 2006). However most agree that the working memory system has

limited attention in a form of central executive and support Baddeley and Hitch's original idea of storage systems.

The visuo-spatial sketchpad combines information on form and colour with spatial location, and to some extent kinaesthetic and motor information (Smith and Jonides, 1997). The phonological loop captures and retains the internal dialogue, and specifically speech stimuli, its 'system can be employed as an attentionally undemanding method of maintaining goals and guiding behaviour' (Baddeley *et al.*, 2001). In addition to retention of auditory stimuli the phonological loop can also be activated by lip-read information or sub-vocal articulation of visually presented stimuli. This may relate to the non-classical auditory pathways with the possibility that the auditory information could have been coded visually. One study of the visual memory of Japanese Kanji symbols found that the visual memory was aided by verbal encoding (Dent and Smyth, 2005).

The third component of the Baddeley and Hitch 1974 model is the central executive, involving attentional control and dual processing (Cohen-Mimran and Sapir, 2007). Norman and Shallice (1986) proposed that the central executive primarily controls well learned-responses, relying on environmental cues for routine responses as well as controlling novel behaviour through the supervisory attentional system (SAS) which intervenes to find a goal orientated solution. However Baddeley's (1986) suggestion that the central executive is in the frontal cortex has been strongly opposed by the lack of damage to executive function in participants with lesions in the area (Andrés, 2003).

As it stood, this original model did not account for working memory's relationship to long-term memory (Baddeley, 2000). To account for this, Baddeley added an episodic buffer to his model of working memory. This is the limited capacity store for multidimensional coding to integrate information from the visuo-spatial and phonological subsystems; from sensory sources, and from long-term memory. It is here that the information is converted into multidimensional chunks (Miller, 1956a) and the episodic buffer provides a location for complex thought which is accessible to conscious awareness (Baddeley and Larsen, 2007). Gathercole described the principle distinction between short-term memory and working memory as whether or not they

incorporate a significant concurrent processing element (Gathercole, 2007) which is shown as the episodic buffer.

Originally it was thought that working memory and long-term memory were independent (Baddeley and Warrington, 1970) but others believe that there is a strong inter-relationship (Atkinson and Shiffrin, 1968). More recent MRI studies have supported the idea of long-term memory being involved in working memory after scans showed strong activations in the medial temporal lobe during working memory tasks (Ranganath and D'Esposito, 2001; Ranganath and Blumenfeld, 2005). However it is unknown whether the activation is due to memory retrieval from long-term memory or the formation of new memories.

Gathercole discusses two distinct short-term memory systems: phonological short-term memory which contributes to vocabulary acquisition and reading development (Gathercole and Baddeley, 1993); and complex working memory, which is closer linked to academic progression as a whole (Gathercole and Pickering, 2000).

1.4.1.2 Anatomy of auditory memory

In right handers, imaging and lesion studies have located the phonological loop in the left temporo-parietal cortex with rehearsal dependent on Broca's area. The visuo-spatial sketchpad is dependent on the occipital parietal and frontal regions predominantly in the right hemisphere. The central executive has been located in the frontal lobes (Smith and Jonides, 1997; Henson, 2001). However the relatively recent addition of the episodic buffer suggests the specification of right frontal areas (Prabhakaran *et al.,* 2000).

Executive attention is mediated by brain circuits in the prefrontal cortex and the anterior cingulate. Dopamine is the principal neurotransmitter for cognitive control and the abilities have genetic underpinnings especially relating to the COMT gene (catechol-O-methyltransferase) which is critical for dopamine production. This may explain why working memory is responsive to stress and emotions. Life event stress (Klein and Boals, 2001), stereotype threat (Johns *et al.,* 2005) and fatigue all result in a reduction in working memory capacity.

1.4.2 Auditory working memory

In a collection of unpublished studies, the work of Rose and Rosner (Rose and Rosner, 2005; Rose *et al.*, 2007) investigated the auditory working memory capacities of dyslexics through a novel sequence recognition paradigm (used in this thesis). In their initial study educationally unspecified groups of dyslexics and controls were tested on verbal (digit) and nonverbal (tonal) sequence recognition. In this task they found the dyslexics to have deficits in both verbal and nonverbal recognition; however dyslexics showed a weaker, though still significant, correlation between the two recognition tasks than the strong correlation of the controls.

In their latest paper the tests have been restricted to university attending participants. Restricting the sample they found that although the underperformance in the digit recognition was maintained the tonal recognition difference between the two groups had gone. Also while the controls' performance on the two tasks correlated strongly that of the dyslexics did not. In fact the lack of correlation shown by the dyslexics matched that of children performing a shorter version of the same task.

Rose and Rosner took this to imply an immature working memory in dyslexia, which has not yet fully developed to perform digit recognition despite its role in everyday life. As the children in the investigation were 10 years of age they concluded that maturation of the auditory working memory requires over a decade to develop in normal readers.

1.4.2.1 Verbal working memory

In one of the many ways to test verbal working memory, Conway *et al.* (2001) presented two different lists of words to participants simultaneously, one into one ear, and one into the other, before asking them to repeat as many as they could from one attended ear. Included into the non-attended list played to the other ear was the participant's name. It was discovered that those with higher memory spans noticed the inclusion of their name less (20%) than those with lower memory spans (65%). Those with higher memory spans seemed to be better at 'rejecting' distracting information. This helps predict that the dyslexics, renowned for poor memory abilities, may have less problems discriminating between tones if interrupting tones are included.

1.4.2.2 Non-verbal working memory

Visuo-spatial working memory has been tested through delayed response tasks in monkeys, showing them food before hiding it from view and delaying their ability to access the food. Circumscribed bilateral lesions in the region of the principle sulcus, Area 46 in the monkey brain, devastate performance of the task (Pribram *et al.*, 1952). Prefrontal cells exhibit long lasting activity during the 'memory' delay period (Fuster, 1973).

Large bilateral lesions to the medial temporal lobe didn't impair performance in the same way if the task had a short 10 second delay. However if the delay was extended, thus taxing the memory more, the impairment was seen (Zola-Morgan and Squire, 1985). Therefore maybe the prefrontal cortex is important for short-term or immediate memory and the medial temporal lobe is critical only for longer delays.

This could imply that during the discrimination of tones at different shorter intervals the medial temporal lobe is redundant and it is the prefrontal cortex which is processing the discrimination between the two frequencies.

1.4.3 Effects of dyslexia on working memory

Gathercole describes working memory as a 'bottleneck for learning'. It affects children's performance in the classroom with tasks such as following lengthy instructions, place keeping tasks and combined processing (Gathercole, 2007). All these elements act as a gateway to learning, and problems at this stage profoundly inhibit the child's ability to perform.

In 2004 Unsworth *et al.* tested participants with high and low memory spans on an anti-saccade task. They found that those with lower memory spans found it harder to go against attentional capture and look at the non flickering box (2004). This same effect is seen in dyslexics (Fukushima *et al.*, 2005). When assessed against Baddeley's working memory model, dyslexics specifically, have an impaired phonological loop; however their visual-spatial sketchpad and central executive function seems to be intact (Kibby *et al.*, 2004).

1.4.3.1 Dyslexia and the verbal working memory

Working memory plays an important role in language acquisition. Temporary phonological storage of unfamiliar phonological forms of new words contributes to learning of lexical phonology via gradual abstraction across repeated exposures (Baddeley *et al.*, 1998). This is the most dominant learning problem when existing knowledge cannot be ‘bootstrapped’ to existing knowledge to mediate learning.

2 Dyslexia as a specific learning difficulty

2.1 Dyslexia overview

2.1.1 History of dyslexia

It has been over a hundred years since it became understood that someone could have deficient reading despite competence in intelligence and schooling. In 1896 Pringle Morgan published an account of a 14-year old boy named Percy (1896). Morgan named his condition 'congenital word blindness,' following the studies of Kussmaul (1878) who introduced the concept of 'word blindness' (*surditas et caecitas verbalis*). He writes, "*a complete text-blindness may exist even though the power of sight, the intellect, and the power of speech are intact*". For the next decade it was strongly believed that deficits in reading ability were due to a deficiency in a 'visual centre' (Hinshelwood, 1917; Fildes, 1921).

In the 1930s, Orton noted that children with reading-specific problems had a tendency to distort the order of letters as they attempted to recall words to read or spell them, for example the transposition of 'emeny' for 'enemy'. He proposed the term 'strephosymbolia' (twisting of symbols). He also made the connection between affected persons and unusual patterns of handedness or eye preference (1937).

In the 1940s, the involvement of visual problems was rejected and the term 'dyslexia' became increasingly used. In 1950, the Orton Society was set up in Orton's memory. It is now known as the International Dyslexia Society, and in 1972 it was joined by the formation of the British Dyslexia Association. In 1970, the acceptance of dyslexia was such that it was included in the British legal system for the first time. Reference was made to 'acute dyslexia' in the Chronically Sick and Disabled Persons Act (1970, section 27).

In the 1970s, Rutter and Yule (1975) differentiated specific reading disability (dyslexia) from poor reading due to low general ability. Their justification was that dyslexics had a discrepancy between their IQ and their literacy performance, whereas, the 'garden variety poor readers' performed in line with their other cognitive skills.

Predominantly it was the slower progression of the dyslexic group in comparison to the other poor readers over a two-year period of teaching which drove the differentiation. It seemed that the effects of dyslexia were more enduring than the literacy deficits experienced by the other children. More recent studies have been unable to confirm their 1975 findings: dyslexics' recent ability to advance their literacy skills has been explained as a result of better teaching strategies, as dyslexia has become better understood.

2.1.2 Current thinking

Dyslexia is defined as '*an unexpected, specific, and persistent failure to acquire efficient reading skills despite conventional instruction, adequate intelligence and socio-cultural opportunity*' (American Psychiatric Association, 1994). Its reported prevalence ranges from 5–15%, depending on the sample. The depth of the deficit is still under debate, and whether perceptual impairments are limited to speech-specific stimuli or occur due to general sensory deficits, provokes much enquiry (Studdert-Kennedy, 2002). The numbers of people diagnosed dyslexic are higher in children than in adults, as it has become more easily diagnosed in recent years. Because of this, children are usually diagnosed in school; however adults tend to learn compensatory strategies, which can conceal many of their dyslexic tendencies.

Inadequate reading ability is the most prominent symptom in children, but it is not exclusive. Children with dyslexia may suffer visual deficits, slowed temporal processing and global sequencing problems, which may partly stem from deficient memory systems. As a child grows into an adult many dyslexics manage to compensate for their dyslexic difficulties, to acquire adequate reading decoding skills. In adulthood spelling is more likely to show an underperformance rather than reading, short-term memory or speed of processing.

It is not all bad news for dyslexics, however. Although schooling is often a difficult experience for dyslexic individuals, with many children resorting to bad behaviour to avoid embarrassment amongst peers, there are many dyslexics who have excelled. Dyslexics are often reported to be more artistic and creative than their unimpaired peers. Their unusual way of thinking often allows them to 'see outside the box'.

Those who work with dyslexia have realised that significant opportunities can be presented by studying the deficits of the condition. Not only can we discover the causes of dyslexia and develop treatments but we can also advance the understanding of reading and communication in general.

2.1.3 Current approaches

As no two cases of dyslexia are the same, it is very difficult to pinpoint the reason why dyslexia occurs. There are potential reasons at each influencing level: biological, cognitive, behavioural and environmental can each have large effects on the reading abilities of a child. The definition of dyslexia requires the control of the environmental influences. However, one large environmental effect is the complexity of English orthography. Countries with languages with a more transparent orthography, such as Italy, report far better reading skills in their dyslexics, and diagnose dyslexics on account of their poor verbal memory and slow processing speed, rather than reading errors.

Dyslexia is viewed in different ways by different schools of thought. The medical model places its understanding of dyslexia in empirical science with a view to finding the best ways to assist those with special educational needs. There have been some notable successes in the medical model of dyslexia, such as the basic neurology underlying it (Stein, 2008); the benefits of omega-3 oil supplements (Richardson, 2006) used to correct the fatty acid imbalance between omega-3 and omega-6 (Richardson *et al.*, 2000; Cyhlarova *et al.*, 2007); or the location of genes related to dyslexia on chromosomes 1, 2, 6, 15 and 18 (Grigorenko *et al.*, 1997; Schulte-Körne *et al.*, 1998; Fisher *et al.*, 1999; Cope *et al.*, 2005).

The social model suggests that dyslexia is best helped by remoulding society to fit the needs of those who find a basic education hard to access. This carries on throughout life, thanks to new laws protecting the rights of the learning disabled in the work place. I find it is crucial to combine elements of both models to support those with special needs in the most effective ways. .

Perhaps the best way to describe the other explanations for dyslexia is by looking at the different theories. The Department for Education and Skills (NIACE, 2004)

separates the current theories into biological or cognitive theories, though all theories have a behavioural element.

There are too many different theories of dyslexia to mention them all in full: they include the cerebellar deficit hypothesis (Fawcett and Nicolson, 2001); the double deficit hypothesis (Wolf and O'Brien, 2001) and the working memory hypothesis (McLoughlin, 2002). There is even evidence that dyslexia can be caused by a maternal antibody (Vincent *et al.*, 2002). However, the most influential theories are the phonological, genetic linkage, magnocellular and temporal deficit theories. It is important to realise that these theories are not mutually exclusive; they could all be correct to some extent. Each theory adds valid insight into the disorder and contributes to the remediation techniques available, but I do not believe that any one theory fully explains all the symptoms or causes of dyslexia.

The phonological deficit theory was originally developed in America by the Latvian Isabelle Lieberman in the 1970s and further developed in the UK by Bradley and Bryant (1981); Frith (1997), and Snowling (2004). The phonological deficit causes problems identifying, sequencing and reproducing sounds within a word. Credited as the only theory to meet the criteria of a neuro-constructivist approach (Goswami, 2003), the phonological theorists believe that deficits in speech perception play a causal role in the phonological deficit, resulting in reading failure (Chiappe *et al.*, 2001; Temple, 2002; Chiappe *et al.*, 2004). They put the neurological deficit down to impaired development of the perisylvian region of the left hemisphere (Frith, 1997). As a treatment, phonological training, such as ‘Toe-by-Toe’ (Cowling and Cowling, 1997), or synthetic phonics is recommended. In a recent paper Ramus and Szenkovits (2008) investigated the input and output of phonological representations in dyslexics. They surmised that the phonological deficit is only a function of certain task requirements (i.e. short-term memory) and thus they believe that the deficit is limited to the access of phonological representations rather than a global phonological deficit causal to dyslexia.

De Fries, Olson and Pennington’s genetic studies promote the most biological theory of dyslexia: genetics (Pennington, 1999; Deffenbacher *et al.*, 2004; Friend *et al.*, 2008). Phonological awareness has been attributed to a site on chromosome 6 and

single word reading on chromosomes 3 (Nopola-Hemmi *et al.*, 2002), 2 and 15 (Grigorenko *et al.*, 1997), although it now seems highly unlikely that genetic influences are that specific. Nevertheless, twin and family studies have strongly supported the view that dyslexia is due to a genetic vulnerability that runs in families (Fisher and DeFries, 2002).

However, it has also been suggested that reading may be too recent a skill, in terms of evolutionary scale, to be 'in the genes' (Pinker, 2003). Thus the rising number of chromosomal locations linked to dyslexia probably indicates that there are a number of different genetic pathways interfering with reading at more basic physiological processing levels. However, greater genetic knowledge of the disorder would allow screening prior to literacy acquisition, so that earlier assistance could be targeted during the crucial early years for those at risk. The concept of an underlying genetic basis in dyslexia is now incorporated into the majority of the other theories, as the evidence has been widely accepted.

Stein has put forward the theory that the basic neural abnormality underlying dyslexia is genetically-based impaired development of magnocellular neurons. He has traced dyslexia to impaired magnocellular function affecting visual, auditory and motor processing (Stein, 2001). The larger magnocells in the brain are responsible for sensory timing and motor events. Stein believes that the impaired magnocellular pathway is responsible for poor visual motion sensitivity, that leads to visual perceptual instability during reading (Stein and Walsh, 1997). To treat these visual symptoms, blue and yellow glasses or filters are used to stimulate the magnocells to stabilise binocular vision, thus enabling children to see the words clearly without the reported 'jumbling' of the letters.

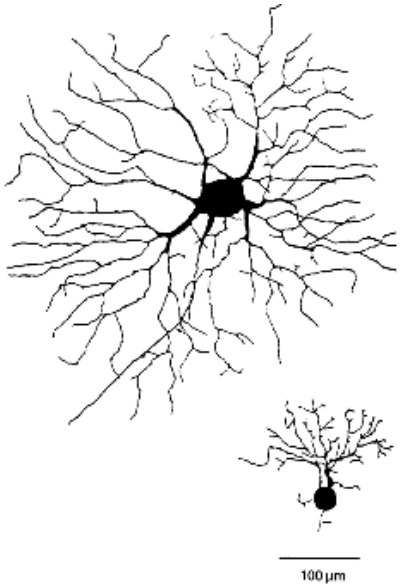


Figure 2-1 Visual pathways' magnocell in relation to a parvocell
Magnocell (top) and parvocells (bottom);
diagram with permissions from Stein and Stoodley, p134 (2006)

Others have disputed the magnocellular theory, claiming that the deficits of disabled readers are not specific to a magnocellular impairment (Amitay *et al.*, 2002), that the link between reading and the magnocellular system cannot be causally linked to dyslexia (Sperling *et al.*, 2003; Hutzler *et al.*, 2006). Some restrict the magnocellular deficit to a subgroup of dysphoneidetic dyslexics (difficulties with both phonological and orthographic skills) leaving the dyseidetic (difficulties with orthographic skills) unaffected (Borsting *et al.*, 1996) or attributing the evidence supporting the magnocellular deficit to inattention (Stuart *et al.*, 2001). Sperling and colleagues attributed the deficits seen in dyslexics' motion and contrast sensitivity to impairment in the exclusion of noise. They claimed that without noise, magnocellular tasks revealed no dyslexic impairment. However, when high noise was present deficits could be seen in both the magno and parvocellular visual pathways (Sperling *et al.*, 2003, 2005, 2006a, 2006b).

Tallal (1980, 1984) proposed that dyslexia may be caused by difficulties in a specific brain circuit that handles rapidly flowing auditory information. Her temporal processing deficit theory is widely supported in neurological studies (for review see: Farmer and Klein, 1995; Habib, 2000). Her theory was supported by the discovery that dyslexics have prolonged after-illusions post temporal processing in both the auditory (Hari and Kiesila, 1996) and visual modalities (Hari and Renvall, 2001).

Stein and Walsh (1997) pointed out that a magnocellular deficit would cause difficulties processing any fast incoming sensory information (Talcott *et al.*, 2003). Thus Stein has linked this temporal deficit hypothesis together with his own magnocellular deficit theory, as magnocells' synapses are the fastest (Stein and Talcott, 1999; Kinsey *et al.*, 2004).

Table 2-1 Summary of theories about dyslexia

Approach	Evidence	Criticisms	Contributions
Phonological deficit theory A congenital dysfunction of left-hemisphere perisylvian brain areas causes problems connecting phonological and orthographical representations.	Dyslexic individuals perform particularly poorly on tasks requiring phonological awareness.	None dispute the existence of a phonological deficit; rather they see it as one of the aspects or consequences of a more general sensory, motor or learning disorder.	Phonics programmes.
Genetic theory Specific alleles are responsible for reading abilities and disorders.	The heritability of dyslexia is now widely accepted. Ten genes have so far been linked to reading abilities and dyslexia.	Invention of writing is too recent have exerted any significant selection pressures.	Familial screening.
Magnocellular deficit theory Magnocellular pathways are selectively impaired, leading to deficiencies in visual and auditory processing.	Anatomical abnormalities in the magnocellular layers of the LGN. Functional imaging and psychophysical evidence of reduced dorsal stream function.	The magnocellular / parvocellular divide has not been conclusively proved in sensory systems other than the visual. Difficulties replicating psychophysical results have also cast doubt on the theory.	Visual exercises and colour treatments.
Temporal processing deficit theory Physiological abnormalities similar to those proposed by the magnocellular theory cause deficits in the perception of short or rapid variation in sound or visual stimuli.	Dyslexic individuals have poor performance on rapid auditory and visual judgement tasks.	Conflicting evidence: evidence for deficits in slow sensory processing with normal rapid processing.	Rhythm training and musical remediation

My aim in this thesis is to clarify the basis of the auditory deficit in dyslexia. Should the deficit extend deeper than the phonological processing level I hope to investigate speed of auditory processing. I shall not be investigating the genetic theory of dyslexia. However I hope to incorporate elements of all the theories into my research.

2.1.4 Anatomy of dyslexia

2.1.4.1 Brain morphological differences

The brains of dyslexics are shown to be significantly morphologically different from controls. These distinctions emphasise the distinct phenotype of dyslexia, and the individuality among learning disorders. Despite frequent co-morbidity between dyslexia and other learning difficulties, distinct morphological abnormalities have helped to define the different learning disorders.

In a normally functioning right handed human brain, up to 65% of cases show larger planum temporale on the left than on the right (Geschwind and Levitsky, 1968). It is this asymmetry that is believed to be reduced in dyslexics. Symmetry of the planum temporale is caused by a larger right hemisphere (Galaburda and Kemper, 1979; Chiarello *et al.*, 2006). In comparison, ADHD shows abnormality in prefrontal and striatal regions; autistic spectrum disorders show temporal lobe abnormalities and abnormal interaction between frontal and parietal areas (Frank and Pavlakis, 2001).

At first, the claimed neurological differences were viewed with scepticism, as the studies were performed post mortem. This meant that the extent of the individual's dyslexic weaknesses was often not recorded. However, with the advancement of new technologies, the imaging of human brains in vivo became possible. Using MRI the symmetry of the planum temporale was confirmed in dyslexics (Hynd and Hiemenz, 1997) and linked to their behavioural deficits (Larsen *et al.*, 1990). More recently, the use of voxel based morphometry found that dyslexics have less grey matter in the left temporal lobe, bilaterally at the pars triangularis (Broca's area) and at the temporo-parieto-occipital juncture (Brown *et al.*, 2001), frontal lobe, caudate, thalamus and cerebellum (Rae *et al.*, 1998; Eckert *et al.*, 2003; Eckert *et al.*, 2005). There is also disruption in the white matter connectivity, between the posterior and frontal regions (Temple, 2002).

The physical differences do not stop at the anatomy. Biochemical differences have been recorded. Changes in cell density in the temporo-parietal region (Rae *et al.*, 1998) indicate metabolic abnormalities in dyslexics. Rae found the cerebellum to be biochemically asymmetric. MacDonell and colleagues associate this with increased levels of cytosolic phospholipiase A2 (MacDonell *et al.*, 2000). This phospholipid metabolism abnormality is one also seen in schizophrenics. Both disorders show more of the cPLA2 enzyme than controls. Other parallels have also been made with schizophrenia, as discussed in Stein's paper (1994).

Other morphological discoveries are on a smaller scale. Microscopic examinations of dyslexics' brains have shown neuronal differences. Galaburda (1979, 1994) found ectopias and dysplasias in dyslexic brains. During normal brain development the neurons migrate to their correct destinations according to their genetic blueprint. In dyslexia it seems some cells (Stein reports them to be magnocells) travel too far. The neuronal displacement of the larger neurons causes the ectopias. Magnocells are best known for their presence in the visual pathways; however, large fast neurons of this type can be seen all over the brain including the auditory system (Oertel, 1997; Ahveninen *et al.*, 2006).

2.1.4.2 Functional differences

With the advance of MRI, it wasn't long before a whole host of technologically advanced studies could detect the ways in which dyslexics processed information differently to the normally reading population. Functional MRI; event-related potential (ERP) recording; positron emission tomography (PET); magnetoencephalography (MEG), and diffusion tensor imaging (DTI) all found under-activation and abnormal processing in dyslexics. Deficits could even be seen in dyslexics when their psychophysical performance matched that of controls (Stoodley *et al.*, 2006b).

An extensive imaging study of 144 children found that dyslexic children showed disruptions in the posterior neural systems during reading. The parieto-temporal and occipito-temporal sites showed abnormalities in functioning. Reading skills were found to correlate positively with activations in the left occipito-temporal region

(Shaywitz *et al.*, 2002; Shaywitz and Shaywitz, 2005). The under activation of the left inferior occipito-temporal cortex is a consistent finding in dyslexics in both neurophysiological and hemodynamic studies (Salmelin and Helenius, 2004).

One theory is that dyslexia is an insula-disconnection syndrome (Paulesu *et al.*, 1996). It is suggested that, unlike normal readers, in dyslexia the Wernicke's and Broca's areas are working in isolation. In normally functioning readers the two areas are linked automatically by the arcuate fasciculus, so proficient readers can rapidly associate a written word with what it sounds like. In dyslexics, on the other hand, the link is weaker, so they have to laboriously think about each word they see and consciously translate it from one form (visual) to another (auditory). However this theory does not explain the sensory deficits in dyslexia where deficits are seen in each area in isolation.

2.1.4.3 Genetics

It has long been understood that dyslexia is strongly hereditary. In 1917, Hinshelwood noted the hereditary nature of 'congenital word blindness' and described that it was more common in boys than in girls (Hinshelwood, 1917). In 1925, Orton also proposed that language problems were common among the family members of dyslexic children (Orton, 1925). Research on twins has further supported the hypothesis for genetic function in dyslexia (Stevenson *et al.*, 1987; Paracchini *et al.*, 2007). A recent twin study found that genetic influences on non-word repetition ability were greater than from any shared environment. This implies that phonological skills have strong heritability (Bishop *et al.*, 2004; Byrne *et al.*, 2006).

Together with Tony Monaco, the Dyslexia Research Trust carried out linkage studies in over 300 families with dyslexic children. Published findings have included the linkage to chromosome 6 (Fisher *et al.*, 1999; Paracchini *et al.*, 2006); chromosome 2, which has been liked to handedness and schizophrenia along with reading ability; and chromosome 18 (Fisher *et al.*, 2001; Francks *et al.*, 2007). Other studies have shown linkage to chromosome 15 (Grigorenko *et al.*, 1997), which has been also linked to ADHD.

Now that it is possible to study the anatomical differences caused by dyslexia in vitro, it has been possible to see just how much of the brain is involved in reading. This skill is possibly one of the most complex processes in the natural world and yet most people manage to achieve such fluency that it is taken for granted.

2.1.5 Dyslexia diagnosis

Over the years, dyslexia has been diagnosed in a number of different ways. There is much debate over the correct procedure and much criticism when things are left unclear. The diagnosis of dyslexia in adults is more complicated than that of children. In today's society the educational system is getting far better at identifying and accommodating learning difficulties at a young age. Also 'second generation dyslexics' are picked up at a younger age, now that genetic findings are making parents more aware (Lyytinen *et al.*, 2004). Unfortunately, this has not always been the case. Previously, children with learning difficulties were unjustly neglected by the education system. Without the specialist teaching so widely used today, children often found school a very daunting and unhappy place.

Diagnosis using the discrepancy between reading and other cognitive abilities (Yule *et al.*, 1973) alone has become highly controversial, as dyslexia occurs as part of a continuum which includes normal reading ability. In a three-year longitudinal study an initial assessment was performed on a group of school children in grade one (six years old). Using the discrepancy criterion, 25 children were diagnosed dyslexic. At the end of grade three (eight years old) the children were reassessed, and it was found that only seven of those 25 children originally diagnosed with dyslexia still had a discrepancy score large enough to retain a dyslexic label. For this reason, it is believed that the diagnosis of dyslexia should be quantified and predicted with a normal distribution model (Shaywitz *et al.*, 1992). Hopefully, one day the advances of neurological understanding of dyslexia shall enable objective neurological evaluations to be part of the diagnostic process of dyslexia. This would enable the determination of source difficulties and any neurocognitive strengths that can indicate the best format of compensatory strategies and treatment options (Silver *et al.*, 2008).

2.1.6 Subgroups of dyslexia

Despite the fact that no two dyslexics have exactly the same profile, one starts to see patterns of abilities reoccurring within the groups. Many have used these trends to split the umbrella diagnosis of dyslexia into subgroups.

Cortical damage following a stroke, lesion or trauma may result in many different forms of acquired reading disability. Generally, they can be categorised as peripheral/surface (affecting visual analysis of letters) or central/deep (affecting the more complex grapheme to phoneme correspondence) to reading processes (Shallice and Warrington, 1980). These generalisations used in acquired dyslexia have helped develop theories about subgroups in developmental dyslexia.

Morton, Kinsbourne, Warrington and Coltheart all contributed to the development of the model of dual routes of access to the lexical units during reading, following studies into acquired brain damage which demonstrated the independence of phonological and orthographical processing skills (Kinsbourne and Warrington, 1962; Morton, 1969; Coltheart, 1978; Fawsett and Nicolson, 2001). Using a pseudo-homophone discrimination task, Olson and colleagues suggested that orthographic and phonological skills may be independently inherited (1984), although this is now disputed (Marlow *et al.*, 2001). Annett (1996) also suggested a double dissociation between the type of cognitive disabilities and laterality of handedness, implying that there may be a genetic basis to the subgroups of dyslexia.

Assessing dyslexics' single word reading ability, Castles and Coltheart identified isolated disorders of either the orthographic or the phonological skills in a third of their sample (Castles and Coltheart, 1993). Others have found only 20% (Manis *et al.*, 1996). They called those who were experiencing difficulty decoding words 'phonological dyslexics', and those with difficulties accessing sight vocabulary 'surface dyslexics'. However, it has been contested whether an individual remains the same subtype throughout life, as some have suggested that it is a manifestation of reliance on particular reading strategies (Ellis, 1993; Riddick, 1996; Miles and Miles, 1999).

Another model of subgroups is the double deficit hypothesis put forward by Wolf and colleagues. They postulate either a disorder of phonological skill, reduced rate of reading, or both (Mattis *et al.*, 1975; Mitterer, 1982; Bowers and Wolf, 1993). However, their distinction between the double deficit hypothesis and the dual route hypothesis may not be so clear. Wolf and Bowers (1999) found that subjects with a reduced rate of reading may have larger problems with orthographic skill.

By splitting the dyslexics into subgroups, one might be able to provide dyslexics with tailored advice on the specific support and strategies that would help them best. This would save them exhausting valuable effort and resources with strategies that are better suited to a different subgroup.

2.1.7 Opinions of dyslexia

Dyslexia is seen by many as a controversial subject. Its popularity changes regularly. In 2005, a damning documentary by Channel 4 *'The Myth of Dyslexia'* challenged the idea that it exists at all. The debate was headed by Julian Elliott of Durham University. He argued that as dyslexics benefit from the same treatments as 'garden variety poor readers' there was no cause to make any distinction between the two (Elliott, 2005). His argument was rebutted by York University's Margaret Snowling. She argued the importance of a dyslexic distinction, its genetic basis, and that the phonological deficit theory is a testable hypothesis. Qualitative studies have also found that the testing and diagnosis of dyslexia helped to improve self-esteem in those who participated in the study (McNulty, 2003).

In general, however, the 'literacy crisis' in the UK has regained credibility for dyslexia and the benefits that research into the area can bring. But again in January 2009, a Scottish MP Graham Stringer described dyslexia as a "false condition" that should be "consigned to the dustbin of history" (Hurst, 2009). Within hours he was shouted down, and discredited as misunderstanding dyslexia by the British Dyslexia Association. His accusations that the provisions were a waste of money did not last long. Needless to say the recent arguments demonstrate that the controversy still exists despite dyslexia's worldwide acceptance.

No one theory explains everything in dyslexia: a combination of the different theories is most feasible. There is no doubt that dyslexia has a deep-seated biological foundation, which manifests in varying ways. This thesis explores the compensatory strategies that so many dyslexic individuals employ. I hope that by understanding these strategies I can enable the teaching of compensatory strategies at an earlier age.

Thanks to the success of research in dyslexia the development of different treatments has been possible. Coloured spectacles, overlays and different coloured paper are the most recently recommended treatments for visual magnocellular deficits. There are also eye exercises and monocular occlusion to re-educate visual localisation skills. To treat auditory deficits, auditory music training courses have used atonal notes to improve sound discrimination in children with phonological deficits. There are plenty of one-to-one specific teaching strategies using phonemes and the like. Recently more physical techniques such as Dennison's controversial Brain Gym have developed (Dennison, 2007).

Many of the above treatments are similar to those used in other specific learning difficulties, of which many occur alongside dyslexia. This further complicates diagnosis, treatment and research.

2.1.8 Co-morbidities

Between 25% and 40% of individuals diagnosed with attention deficit disorder (ADD) also fulfil the diagnostic criteria for dyslexia (Stevenson *et al.*, 2005; Gayán *et al.*, 2005; Willcutt *et al.*, 2005). This is what seems to cause so much controversy around the diagnosis of dyslexia.

In this thesis great care has been taken to control for co-morbidities within the dyslexic groups. All dyslexics have a specific diagnosis of dyslexia without any recorded dominant co-morbidities, however the extensive psychometrics help ensure there are no others. In this work any subject with clear co-morbidity has been removed: one participant was removed having displayed a dominant profile of a different disorder after the psychometric tests. Those regarded as dyslexic have a dominant diagnosis of dyslexia.

It is important to be mindful that no two children with these specific learning disorders are the same. Each child's symptoms family history and background will be different, and thus the treatment of any learning disorder should be as individual as the child him or herself. Ideally those with co-morbidities need to be treated as a separate group (Eisenmajer *et al.*, 2005), in this thesis the participants may have shown mild symptoms of other disorders, i.e. mild attentional difficulties, but any who displayed dominant profiles of other disorders were removed. Below is a brief summary of some of the other learning disorders which can coincide with, or are linked to dyslexia.

2.1.8.1 Dyspraxia

Dyspraxia is a developmental disorder of purposive movement, not caused by any motor or sensory dysfunction (Miyahara and Möbs, 1995). Diagnosis of the disorder is difficult and typically requires a detailed history of the developmental motor skill milestones. In children and adults alike, symptoms may include clumsiness, poor handwriting and/or a reduction in perceptual organisation or motor skills in comparison to their verbal abilities. The dominant researchers in this field include the likes of Dewey, Lee and Smith, among others (For review see Dewey, 1995).

2.1.8.2 Dyscalculia

Dyscalculia is a disorder of the ability to perform arithmetic, miscorrelating with intelligence and educational opportunities. Its prevalence is reported as between 3-6% (Shalev *et al.*, 2000; Shalev, 2004). Interestingly the number of girls with dyscalculia is equal to that of boys (Koumoula *et al.*, 2004; Cohen Kadosh and Walsh, 2007); unlike dyslexia, which is more prevalent in boys. Up to a quarter of those with dyscalculia suffer co-morbidity with dyslexia and/or attention deficit/ hyperactivity disorder (ADHD) (Gross-Tsur *et al.*, 1996).

2.1.8.3 ADHD

Attention-Deficit Hyperactivity Disorder (ADHD) affects up to 5% of the population (Polanczyk *et al.*, 2007). ADHD is marked by difficulties focusing adaptively on the task at hand, by inappropriate fidgeting, antisocial behaviour and/or excessive non-goal-directed behaviour (Davison *et al.*, 2004a). Hyperactivity is predominantly found in children. On reaching adulthood, it is thought that approximately 50% manage to

control many of their hyperactive tendencies, they are said to suffer only from ‘attention deficit disorder’ (ADD).

ADHD is genetic in nature (Thapar *et al.*, 2001). Neurological under-activation of the frontal lobes may lead to deficits in actions such as inhibiting behavioural responses. Some forms of ADHD have been seen to result from brain injury (Bate, 2001). Some believe the cause to be environmental, such as nicotine consumption of the mother during pregnancy (Reddy and Devi, 2007) or sugar intake (Schnoll *et al.*, 2003).

ADHD is often treated with stimulant medications such as methylphenidate (Ritalin). These medications have been in use since the 1960s and are still prescribed today. More recently, more psychological treatments are being used. By training teachers and parents, the children can be stimulated in a way that controls their hyperactive tendencies, allowing them to concentrate enough to do their work without the medication.

2.1.8.4 Specific language impairment

Specific language impairment (SLI) is often seen as similar to dyslexia. Some researchers such as Snowling and the research clinic at Reading University work closely with both disorders drawing a very fine line between the two. Both groups seem to have shared impairment during auditory tasks such as temporal order discrimination, frequency discrimination and impaired binaural processing (Bailey and Snowling, 2002). The important distinction between the two seems to be the more normally functioning language comprehension of dyslexics compared to the SLI cases (Bishop *et al.*, 1994; Bishop and Snowling, 2004).

2.1.8.5 Schizotypy

A growing number of research studies have shown parallels between dyslexia and schizotypal personality disorder. Many propose that there are important common features in the predisposition to both dyslexia and schizophrenia.

Both disorders have high levels of male dominance (James, 1992), indicating a possible genetic basis. In both disorders the genetic code is transmitted paternally with

maternal down regulation (Francks *et al.*, 2007). Francks and colleagues located a shared genetic component on chromosome 2, LRRTM1.

Both dyslexia and schizotypal disorders show metabolic irregularities, both have phospholipid metabolism anomalies with abnormally high levels of the cPLA2 enzyme (cytosolic phospholipase A2), though the effects of this are not yet fully understood (Macdonnell *et al.*, 2000).

Another shared feature between dyslexia and schizotypal disorders is that of increased mixed handedness (Stefanis *et al.*, 2006). Distinct from being ambidextrous, mixed handedness is when an individual is left side dominant in some activities and right side dominant in others. This, in combination with reports of both groups having reduced visual directional sense (Revheim *et al.*, 2006), and shared auditory cortex asymmetries (Heim *et al.*, 2004; Edgar *et al.*, 2006), indicates that both groups may suffer reduced lateralisation. Imaging studies have shown both disorders to have a loss of cerebral asymmetry specifically in the area of the planum temporale (Tervaniemi and Hugdahl, 2003).

This reduced lateralisation may explain the most remarkable finding too. In 1994, Alex Richardson (Richardson, 1994) discovered that dyslexics display significantly more schizotypal personality traits than a group of controls, and perform in a similar way to a clinical group of schizophrenia sufferers. A psychosis-proneness questionnaire was developed with the subcategories ‘active’ (behavioural over-activity, pressure of speech, manic or grandiose ideas, exaggerated or inappropriate affect); ‘withdrawn’ (reduced behavioural activity, poverty of speech, blunted affect, social and emotional withdrawal); and ‘Schneiderian / unreality’ (Schneiderian ‘first-rank’ hallucinations and delusions). The dyslexics were similar to the schizophrenics, reporting elevated numbers of the positive symptoms ‘active’ and ‘unreality’ in comparison to the controls. However, the dyslexics differed from the schizophrenics in that they showed no increase in the negative symptoms, ‘withdrawn’.

This finding in combination with the reduced lateralisation in dyslexia could account for their unusual perceptual experiences, which in turn could explain their delay in acquiring competent reading abilities.

2.1.8.6 Autistic spectrum disorder

In dyslexia, the child's comprehension surpasses their literacy ability, in autistic spectrum disorder (ASD) it may be the opposite. In high achievers, the child's ability surpasses their comprehension. ASD covers a group of disorders: Asperger's syndrome and autism represent the different severities. It affects how a person makes sense of the world and how they communicate with and understand the people in it. Dyslexia is often seen as the opposite end of the spectrum to ASD. There are similar neurological abnormalities between the two (Frank and Pavlakis, 2001; Casanova *et al.*, 2002).

It is thought that around 1% of the UK population suffers from ASD. It affects four times as many males as females. This gender bias implies a genetic link; however, there are still environmental factors such as pollution and viruses which may play a part (Fido and Al-Saad, 2005). In 1998, Dr Andrew Wakefield published a study in which he claimed a link between Autism and the measles, mumps and rubella (MMR) vaccine (Wakefield *et al.*, 1998). The paper caused panic amongst the parents of young children, with the numbers of children receiving the immunisation dropping drastically. Since this publication many other studies have totally discredited these findings. However, the number of children with autism is on the rise, which could support the suggestion that it could be affected by higher pollution rates or the trend for rising paternal age.

There is no cure for ASD, but there are many interventions that can help those suffering from the disorder live as normal a life as they can. Verbal behaviour therapy, speech therapy and physiotherapy all help children to acquire the skills to deal with life and access their education. Applied behavioural analysis, developed by Lovaas (1993), has proved very successful and many autistic children benefit from the polysensory stimulation of Delacato (1984).

2.2 Compensation

Just because a disorder has a genetic basis does not mean that it is not susceptible to environmental interventions. During the first two years of life the dendritic connections between brain cells, which allow for thought processes, increase greatly; over these first two years of life these are made and discarded at an astounding rate

(Gazzaniga, 2000). Even in identical twins that may be born as identical copies, it is not the brain cells that are different as they are born with identical copies, but it is their interconnections that change strength differently according to their different experiences.

2.2.1 Behavioural differences

Dyslexics who have achieved higher education still have some deficits in reading and related phonological processes, but do not differ in general cognitive ability from controls (Hatcher *et al.*, 2002). However, when Miller-Shaul (2005) compared compensated university educated dyslexics with fourth graders (nine years old), she found that the adults had compensated for their orthographic difficulties but difficulties in phonological processing had increased relative to their overall ability. She also found that slower processing speeds in dyslexia persist in compensated dyslexics in both verbal and non-verbal tasks.

Gang and Siegel (2002) found that compensated dyslexics had higher phonological rehearsal, more iconic memory and better associative memory than those with persisting dyslexia. Campbell and Butterworth (1985) also emphasised visual memory as the compensatory strategy for dyslexics' deficient use of the articulatory loop. This implies that the two dyslexic groups in this thesis – those who have, and those who have not received a university education - should show differences. The university educated dyslexic may be able to employ better memory skills during the recall tasks.

2.2.2 Neurological changes

Shaywitz *et al.* (2003) found that compensated dyslexics use distinctly different neural systems than adult dyslexics or controls. The controls and adult dyslexics both activate the occipito-temporal regions; whereas the compensated dyslexics have relative under-activation in the posterior regions for reading in both the left parieto-temporal and occipito-temporal regions, but more activity on the right side. In controls, the left inferior frontal gyrus, which is the area responsible for language, is highly active during reading, but in adult dyslexics the right prefrontal working memory regions are more active.

It seems those who compensate are relying less on the working memory for orthographic cues while reading, like the persistent dyslexics, but aren't using the regular language areas as utilised by normal readers. Instead they seem to take on the characteristics of normally developing children, decoding each word as they come to it when reading. This means that even though dyslexics may become competent readers, they are usually left with slower reading speeds than their normally developed peers.

An extensive fMRI study of right handed, dyslexic children as they read, found that as the children get older they have increasing activation in the left and right inferior frontal gyri, which may be showing a shift in activation to apply compensatory strategies during reading (Shaywitz *et al.*, 2002).

In 2008, Sebastian and Yasin discovered that compensated university dyslexics showed smaller mismatch negativity event related potentials (MMN ERPs) on tonal discrimination tasks than controls; however, no differences were found for speech stimuli. They associated this finding with a lack of right hemisphere preference for tones in dyslexics as is seen in controls (Sebastian and Yasin, 2008). This indicates that dyslexics' cortex organisation is less specialised than that of controls.

Richards *et al.* (2002) reported brain lactate level differences during language tasks, after language remediation. They found that where dyslexics receiving no treatment had greater lactate elevation in left frontal regions during phonological tasks, the levels had been reduced by remediation. Interestingly, the treatment effect was larger with morphologic text than phonological components.

Pugh *et al.* (2000) found that the right hemisphere posterior regions play a compensatory role in mediating phonological performance in dyslexic readers' abilities. Certain forms of brain organisation were found to lead to successful compensation in adulthood. The extreme asymmetry of the planum temporale and the rare Chiarelli Sylvian fissure abnormal morphology (Chiarello *et al.*, 2006) provide enhanced top-down processing to compensate for deficient bottom-up word decoding skills.

2.2.3 Remediation

In the past, remediation was entirely made up of multisensory structured phonic programmes; however, many new interventions are being explored, such as the effects of music classes on literacy learning.

2.2.3.1 Teaching

Stanovich and Stanovitch (1995) went so far as to suggest that an exclusive focus on whole words in teaching may seriously constrain children's ability to read. Others believe that phonemes, more so than rhymes, are the mechanisms of reading development (Hulme, 2002). Some of the more outlandish treatments involve biofeedback interventions: some improvements have been seen when visual stimuli were synchronised with the participants' own cardiac cycles (Liddle *et al.*, 2005).

2.2.3.2 Musical interventions

Many studies have found correlations between musical skills, phonological skills and early literacy ability. In preschool children, musical perception contributes unique variance to predicting reading ability, even when phonological skills and cognitive abilities are controlled for (Anvari *et al.*, 2002; Forgeard *et al.*, 2008). It has also been shown that musical instruction can have significant positive effects on some literacy skills (Peynirciogˇlu *et al.*, 2002; Overy, 2003) and spatial-temporal reasoning abilities (Bilhartz *et al.*, 1999). It is this type of remediation which is accessible to all non-verbally, which I hope to support with the findings of this thesis.

Douglas and Willatts (1994) reported significant correlations between rhythm and reading and rhythm and spelling. Twelve children who received rhythmic and pitch training obtained better scores on a reading test than an untrained control group (both groups were selected by their teacher as those who would benefit from extra literacy help). However, they do not comment on the lack of correlation between literacy and tonal discrimination abilities once vocabulary was partialled out, which was also tested in the original study.

2.2.4 Effects of compensation

Compensatory strategies take on different forms in different individuals; however, whichever form they take, they dictate individual differences in literacy skills. This

has been emphasised by dyslexics' use of different coding strategies during verbal memory tasks (Olson *et al.*, 1984; Rack, 1985).

Semantic skills have been found to act as a compensatory resource for poor readers whose phonological skills are weak (Goulandris *et al.*, 2000; Chiappe *et al.*, 2004). Some believe that compensatory strategies revolve around the extended use of working memory (Shaywitz *et al.*, 2003). However, syntactic and semantic features are not enough to fully compensate for dyslexics' deficits in the comprehension of 'sine-wave speech' in a task by Rosner *et al.* (2003).

2.2.5 Development with age

In normal readers, the main effect of aging on literacy networks is in the early activation in the superior temporal gyrus (Aine *et al.*, 2005). Tallal *et al.* (1981) commented on the importance of age as a variable underlying modality specificity of perceptual performance in the language impaired. When the language impaired are younger their auditory and visual deficits seem equal in impairment; however, as they age, their auditory deficits are twice that of their visual impairment. The difference in performance as a reader ages does not differ in controls.

Swanson recently reported age-related difference in the working memory of both learning disabled and skilled readers (Swanson, 2003). Those who had learning difficulties performed consistently lower than controls on initial retrieval efficiency and storage capacity on both verbal and visuo-spatial working memory tasks. However, the difference between the learning disabled and the controls increased in the older groups under the conditions with cues (gain) and under the asymptotic conditions (maintenance). The authors also came to the conclusion that, because both the verbal and visuo-spatial working memory tasks were affected, demands on both assessing new and maintaining old information extend beyond the phonological system.

2.2.6 Consequences

2.2.6.1 Scholarly

When dyslexics find it difficult to find a compensatory strategy that works for them, their continued literacy underperformance has a knock-on effect to their other skills. During a study in which university dyslexics were asked to perform a series of tasks (spatial reasoning, facial and object recognition and a spelling task), the order of the tasks was found to have great effects on performance (Everatt and Brannan, 1996). Of the above mentioned tasks, all but spelling were dyslexia 'neutral' tasks. When the reasoning and recognition tasks were performed before the spelling task, the dyslexic participants showed little difference to the controls. However, when the spelling task preceded the other tasks, performance in all subsequent tasks was reduced in dyslexics. This was not the case with the controls.

Dyslexics' attempts at coping with spelling during assessments may lead to major problems in other areas, i.e. the recall of facts and reasoned arguments. When Simmons and Singleton (2000) looked at dyslexics in higher education, the dyslexics could perform as well as the controls on literal questions; however, inferential questions still showed poorer performance. Their poorer performance indicated that they still suffer reading comprehension difficulties.

2.2.6.2 Emotional

There are also the emotional side effects of dyslexia to contend with, and these effects can be just as devastating as the academic difficulties. Low self-esteem and comparatively higher levels of anxiety than in controls can still be detected in those who reach university education, regardless of their acquisition of some level of academic success (Riddick *et al.*, 1999). Despite dyslexics having an adequate IQ, they perceive the association between reading ability and intelligence as a significantly stronger than do controls, and they often attribute academic success to teachers rather than giving themselves credit (Humphrey and Mullins, 2002).

Currently, research is being performed on those who are shown to suffer from often devastating consequences of the emotional effects of dyslexia. Many believe that dyslexia leads to a lack of options for some people who do not receive the support

they need, and this in turn may lead to crime. The percentage of prisoners in UK jails, that show indicators of dyslexia, ranges from 31% to 52% in different studies (Morgan, 1996; Davies and Byatt, 1998; Klein, 1998). This finding has been replicated internationally in Sweden and the United States (Haigler *et al.*, 1994; Alm and Andersson, 1995).

These 'downsides' of dyslexia emphasise the importance of research into this delicate area. However, there is a flip side to dyslexia. Results of a recent study by Logan (2009) suggest that there is a significantly higher incidence of dyslexia in entrepreneurs than in the general US or UK populations. She found that the compensatory strategies they adopt to cope with their difficulties suited working in business. Other authors discuss dyslexics' reputation for being more creative; von Károlyi and colleagues (2003) attributed this reputation to an enhanced ability to process visual-spatial information globally (holistically) rather than locally (part-by-part). In the modern computer age, these abilities may lead to a reversal of fortunes for dyslexics who would have suffered serious educational disadvantage in the past, due to technological advances that will make traditional text-based educational methods less important.

2.3 Psychometrics

"A psychometric test, then, is a pattern of stimuli selected and organised to elicit responses which will reveal certain psychological characteristics in the person who makes them." J.Mursell (1950)

Psychometric assessments, when performed correctly, give valuable insights into the pattern of cognitive traits of each participant. This provides a standardised, qualitative platform from which participants' data can be grouped for analysis. Standardisation enables us to compare the abilities of an individual to a population norm. This has been invaluable for the assessment of disabilities, potential damage and improvements following interventions. Without the standardised norms the psychometric data would be meaningless.

2.3.1 Assessments

Assessments have been developed to test many different things in different ways. Below I provide a summary of the different forms of assessment so useful to both clinicians and researchers.

'To assess' means to evaluate or estimate the nature, value or quantity of something. Dockrell and McShane (1993) believe that assessments require more than psychometric testing: '*Assessment is not a synonym for testing, although appropriate testing may well form an integral part of the process. In fact a single isolated test score is of little or no value*.' Nevertheless, psychometric tests form an important part of any assessment of an individual.

There are three main types of test: ability, attainment and aptitude tests. These test current performance, retention of information provided during a period of intervention, and the potential for achievement, respectively.

However, there are three entirely different aims of an assessment: formative, summative and - a little controversially - dynamic assessment.

Formative assessment is most useful in education. It provides feedback to teachers on the response of children's performance to different teaching methods. Once a learning disability has been revealed, it is crucial that this type of assessment should be carried out in order to find the best methods of helping the child receive the best education they can.

Summative assessments are used to see how much a child has learned to-date. Often large scale norm-referenced tests are administered at various points during a child's education, for example the General Certificate of Secondary Education (GCSE) and the Scholastic Aptitude Test (SAT).

Dynamic assessment is a relatively new concept and not necessarily viewed as a test. It is based on teacher-child interaction, so the child can 'teach' the teacher the best way to teach them.

An assessment is a synergistic combination of both qualitative and quantitative sources. The quantitative measures give a valid, standardised view of actual ability, where a coinciding qualitative review gives insight into as many of the external influences as possible.

No assessment gives a 100% accurate view of a participant. This is why most tests are reviewed and re-standardised every few years to keep the material up to date and relevant to today's society.

Special Educational Needs Coordinators (SENCo) in schools have an advantage compared to researchers when looking at the more external qualitative aspects of a participant's assessment. Educational Psychologists and those performing assessments for research have very limited contact with the participant and often have to rely on qualitative reviews performed by others, or self reports, which are often based on personal opinion and are dangerously subjective.

When there is a suspicion of special needs, assessments are necessary. In addition, they are also required for research.

> "*Assessment should be hypothesis driven and the hypothesis should be based on an understanding of the child and the cognitive components of learning difficulties, as well as an analysis of the child's current learning environment.*"
> Dockrell and McShane (1993)

In research, assessments are used to place the performance of volunteers on a scale from which correlation can be drawn with different aspects. For example 'poor reading scores correlate with poor phoneme detection'. Findings like these are used to help individuals with special needs on a large scale. Research studies need to be driven by a clear hypothesis. In this thesis, the underlying hypothesis is that reading problems may be caused by underlying auditory processing deficits.

The effects of research are not seen as immediately as the assessments within the education system, but inevitably they strive to achieve the same goals. Both researchers and those in education have to carefully justify the purpose for their

testing, choose the most relevant tests, take environmental influences into consideration and finally bring together all the information to utilise the procured knowledge to the best effect for the individual or group.

2.3.1.1 Types and uses of assessments

There are eight different types of quantitative tests, each having a different role in the assessment of a participant:

Ability tests: '*The essence of the term 'ability' is that the person can perform this task* ***now****, no further training is needed*' (Reber and Reber, 2001). Ability tests are derived to quantify the level of cognitive ability a participant has at any given time. They are often made up of a large battery of sub-tests aiming to test as many areas as possible. Most put these tasks into four main categories: verbal reasoning, numerical reasoning, spatial awareness and mechanical reasoning. These categories are flexible and often go by different names. However, whatever the sub-groups, when brought together the ability test gives an overall perspective of a subject's general ability score. An example of an ability test would be the Wechsler Adult Intelligence Scale III (WAIS-III).

Attainment tests: These tests are used to understand how much a participant has retained from a period of learning from instruction. Most educational assessments performed by all children are attainment tests, for example A levels or GCSE's. Tasks such as these are standardised nationally and performed on a wide scale.

Aptitude tests: These tests are designed to measure potential for achievement. They are most often distinguished into one of three categories; specific, general or multiple. Specific is often related to professions and specific skills. General aptitude tests are broad based tests '*designed to determine the potential in relatively non-specific domains*' (Reber and Reber, 2001). Multiple aptitudes are often a combination of either specific or general tests: '*Aptitude test is a paper-and-pencil assessment of a person's intellectual functioning that is supposed to predict how the person will perform at a later time*' (Davison *et al.*, 2004).

Formative assessment: This is an assessment mostly carried out in education. The reason for this type of assessment is not for grades, but to feed back on children's responses to teaching techniques and inform on new ways to change their future performance. Examples of these types of assessment are in-class assessments carried out by teachers. Through working with the children, they devise new ways of increasing the child's performance.

Summative assessment: This is a summary of how much has been learnt to date. Attainment tests are summative assessments such as A-levels or other curriculum based tests. They are not however, nationally standardised as the attainment tests are.

Norm-referenced tests: This type of test compares the scores of the participants with an average score procured from the whole comparative population of the same age. The test provider creates the norms by administering the test on a large group and creates and average score norm for each age group before publishing the test.

Criterion-referenced tests: This test assesses the participant's knowledge within a 'specific domain' in absolute terms. The test is often administered as a checklist and the participant's score seen as a percentage.

Curriculum-based tests: This test is based on participant's on-going performance on regular educational curriculum. Often performed by teachers testing exactly the areas they have been teaching.

Dynamic assessment: '*Educationally relevant research suggests that more can be learned about a person's intellectual ability through dynamic testing, which provides an opportunity to evaluate how the student learns over the course of a session*' (Mayer, 2000). By involving the participant in the testing procedure, they combine testing with the self reports of the participant. It is a combination of both qualitative and quantitative analysis. Dynamic assessment is not a type of test per se; however, many are starting to see the advantages of a combined assessment.

'*Research on dynamic assessment provides an important incentive for revising the view of intelligence as a static skill, and again demonstrates how education based*

research can reshape theories of intelligence' (Mayer, 2000). The many critics of a test-based education find reassurance in the development of the dynamic assessment.

Each of these kinds of test provides valuable insight to the cognitive abilities of the participants. In the test battery, each of the tests is performed as a norm referenced dynamic assessment. Feuerstein (1979) concluded that static testing fails to provide an accurate picture of a child's potential to learn, whereas dynamic testing in which students are placed in a learning situation allows them to demonstrate their ability to learn. It is for this reason that the choice of assessments has to be reviewed often and updated where possible.

2.3.2 Development

As the use of assessments was so pivotal to this thesis, I have found it interesting to look at how assessments and their uses have developed. By looking at the origins of assessments one can start to predict the format and applications of assessments in the future.

The use of psychometrics is relatively novel in the Western world with the likes of Galton and Binet regarded as the grandfathers of psychometrics. However, this is not the case globally; evidence suggests that as far back as 4000 years ago the Chinese had a state civil service testing programme (Dubois, 1970). These tests developed during the Han dynasty (206 BCE-220 CE) into batteries of assessments, used for government recruitment. During the Ming dynasty (1368-1644 CE) their use had developed to the extent of national multistage testing, performed in specialised testing centres around China. Only those who progressed to the 3rd stage were eligible for civil employment.

With the development of the silk trade, the use of psychometrics made its way to the West in the 1800s. In 1832 the English East India Company replicated the Chinese testing procedure for their employees. The procedure was quickly adopted by the English civil service in 1855 and it spread around Europe and America. At this time, the use of psychometrics was still largely occupational; tests performed on adults to test their appropriateness for a position. It was only in the late 1800s that the full potential of psychometrics began to be explored.

In 1859 Darwin published *'The Origin of Species'* and the theory of 'individual differences' developed. Subsequently, Sir Francis Galton applied Darwin's theories to intelligence and in 1869 published *'Hereditary Genius'*, sparking an interest in intrinsic abilities and their analysis. In 1890 James Mackeen-Cattel, coined the term 'mental test' in his development of Galton's work.

In the meantime, the contribution of psychometrics to clinical science was being developed by Seguin. In 1866 he developed the 'Form Board Test' as a clinical aid to help identify and educate the mentally disabled. By 1912 Kraepelin had used the same methodology to diagnose the emotionally impaired. It was the American Army that first acknowledged that literacy is not required for intelligence. In 1921 Yerkes created the Army Alpha and the Army Beta tests, where literate recruits were tested with the Alpha and illiterate recruits were tested with the Beta test, acknowledging that despite their lack of learning opportunity, many still had high intelligence to offer (Yerkes, 1921).

Binet's first educational psychometric scale (Binet and Simon, 1905) promoted the use of standardised samples. Initially, his first edition included only 30 children in the standard sample, though it quickly improved to 200 in the second edition. By 1936 the Stanford-Binet revision included 3000 people in the standard sample. Currently, the importance of standardised samples cannot be emphasised enough. Fleming and Garcia (1998) maintain that one 'cannot compare a person with a group that didn't include them'. The emphasis on relevant standardised samples has increased the validity and reliability of psychometric evidence. Now the production of each new test involves thousands of people representing all subcultures to be tested for the standardised sample. This reduced the bias of tests.

Two years after Binet's initial assessment was published, in 1939 Wechsler produced the first version of the assessment used in this thesis. It was the first assessment to acknowledge different indices within the testing materials. Using these different scores, it became possible to analyse the different patterns of intelligence. In this thesis, it is these different patterns which are used for diagnosis.

Having reviewed the development of assessments one can see how they are becoming more and more widely used. Becoming part of one's education, career and now even relationship searches, as personality profile matching, used in internet dating, is becoming increasingly popular. Assessments are becoming increasingly mechanised too. Many companies and schools use online assessments and while they can never replace the need for a face-to-face meeting they do help decrease the risk of tester bias and human error. It is my belief that computer's role in assessments shall continue to grow.

3 Literature reviews

This is a comprehensive review of the literature appropriate for each of the experimental chapters.

3.1 Literature review for pure tone discrimination

The functioning human ear can detect impressive frequency differences, however, it has been suggested that dyslexics have poorer frequency discrimination than the rest of the population when tested with two-tone comparison designs (McAnally and Stein, 1996a). The studies performed in this thesis have been performed to investigate this claim further.

3.1.1 Frequency discrimination in the normal population

Tonal discrimination is a necessary auditory prerequisite for differentiating between the different phonemes in speech. Frequency discrimination as a tool for language acquisition is thought to be possible even by neonates (Leventhal and Lipsitt, 1964). Discrimination is such a basic task that even fish, whose auditory system functions without a cochlea, can discriminate frequency up to 3%. However the duration of the stimulus does need to be long enough to process the pitch. For humans, pitch perception needs tones to be at least 6 milliseconds in length; however at low frequencies it can take up to 100ms to process the pitch.

Henning (1966) found that tones of random amplitude are discriminated far worse as their frequency is increased; but above 1000Hz there was little difference. It is generally accepted that if the intensity is below 1000Hz the perceived frequency drops as intensity increases. However if the intensity is above 4000Hz the opposite occurs; the perceived frequency rises as the intensity increases.

Other studies have also experimented with frequency discrimination during noise. If the signals to be discriminated are only faintly audible, the discrimination performance is better when the signals are in-phase at the ears, rather than when they are out-of-phase. Discrimination at low signal-to-noise ratios can be detected equally well, as long as it is within the audible range (Galambos, 1954).

3.1.2 Frequency discrimination in dyslexics

Deficits in dyslexics' pure tone discrimination have been claimed and denied over the years, without even reaching a conclusive decision if the deficit goes further than speech specific difficulties. Frequency discrimination deficits have been found using direct discrimination paradigms (McAnally and Stein, 1996; France *et al.*, 2002; Halliday and Bishop, 2006; Kujala *et al.*, 2006); amplitude modulation sensitivity (Goswami *et al.*, 2002) and frequency modulation sensitivity (McAnally and Stein, 1996; Witton *et al.*, 1998; Hill *et al.*, 1999; Witton *et al.*, 2002; Stoodley *et al.*, 2006). Frequency discrimination deficits have also been recorded in children with specific language impairment (Mengler *et al.*, 2005). However, others have found no such deficits in Chinese dyslexic children (Meng *et al.*, 2005), or with the addition of noise (Hill *et al.*, 1999).

Halliday and Bishop (2005, 2006) found contradictory evidence in two of their studies. In their initial study of mild to moderate hearing loss, they decided that impairments perceiving dynamically modulated auditory stimuli were not associated with difficulties learning to read (Halliday and Bishop, 2005), but they later found that dyslexic children had significantly higher discrimination thresholds than controls at 1 and 6 Hz (Halliday and Bishop, 2006).

France and colleagues (2002) found that dyslexics require consistently larger frequency differences to discriminate successfully between two tones. Signal detection analysis suggested that both sensory variance and trace variance were larger than in controls.

Quite often researchers have found that many dyslexic individuals - particularly those who have attained a university-level education - have performed as well as controls psychophysically. However Stoodley *et al.* (2006) found that the mismatch negativity responses (MMN) of dyslexics were abnormal despite their normal psychophysical performance. This implies that the dyslexics' successful coping strategies may positively influence their performance on the auditory behavioural measures: they were probably employing both bottom-up and top-down strategies to compensate. These findings are not the first of their kind. Baldeweg *et al.* (1999) showed that

dyslexics show persistent sensory deficits in monitoring the frequency of incoming sound stimuli which may impair the necessary feedback control to develop adequate phonological skills.

Dyslexics' ability to process tones has been questioned many times, though their deficits have been interpreted in different ways. Those who look at subgroups in dyslexics theorise that an auditory discrimination deficit is limited to only a subgroup of dyslexics (Hill *et al.*, 1999), possibly those with orthographic difficulties but no phonological problems when reading (Lachmann *et al.*, 2005).

However Brandt and Rosen (1980) maintain that dyslexics at all ages perform categorical identification and the discrimination of stop consonants in the same way as controls. They argued that as dyslexics' performance was similar to controls in this case, it would be unexpected for them to be deficient at a simpler tonal discrimination task. However this study had a limited number of participants with only four controls and 12 dyslexics participating.

3.1.3 Neurophysiology

Electrophysiological evidence has been useful in detecting auditory processing differences. The systems are sensitive and yet non-invasive so that they can be used on anyone, passively or consciously. Evidence from ERP studies has shown that even neonates can detect frequency changes (Novitski *et al.*, 2007).

Baldeweg *et al.* (1999) used mismatch evoked potentials to uncover abnormally deficient frequency discrimination in dyslexics, despite their normal duration discrimination performance, during inattentive auditory oddball tasks. Their ten dyslexics showed a persistent deficit, in comparison to the ten matched controls, when monitoring the frequency of incoming sound stimuli affecting the feedback control required to develop the phonological skills needed for normal reading acquisition.

More recently, using another passive oddball paradigm, Paul *et al.* (2006) discovered reduced hemispheric asymmetry of the auditory N260m in dyslexics. Controls showed the typical asymmetrical pattern with more anterior sources in the right hemisphere, whereas the dyslexics had more symmetrical planum temporale organisation which

may have resulted from a maturational delay. They also managed to correlate the asymmetry of the N260m with the participants' spelling performance. This further supports the connections between the maturational delays and the dyslexic profile.

A frequency discrimination threshold can be investigated in one of two ways:

a) Successive tone comparison

This is where participants are asked to judge which of two successive steady tones has a higher pitch, or as used in this thesis, whether the two successive tones are identical or different. Often the difference limen is agreed at the point at which the participant can achieve 75% accuracy.

b) Frequency modulation detection

This is where two tones are presented and a participant is required to state which of the two tones is pure and which is modulated. The frequency of the modulation can be varied to discover the limen. This procedure has been used by several researchers including McAnally and Stein (1996a), Witton (2002) and Stoodley *et al.* (2006b).

Wier *et al.* (1977) combined many different discrimination task results into one comprehensive table as in Figure 3-1. Sek and Moore (1995) compared the results from the two different task conditions on the same participant group. They found that the frequency modulation method varied less with frequency than the comparison test method. In the comparison task the difference limen is smallest at low frequencies and increases monotonically with increasing frequency. Both task procedures were equally affected (limens reduced) as sound level increases.

Henning (1966) decided that there could be a problem with measuring frequency difference limens at high frequencies, as they could be accompanied by correlated loudness changes due to irregular headphone responses at high frequencies. There is also a loss of absolute sensitivity at high frequencies (Killion, 1978). These changes

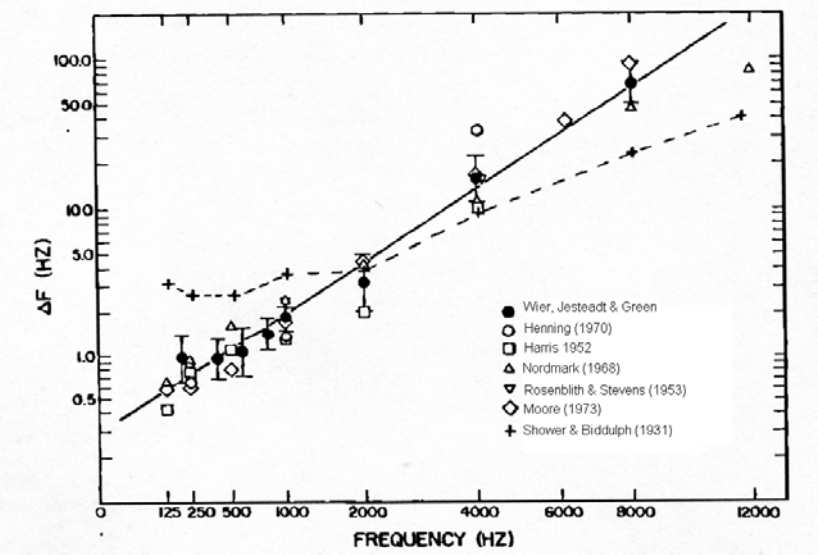


Figure 3-1 Data combined from experiments of frequency discrimination

(Wier *et al.*, 1977, p180)

could provide the cues for detection of frequency changes. Therefore Henning re-ran the choice task with the level carried randomly from one stimulus to the next. He found high frequency (4 KHz +) difference limens were markedly increased by the variation; however the lower frequencies were not affected. Therefore I cannot disregard intensity as a factor; however thankfully today headphones have become far more efficient at minimising loudness changes and one can chose from a range of styles to suit the task.

Evidence suggests that the discrimination limens are determined by temporal mechanisms at low frequencies and by place mechanisms at high frequencies. Thus phase-locking occurs at low frequencies and place identification at high. For this reason I wish to examine a range of different frequencies in this thesis.

One study found that only dyslexics with a poor performance in their tonal frequency discrimination task had significantly impaired verbal working memory in comparison to the matched controls (Banai and Ahissar, 2004). For this reason the psychoacoustic abilities of dyslexics will also be looked at in terms of their working memory.

3.2 Literature review for interstimulus interval length effects

Dyslexics may have difficulties with their auditory perception, rather than a general auditory deficit involving the rate at which they can process perceptual information

(Lieberman *et al.*, 1985). No single deficit characterised the entire dyslexic group. It seems there may be subgroups.

3.2.1 Long or short interstimulus interval deficit

Share *et al.* (2002) suggested that the reading disabled are impaired at longer interstimulus intervals but not at shorter interstimulus intervals. Should the performance of dyslexics' frequency discrimination be limited by memory abilities (Banai and Ahissar, 2004), there may be a case that the larger interstimulus intervals would prove more difficult for the dyslexics. However Tallal and other temporal theorists share the belief that dyslexics' underperformance should be more prominent at the shorter intervals due to their delayed processing of rapid sensory information.

Musicians have been found to outperform controls in pitch discrimination tasks when there are longer interstimulus intervals; however their advantage is diminished as the interstimulus interval is shortened (Berti *et al.*, 2006). As musicians as a group have superior auditory processing even in tasks not requiring attention (Koelsch *et al.*, 1999) this may imply that the longer interstimulus intervals are harder to process. It is thought that their advantage in the storage of auditory information is due to better processing abilities in working memory rather than during the encoding stages. Perhaps this advantage of musicians over a control group is the same as that between controls and dyslexics.

3.2.2 Temporal theorists

Dyslexics have a deficit in processing rapidly changing sound sequences. As seen in prolonged auditory illusions by Hari and Kiesilä (1996), the deficit can manifest in significant delays in their conscious auditory precepts and persists throughout life, so it is hypothesised that it will be seen in the adult samples of this chapter.

In normally developed readers, the temporal order of two auditory events can be correctly identified if the interstimulus interval is greater than 30ms. In an auditory evoked potential study of 21 students, the amplitude of a P2 component was significantly higher with a 10ms interstimulus interval than with a 60ms interstimulus interval. It was also found that correct responses were accompanied by lower P2 amplitude than incorrect responses (Lewandowska *et al.*, 2008). Therefore

Lewandowska concluded that the P2 component was associated with temporal order perception, requiring more activation for more difficult tasks. They deemed the 10ms interval to be harder than the 60ms.

Dyslexics concentrate for longer on a given target. Their attentional dwell is prolonged by approximately 30% in comparison to controls (Hari *et al.*, 1999b). This supports the idea that dyslexics have slower temporal processing.

Ben-Yehuda *et al.* (2004) tested frequency discrimination between two groups of adult Hebrew dyslexics. They tested a group with high cognitive abilities and another with similar reading abilities but average cognitive abilities. It is unclear if the dyslexic groups were all in the higher education. However the controls were matched for age and education.

They found dyslexics with average cognitive abilities performed poorly at all interstimulus intervals, however those with excellent cognitive abilities performed on a par with the controls at the longer intervals (>=1 second) but performance gradually deteriorated if the interstimulus interval was shortened. Ben-Yehuda took this to show dyslexics have slow yet adequate stimulus identification and comparison mechanisms. This in turn goes to support the theories of Tallal that dyslexics have problems working with the fast presentation of stimuli, and it also supports the theory that compensation in dyslexia can improve but not eradicate the effects of dyslexia on performance.

3.2.3 Phase-locking

Phase-locking occurs when neuronal discharges in the auditory system synchronise their phase oscillations with the waveforms of the vibrations of the basilar membrane. McAnally and Stein suggested that dyslexics are selectively impaired on tasks which rely on decoding neural discharges phase-locked to the fine structure of the stimulus as the discharges are significantly smaller in dyslexics as seen in ERP's (1996b).

Hari and Renvall (2001) decided that slower attentional shifting accounts for the impaired processing of rapid stimulus sequences in dyslexia. This study led them to theorise that the differences in cortical performance could be explained by insufficient

triggering of automatic auditory attention, possibly due to a magnocellular system deficit (Renvall and Hari, 2002). In a previous study Hari and colleagues found that dyslexics were worse at both periodicity and spectral pitch detection (1999a). Therefore impaired neuronal phase-locking cannot wholly explain dyslexics' problems with rapid sound sequence processing.

Plack (1996) found that dyslexics were impaired on tasks which rely on decoding neural discharges phase-locked to the fine structure of the stimulus. The ERP phase-locked discharges were significantly smaller in dyslexics and the low level auditory impairments are traceable to the brainstem nuclei.

3.3 Literature review for distraction during tonal discrimination

Inserting an irrelevant tone between target and test tones is thought to give differing disruptive effects dependent on its frequency. The maximum disruption seems to come from an irrelevant tone interposed at 2/3 of a tone separation (Deutsch and Feroe, 1975). This supports the concept of mutual inhibitory interactions between pitch memory elements. A comparable similarity effect can be seen in verbal phonemic memory tasks (Saito and Baddeley, 2004).

Distractor tones need not only impair performance, the repetition of a target tone during an interrupting sequence, may facilitate an improvement in recognition memory. The earlier the repetition within the sequence the stronger the memory gain (Deutsch, 1975).

Deutsch (1970, 1972a, 1972b) hypothesised that tonal pitch memory is encoded on both a pitch and temporal continuum, which are comprised of individual tonotopically organised elements. Deutsch suggests that information on the absolute pitch is rapidly discarded and pitch is stored in an abstracted or recoded form.

Aspects of Deutsch's studies (1970, 1972a) are replicated in three conditions of pitch differentiation, where Hari *et al.* (1999b) found that tonal memory deteriorates with time, and that interruption of memory consolidation by irrelevant tones further

depletes auditory memory. Neither Hari nor Deutsch specified the educational backgrounds of their participants in these studies. Hari states only that ‘the dyslexics were comparable in education to the control subjects’. The methods used in the following work are based on Hari’s results.

In the second of the two tasks outlined in this chapter, ‘Task 6’, a single distractor tone interrupted the interval between the target and comparison tones of a recognition paradigm. The single tone is positioned either in close proximity to the target tone, the comparison tone or centred between the two. The intention is to use this paradigm to observe any forwards or backwards masking effects. The representation of a single sound event can be altered by subsequent events: those with dyslexia have been reported to have increased susceptibility to backwards masking effects (Bailey and Snowling, 2002).

Tones presented first or last in a serial memory set are recognised more accurately than those in the middle (Mondor and Morin, 2004). However recognition of sounds presented in the final position is compromised when the memory set is followed by a ‘post-list suffix’ of a similar pitch, spectral composition and spatial location. This implies that the interrupting tone in the tasks of this chapter should make the discrimination task harder for both the dyslexics and controls. The recency and suffix effects seen in auditory presentation are considerably larger than those seen in visual presentation of verbal items (Greene and Samuel, 1986) indicating that regardless of stimulus type, effects are larger in auditory presentations.

3.4 Literature review for verbal and non-verbal auditory memory spans

In adulthood, dyslexia diagnosis relies on showing more subtle underlying cognitive deficits such as impaired phonological encoding, short-term memory or sensory processing deficits. In the general population working memory can store seven items with a variation of plus or minus two (Miller, 1956b). Deficits in digit recall have been shown to correlate strongly with the phonological deficiency (Snowling, 2000; Ramus *et al.*, 2003), assisting in the diagnosis of dyslexia. Word string retention has

even been shown to predict future reading problems in kindergarten (Mann and Lieberman, 1984).

It is widely accepted that there is a verbal auditory deficit in dyslexia (McDougall *et al.*, 1994; Snowling, 2000; Ramus *et al.*, 2003) but some remain unconvinced by Tallal's (1981) suggestion that this may be due to an underlying basic auditory temporal processing deficit. However there is now much evidence in favour of this idea (McAnally and Stein, 1996a; Stoodley *et al.*; 2006a, Banai and Ahissar, 2006).

It was suggested that perceptual difficulty in poor readers is specific to speech stimuli (Brady *et al.*, 1983) after speech perception and memory coding was found to be deficient in dyslexics. They made more errors of transpositions and recalled word strings less well than controls in both rhyming and non-rhyming paradigms but were indifferent to controls in their performance of the recall of sounds.

Kujala (2003) found pitch discrimination deficits in dyslexic adults and France *et al.* (2002) found correlations between dyslexics' digit span and auditory frequency discrimination which were not evident in controls. Each of these findings has been linked back to a deficit in the phonological loop of the working memory (Baddeley, 2003). A global auditory memory deficit could lead to poor phonological understanding and subsequently poor literacy skills. Rose and Rosner studied auditory working memory in developmental dyslexia (Rose and Rosner, 2005; Rose *et al.*, 2007). They used both verbal (digit) and non verbal (tonal) stimuli in a novel staircase paradigm to measure recognition memory spans in adults with and without developmental dyslexia. They found that dyslexics performed worse in both the verbal and nonverbal memory tasks. They suggested that this indicated a general deficit in auditory memory for both verbal and nonverbal stimuli. Sebastian and Yasin (2008) found that EEG mismatch negativity was smaller in dyslexics for tonal discrimination; however there was no difference when using speech stimuli. They attributed this to a lack of hemispheric specialisation in dyslexics.

4 Aims of this thesis

As discussed in chapters one and two, there is evidence that many dyslexic individuals have basic auditory processing impairments, opposing those who argue that dyslexia has only speech-specific deficits. General auditory processing deficits may explain their difficulties with the phonological requirements of reading, and go some way to finding non-verbal symptoms in dyslexia. Many authors have found that dyslexics show reduced pure tone discrimination. Mee Bell *et al.* (2003) described auditory processing as the strongest predictor of the variance across the different achievement areas. However Rose *et al.* (2007) suggested that dyslexics who reach university educational standard may be capable of improving their pure tone discrimination, whereas dyslexics who do not achieve tertiary education may not be.

In this thesis I have set out to test whether frequency discrimination and tonal memory differ between university educated and non-university dyslexics and controls. Initially, the basic experiment of simple tone discrimination was performed on an educationally unspecified group, to see if the dyslexics do perform worse than controls. This task was then extended to see how much of a frequency difference would be needed to discriminate between the two tones, and whether educational background made a difference.

Tallal has claimed a general auditory deficit first in specific language impairment, then in dyslexia (1980, 1981a, 1981b, 1984). However, she attributes the findings to a temporal processing deficit and believes the deficit is restricted to those tasks with short interstimulus intervals. Rosner (Rosner *et al.*, 2003; Rose and Rosner, 2005), however, believes that dyslexics will find longer intervals more difficult due to memory retention difficulties. To investigate these theories, I performed two tasks: the first tested university educated individuals' tonal discrimination at three different long intervals, all of which were longer than those used by Tallal. The second investigated the effects of education on the dyslexic performance at the same time, using a range of different interval lengths in the four different participant groups. This second task covers the interval lengths that both Tallal and Rosner predicted would cause dyslexics problems.

Rosner's theories about memory retention problems in dyslexia prompted the next experiments. Deutsch has previously researched into the effects of interruption during the retention period of a tonal discrimination task (Deutsch, 1970, 1972a, 1972b, 1975; Deutsch and Feroe, 1975). I predicted that dyslexics would find the retention of tones during interruption more difficult than controls and thus would make more errors. The first of my tasks used five interrupting irrelevant tones during the interval of a tonal discrimination task in both university and non-university subjects. In the second task, a single interrupting tone was used but its temporal position was varied to see if any forwards or backwards masking effects could be detected. This second task was performed on the four groups: university dyslexic; university control; non-university dyslexics and non-university controls, dividing the dyslexic and control groups by tertiary education.

Finally, in a replication of the Rose and Rosner study (2005), their tonal and digit recognition tasks were re-performed, but this time they were performed using the four groups dividing the dyslexic and control groups by education. The participants compared two series of tones or digits, which increased in length according to the participants' performance. It was predicted that the educational differences in the dyslexic groups could provide an explanation to the findings of Rose and Rosner. It was predicted that dyslexics with university education would have more compensatory skills improving their performance in the tasks. Below, in Table 4-1 is a summary of the research questions and each of the tasks created to investigate each one.

Table 4-1 Summary of aims

Task number in thesis	Name	Aim
5.1 Task 1	Tone discrimination at a semitone difference.	Do dyslexics discriminate a semitone difference as well as controls?
5.5 Task 2	Discrimination of incremental tone differences.	Do dyslexics have a lower threshold? Is it affected by education?
6.2 Task 3	Effects of long interstimulus intervals.	Do university dyslexics need longer to consolidate the memory of a tone?
6.5 Task 4	Effects of incremental interval length increases.	Do incremental increases in interval effect tonal discrimination? Is it affected by education?
7.2 Task 5	Pitch discrimination with five irrelevant distractor tones.	Do dyslexics react differently to distraction while discriminating a semitone?
7.5 Task 6	Single distractor in different positions.	Does the position of the distraction have different effects on dyslexics and controls? Is it affected by education?
8.2 Task 7	Non-verbal sequence recognition.	Do dyslexics have a non-verbal memory deficit? Is it affected by education?
8.2 Task 8	Verbal sequence recognition.	Do dyslexics have a verbal memory deficit? Is it affected by education?

5 General methods

5.1 Participants

5.1.1 Task differences

In each experimental chapter there are two studies. The initial studies in each (excluding Chapter 8) used either educationally unspecified groups of dyslexics and controls or student only groups. The second tasks in each experimental chapter, and the entirety of Chapter 8, used four experimental groups defined by their educational history: university dyslexics (UD), university controls (UC), non-university dyslexics (NUD) and non-university controls (NUC). In this thesis the term 'university educated' is used to include both past and current students.

As I have been studying both dyslexics with a university education and those without, it was apparent that those who had left education after secondary school were often those who had never been formally diagnosed, despite having a history of literacy difficulties and often previous exam provisions. To be assigned into either of the two dyslexic subgroups participants needed to be diagnosed as dyslexic or show significant evidence of the disorder. As outlined in the DIUS (*Department for Innovation, Universities and Skills)* Specific Learning Difficulties Working Group, dyslexics, of any age, should show evidence of:

- A history of difficulty with the acquisition of literacy skills;
- Persisting difficulty;
- An underlying cognitive deficit;
- Exclusion of other factors;
- Underlying ability/achievement differentials.

Subjects with a documented history of literacy difficulties from an early age were classified in accordance with the classifications of the division of educational and child psychology of the British Psychological Society: Dyslexia, Literacy and Psychological Assessment (2003). Under these guidelines participants with a history of literacy acquisition difficulties, deficits in literacy, working memory and/or a

temporal processing deficit occurring in less than 20% of the population were regarded as dyslexic. This is the same procedure as followed by certified educational psychologists.

To be classified as dyslexic, a reader had to have an educational assessment giving this diagnosis. Participants were re-assessed if the previous assessment was over five years old. Those classified as controls showed no specific deficits in their literacy, working memory or processing speeds.

Table 5-1 Participant groups

Group 1	Group 2	Group 3	Group 4
Two groups of dyslexics and controls with undistinguished educational backgrounds.	Two groups of university educated dyslexics and controls.	Four groups, dyslexics and controls split by educational background. Performed 12 WAIS-III subtests.	Four groups, dyslexics and controls split by educational background. Performed all 14 WAIS-III subtests.
Task 1 Task 5	Task 3	Task 2 Task 4 Task 6	Task 7 Task 8

5.1.2 Recruitment

Participants were recruited with the provision that English was their mother-tongue and they had no known hearing difficulties or neurological problems. It was established at interview that all participants had received adequate learning opportunities during development and no other psychosocial factors were affecting performance.

Participants were excluded from the study if they failed to detect tones to at least 20dB during the audiometric assessment or if control subjects had a distinct pattern of symptoms in the psychometrics which would indicate a different distinct learning disorder. In either case participants were made aware of the discovery and advised on a course of action. In the three studies, Tasks 2, 4 and 6 - pure tone discrimination, effects of short ISI on discrimination and effects of single roving distractor on discrimination - three control participants were removed. Two were due to a failure on

the audiometric assessment and one for having symptoms of another learning disorder, in this instance ‘non-verbal processing disorder’.

Participants were recruited using posters displayed in the local universities and around the local community. Online advertisement proved successful towards the later stages of the thesis, especially in contacting a non-university educated population. The internet sites www.dailyinfo.co.uk and www.facebook.com were used to recruit local people into the study. Word of mouth became a rapidly successful recruitment method, creating a snowballing sample.

Remuneration for participants’ time was £5 per hour and any outstanding travel expenses were reimbursed. All participants were informed of the specific requirements in advance of the research session and informed consent was required prior to the start of the research procedure. The research was covered by permission from the Centrally Organised Research Ethics Committee (COREC O01/02). Participants were given ample opportunity to ask any questions and were made aware that they could discontinue at any time: prior, during or even after the research session. Refreshments were offered during all sessions to maintain concentration and motivation.

5.2 Experimental procedures

5.2.1 Programmes

All the programmes used in this thesis were individually programmed, mostly by the author, in Borland C++ to run under DOS format, all of which can be found in the abstracts. Acknowledgement is given to Professor Burton Rosner for allowing the use of his auditory memory span tasks. His assistance and advice given during the programming of the other tasks was also greatly appreciated. Each of the programmes can be found in the Appendices as directed in the individual chapters.

5.2.2 Stimuli

The auditory stimuli were created using PRAAT software. All the nonverbal tonal stimuli are sinusoidal tones of 50ms duration. The frequency spectrum from which the tones were created is the same as that used in Berti *et al*’s pitch comparison task

(2006). All experimental procedures were presented binaurally at 63dB SPL through headphones. Full details of the frequencies used in each task can be found in each individual experimental chapter.

5.2.3 Environment

Where possible the participants were tested in the Oxford University Department of Physiology, Anatomy and Genetics with no distraction or interruption. When this was not possible all care was taken to provide a quiet environment.

In the laboratory all auditory experiments took place within the confines of an acoustic room manufactured by the Industrial Acoustics Company (IAC), who are approved to the BS EN ISO 9001:1994 quality standard. The participant was sat in front of a flat screen monitor and keyboard linked to the external PC. If testing away from the laboratory, great effort was taken to perform the tasks in a silent environment. In all cases the programmes were presented binaurally through Sennheiser HD 25closed dynamic hi-fi stereo headphones.

Before each task the instructions were read aloud and the participants were able to read along, which can be seen in the methods section of each chapter. After the instructions were read it was ascertained whether the participant had understood and any questions they had were answered to assure they complied with the experiment. The participants completed the tasks in their own time initiating each trial themselves with a key press.

5.3 Psychometric procedures

To compare the acoustic psychophysics of the participants in this thesis, an extensive psychometric battery was employed. As a qualified educational psychometrician (member of the BPS Register of Competence in Psychological Testing, CPT3A) I carried out a compilation of different assessments.

5.3.1 Measures of cognitive skill

Each participant was administered a rigorous battery of psychometrics. These included the subtests of the Wechsler Adult Intelligence Scale - Third edition (WAIS III UK); and Person’s Random Automatised Naming (RAN) tasks. Each subtest of

these assessments is testing a different combination of skills. It is only through careful comparison that a participant's pattern of performance becomes apparent.

Here are the details of the WAIS individual subtests and what they are assessing;

- WAIS > Verbal tests > VCI > Vocabulary - This test is proclaimed to be the most stable single measure of general verbal intelligence. It is the least affected by deterioration due to brain damage or emotional factors like schizophrenia (Hebb, 1942). Even when concentration deficits affect other tasks such as arithmetic or digit span, vocabulary is one of the last to be affected. For this reason it is often used in clinical settings to evaluate a baseline intelligence; an indicator of a person's capacity prior to a trauma.
- WAIS > Verbal tests > VCI > Similarities – Participants are required to identify the similarity between pairs of two items, increasing in difficulty. Initial trials involve previously learned associations (Kaufman, 1990). Later trials require abstract thought to see the similarity between seemingly dissimilar items.
- WAIS > Verbal tests > VCI > Information – This task requires the comprehension of questions and providing a response. The questions increase in difficulty. This task is indicative of educational opportunities 'the subtest is linked to alertness to the environment and alertness to cultural opportunities' (Kaufman, 1990; Gregory 1999,). The task involves both intellective and non-intellective components such as curiosity and interest.
- WAIS > Verbal tests > WMI > Digit Span – This task requires the repetition of digits sequences, both forwards and backwards, of increasing length. The task measures short-term auditory memory recall. Performance is susceptible to influences such as attention or anxiety.
- WAIS > Verbal tests > WMI > Arithmetic – This task requires the calculation of relatively simple mathematical problems. Mathematical skill plays less of a role than the ability to retain and manipulate the figures, concentration and reasoning skills.
- WAIS > Verbal tests > WMI > Letter-number Sequencing – In this task randomly ordered sequences of numbers and letters, of increasing length, are reordered into numerically and alphabetically organised sequences. The task involves the loading of working memory and attention (Gregory, 1999, Phares and Trull, 2000).

- WAIS > Verbal tests > Comprehension – This task is not used in the compilation of any index scores, however it is combined in the Verbal IQ. This task measures judgment in everyday practical situations and the use of common sense. In clinical settings this task is often used to reveal emotional difficulties.
- WAIS > Performance tests > POI > Picture Completion – This task requires the identification of a missing important detail in a picture, within a given time constraint. The task requires fine visual attention however no verbal response is required and straightforward example items mean comprehension of the verbal instructions is not compulsory.
- WAIS > Performance tests > POI > Block Design –This task was one of the first developed to investigate non-verbal intelligence (Kohs, 1923; Arthur, 1930) and requires the arrangement of blocks to replicate increasingly difficult designs. The task requires analysis of the spatial relationships, and integration of visual and motor function. Rapaport, Gill and Schafer (1968) praised the tasks measurement of nonverbal concept formation and abstract thinking.
- WAIS > Performance tests > POI >Matrix Reasoning – The task is to identify a pattern or relationship between nonverbal figural stimuli. Developed to assess fluid intelligence, this task is a good measure of information-processing and abstract-reasoning skills (Phares and Trull, 2000).
- WAIS > Performance tests > PSI > Digit Symbol-coding – This task involves the copying of symbols each of which is paired with a digit 1 through 9. The subject is allowed a short practice and then asked to complete as many as possible within a given time. The task assesses visual and motor acuity, visual motor dexterity, degree of persistence, speed of performance and their ability to learn the unfamiliar task (Gregory, 1999, Kaufman, 1990).
    - WAIS > Performance tests > PSI > Digit Symbol-coding > Incidental Learning of Pairings – This task requires the completion of two tables requiring the participant to remember the symbols used in the previous task. This measures their recall of associations between memories
    - WAIS > Performance tests > PSI > Digit Symbol-coding > Free Recall of Symbols – This task requires participants to recall the aforementioned symbols regardless of their order of corresponding digit. The task measures recall of abstract memories.

    - WAIS > Performance tests > PSI > Digit Symbol-coding > Copy – This task requires the direct copy of digits. This measures the speed of fine motor control.
- WAIS > Performance tests > PSI > Symbol Search – The task requires participants to search for one of two target geometric figures from among a set of five additional search figures, to determine if either of the target items are repeated in the search figures. They perform as many trials as they can in the given timeframe. This task measures the speed of information processing.
- WAIS > Performance tests > Picture Arrangement – This task is not used in the compiling of any index scores, however it is combined in the Performance IQ. This task requires participants to rearrange pictures to tell a story. The requirement of a logical sequence of events requires the noticing of relevant details, responding to cause-effect relationships and non-verbal reasoning ability. As some of the stories involve social content Sattler (1982) argues that the task also measures the ability to interpret social situations.
- WAIS > Performance tests > Object Assembly – This task is not used in the compiling of any index scores, however it is combined in the Performance IQ. The task requires the completion of jigsaw puzzles as quickly as possible. Involving 'visual analysis and its coordination with simple assembly skills' (Phares and Trull, 2000). The participant's ability to see the whole in relation to its parts.

When combined the index scores give more information about the pattern of performance. The task performances' are combined to create four individual index scores: Verbal Comprehension Index, Working Memory Index, Perceptual Organisation Index and the Processing Speed Index. In the average performing population these indices should correlate highly with one another to combine into a reliable and valid IQ score. In specific learning difficulties this is not the case. In a learning difficulties profile an IQ score should be regarded with caution, as relative weaknesses due to the learning difficulty can skew the IQ score and make it invalid.

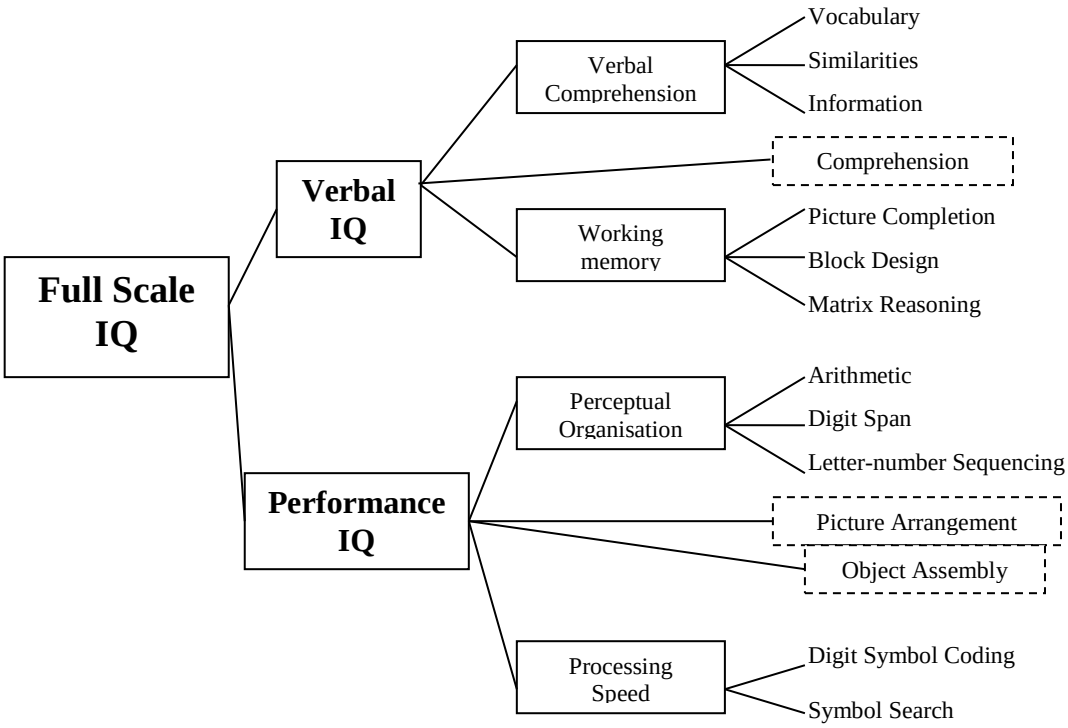


Figure 5-1 Schematic overview of WAIS-III Index scores

In developmental dyslexia, not only is literacy affected but there is an overwhelming body of evidence of a temporal processing deficit and / or working memory difficulties in many dyslexics. When assessing for dyslexia the WAIS can reveal these problems with a reduced performance in either the Working Memory Index or the Processing Speed Index. Many dyslexics retain these deficits even after compensating for the majority of their literacy deficits. The comparison between these indices is a vital tool in diagnosis of learning difficulties. There is now a more updated version of WAIS-IV (Wechsler, 2008) and if replicated it would be important to adapt the battery to the most recent tests available.

To assess participants' speed of processing, in addition to the WAIS-III, the rapid automatised naming task similar to that created by Denckla and Rudel (1974) was used in the participants who undertook each of the tasks with the exception of Task 3. The task is depicted as predicting reading ability and participants' ability to establish arbitrary mappings between visual symbols and verbal labels (Clarke *et al.*, 2005). Useful for distinguishing the naming difficulties present in dyslexia (Griffiths and Snowling, 2001; Faust *et al.*, 2003; Nation, 2005). There are two sub-tests assessing the naming speed of digits and objects.

- RAN > Digits – Participants read aloud a row of 50 digits (1-9) as quickly as they can. Their speed and the number of errors are recorded.
- RAN > Objects - Participants name aloud a row of 50 pictures of objects (random presentation of a ball, door, table, box and a hat) as quickly as they can. Their speed and the number of errors are recorded.

5.3.2 Measures of literacy and comprehension skill

The participants' literacy skills were examined using a range of different tasks: the Wide Range Achievement Test 3 (WRAT 3); the Castles and Coltheart (C&C) single word reading lists (tests of regular, irregular and non-word reading ability); and the Woodcock Reading Mastery Tests – Revised (WRMT) passage comprehension subtest.

In the attainment test WRAT 3 the mathematics subtest was dropped, as it took too long to administer, and the two literacy tasks were performed by all participants.

- WRAT 3> Single Word Spelling – This task includes the spelling of 40 words of increasing difficulty. For those with reduced literacy their own name is used as the initial spelling. This task requires the orthographic recall of word forms. For the later items the participant has to employ phonological decoding skills on words they are less familiar with.
- WRAT 3 > Single Word Reading – This task includes the verbalization of 42 increasingly difficult words. For those with reduced literacy the naming of 15 letters can be performed. This task requires the employment of phonological decoding sills.

The WRAT tasks are combined with the Castles and Coltheart reading lists to establish participants' literacy ability. The Castles and Coltheart lists were originally created for use with children and have no established adult norms; however they are still a valuable tool.

- C&C > Regular Word Reading – this task establishes a baseline reading accuracy and speed for 30 single short words. The 30 words, of increasing difficulty, are all commonly known words with regular spelling phonology.

- C&C > Irregular Word Reading – 30 words, of increasing difficulty are assessed for accuracy and speed. The words are chosen to be phonetically irregular thus requiring the use of orthographic recall to name the words.
- C&C > Pseudo Word Reading – 30 non-words, of increasing length and complexity, are assessed for accuracy and speed. The words are created to follow regular English phonology yet are not real words. Participants are required to use phonological decoding to identify the correct pronunciation.

Those participants that completed task 3 were assessed on the Woodcock Reading Mastery Tests – Revised (WRMT- R) passage comprehension subtest.

- WRMT-R > Passage Comprehension – this test measures the participant's ability to study a short passage and identify a key word missing from the passage. The task is a modified cloze procedure, requiring a combination of comprehension and vocabulary skills.

5.3.3 Questionnaires

Participants were asked to complete a selection of questionnaires including:

- Conner's CAARS Adult ADHD Ratings Scale – The participants were screened for current symptoms of attention-deficit hyperactivity disorder (Conners *et al.*, 1998).
- Handedness questionnaire – Adapted from the Humphrey's inventory, from the M.R.C speech and Communication Research Unit, taken from M. Humphrey's 1951 thesis. Other similar adaptations are the Edinburgh Handedness Inventory (Oldfield, 1971) and (Annett, 1973).
- Musicality Questionnaire – Extract from the Checklist of Visual and Other Symptoms (CVOS) created by Dr. S. Fowler of the Dyslexia Research Trust.
- Adult Dyslexia Questionnaire (ADO) – Created by the British Dyslexia Organisation.

5.3.4 Environment

All psychometric tasks were performed in a quiet room free from distraction or interruption. The stimuli were hidden from the participant until they were used. The

participants were free to progress at their own pace with a break for refreshments. The participant's background and attitude to assessment were gauged through conversations which enabled the assessor to build a rapport with the participants.

5.4 Data manipulation

All data has been handled under the provisions of the 1998 Data Protection Act. The data were processed in Microsoft Office Access 2003 and analysed using SPSS 16. The psychometric data collected from the WAIS III UK was analysed using the 1999 Psychological Corporation's WAIS-III – WMS-III Writer. The use of this software limits the risk of human error during analysis.

5.5 Auditory assessment

Where possible, each participant underwent an audiometric assessment. Their hearing sensitivity was measured using the descending Hughson-Westlake method (Carhart and Jerger, 1959) with a clinical audiometer. The Grason-Stadler GSI 38 Auto Tymp, a single channel, manual audiometer was used. Participants were tested at a full range of frequencies (125 to 8000 Hz) and intensity levels (-10 to 100 dB HL).

The audiometric assessment was performed within the confines of the same acoustic room manufactured by IAC. The assessment used Telephonics' TDH-39P headphones with separated monaural feeds. Only participants who could detect tones at 20dB or less across the used range of frequencies were admitted into the study. Any participants with whom we detected a hearing impediment, were informed, advised to seek advice from their doctor and removed from the study.

6 Pure tone discrimination

6.1 Rationale for tasks

Two studies were used to investigate dyslexics' performance at simple tonal discrimination. It is anticipated that dyslexics will have worse discrimination skills than controls when there is a semitone difference (Task 1).

In order to find the required difference for discrimination in the dyslexics and controls another task is created with a roving difference between the target and comparison tones; (Task 2). It is anticipated that dyslexics will require a larger difference than the controls for discrimination. If dyslexics underperform in comparison to controls at all frequency differences then there is a possibility that the experimental paradigm could be allowing memory deficits to cause any underperformance. However I predict that the dyslexics require a larger frequency difference to successfully discriminate between pure tones than controls, after which point performance should match controls.

To follow the interesting results unearthed by Rose and Rosner, Task 2 was performed on four groups, splitting the dyslexic and control groups by education. Groups were made between those who attended tertiary education and those who didn't. It is predicted that education would not have an affect on discrimination ability.

6.2 Task 1: Methods - two tone discrimination (semitone difference)

6.2.1 Design

This test was created to assess the ability of dyslexics and controls to distinguish one tone from another. A simple two tone frequency discrimination task used a roving exemplar tone and a comparison tone after a stimulus interval of 3050ms, either the same or a semitone different (up or down), to test the discrimination ability of the two groups.

6.2.2 Participants

In all, 58 individuals with undefined educational achievements participated in this study:

- A group of 26, diagnosed by an educational psychologist as suffering from the learning difficulty dyslexia. Henceforth ‘dyslexics’.
- A group of 32 who did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties. Henceforth ‘controls’.

Table 6-1 Participant descriptive statistics
SD=Standard Deviation, IQR=Inter-quartile range of age

Participant Group	Total Number	Male/Female	Age Range	Mean Age	SD	Median Age	IQR
Dyslexics	26	13/13	18-41	23.9	6.4	21.5	6
Controls	32	13/19	16-30	20.1	2.8	19	3

6.2.3 Measures of cognitive ability

Each participant was administered a limited battery of psychometrics. These included: six of the Wechsler Adult Intelligence Scale - Third edition (WAIS III UK) subtests: Vocabulary, Similarities, Block Design, Symbol Search, Digit Span and Picture Arrangement. Also performed were the Random Automatised Naming (RAN), object and digit tests.

6.2.4 Measures of literacy ability

Participants were administered the Single Word Reading and Spelling subtests of the Wide Range Achievement Test (WRAT) and all three of the Castles and Coltheart (C&C) single word reading lists.

6.2.5 Procedure

In their own time, participants were presented 50 trials in a fixed sequence. The target tone was followed by a 3050ms silent delay before the comparison tone. The target frequency was varied between trials to avoid learning effects. For 26 of the trials the comparison tones were identical to the target, 12 differed by a frequency one semitone up and 12 differed by a frequency one semitone down. Participants were asked to detect whether the two tones were the same or different.

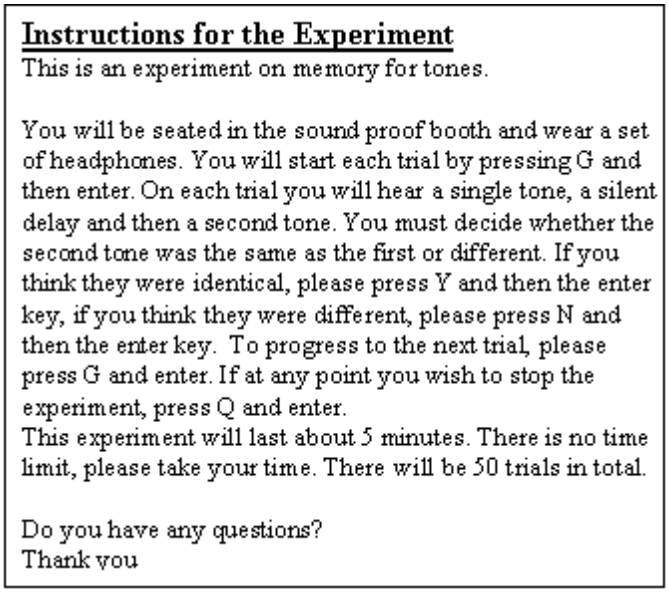
The target tone was chosen at random from a pool of 15, 150ms, sinusoidal tones that cover an octave. The stimuli trials were presented binaurally at 63dB SPL through headphones.

Table 6-2 Target and comparison tone frequencies

Target tone	Comparison tone	
	DOWN	UP
440	415	466
523	494	554
622	587	659
740	698	784
880	831	932

Participants controlled the initiation of individual trials with a key press. After the stimulus the participant indicated whether the target and comparison tones were the same using the 'Y' or 'N' key to indicate 'yes they were the same' or 'no they were different' before initiating the next trial.

The participants read the instructions (Figure 6-1) along with the administrator who answered any questions. The participants performed the task in their own time initiating each trial independently.



Instructions for the Experiment

This is an experiment on memory for tones.

You will be seated in the sound proof booth and wear a set of headphones. You will start each trial by pressing G and then enter. On each trial you will hear a single tone, a silent delay and then a second tone. You must decide whether the second tone was the same as the first or different. If you think they were identical, please press Y and then the enter key, if you think they were different, please press N and then the enter key. To progress to the next trial, please press G and enter. If at any point you wish to stop the experiment, press Q and enter.
This experiment will last about 5 minutes. There is no time limit, please take your time. There will be 50 trials in total.

Do you have any questions?
Thank you

Figure 6-1 Instructions

6.3 Results - two tone discrimination (semitone difference)

The results of the Kolmogorov-Smirnov test of normality indicated that the psychophysical tone discrimination data were not normally distributed. To test the effects of dyslexia on the tone discrimination task, a nonparametric t-test (Mann-Whitney U) was therefore performed. The results showed that dyslexics performed significantly worse than controls on the simple pitch discrimination task. U =240, Z =-2.801, p =0.005**.

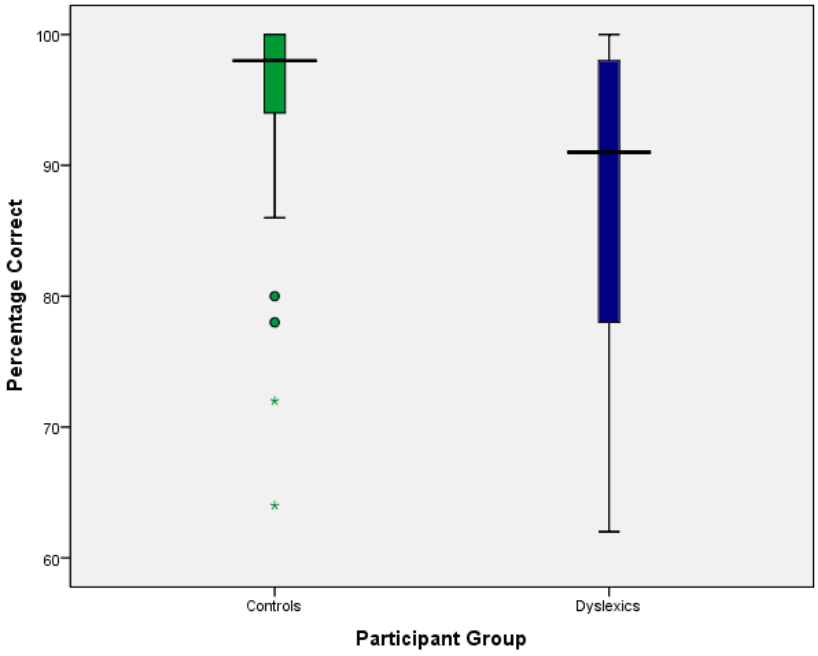


Figure 6-2 Box plot of group differences
Displays median, 2nd and 3rd quartiles, range, outliers and extreem outliers

As the development of auditory frequency discrimination skills is thought to be mature by the age of seven years (Thompson *et al.*, 1999) the difference in age between the participant groups should not have affected their performance. The dyslexics were significantly older than the controls (U =148, Z =-2.566, p =0.01**) however the two groups did not differ in IQ.

As can be seen in Figure 6-2 the significant difference between the two groups was associated with larger variance in scores by the dyslexic group. Figure 6-3 shows that the dyslexics had a broader range of more evenly distributed scores, whereas the controls had a sharp negative skew with many of the participants performing at ceiling level.

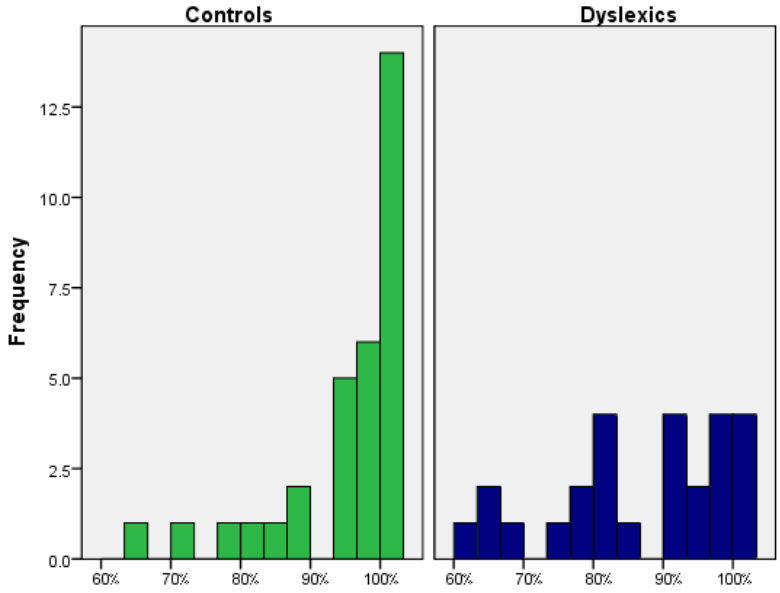


Figure 6-3 Histograms of frequency percentage correct

6.3.1 Tone discrimination correlations

Spearman's two-tailed correlative tests were performed on the data to test for correlations with the psychometric tests.

Table 6-3 Correlations
** = Correlation p ≤ 0.01, * = Correlation p ≤ 0.05, ‧ = Trend p ≤ 0.1, N.S. = Not significant p ≥ 0.1,
⌾ = *correlations that remain when controlling for IQ.*

	Task	Correlation	Two tailed
Simple Tone Discrimination correlated with:	Combination IQ	0.338	0.073‧
	Musical ability	0.557	0.006**
	Digit Symbol	0.448	0.003**
	Digit Span	0.380	0.013*
	Reading	0.289	0.070‧
	Spelling	0.327	0.042*
	Non-word reading errors (phonological awareness)	-0.371⌾	0.052‧

After controlling for IQ (IQ score assumed from a mean combination of psychometric measures), two-tailed partial correlations also showed a negative trend correlation with the number of errors made on the Castles and Coltheart non-word reading test (R=-0.583, p= 0.06). This implies tone discrimination performance may predict phonological ability.

6.3.2 Psychometric group differences

The psychometric battery performed on this participant group was incomplete. Using what psychometrics were available, performance differences between the dyslexics and controls were recorded.

Table 6-4 Psychometric group differences
** = p ≤ 0.01, * = p ≤ 0.05, ˙ = Trend p ≤ 0.1, N.S. = Not significant p ≥ 0.1. D. = Dyslexics, C.= Controls

Task			Dyslexics		Controls		Significance
	Number		*Mean*	*S.D.*	*Mean*	*S.D.*	
ADO questionnaire	*D.*	9	6.29	3.59	8.15	3.997	N.S.
	C.	14					
Vocabulary	*D.*	16	13.14	3.1	14.62	2.9	N.S.
	C.	26					
Similarities	*D.*	16	14.14	2.79	13.85	1.77	N.S.
	C.	26					
Block Design	*D.*	16	12.57	4.23	13.85	3.051	N.S.
	C.	25					
Digit Symbol Copy	*D.*	16	10	2.449	12.38	2.785	0.001**
	C.	25					
Digit Span	*D.*	16	9.86	2.85	11.38	3.429	0.01**
	C.	26					
Picture Arrangement	*D.*	15	12.29	3.729	8.92	2.43	0.08˙
	C.	26					
Reading	*D.*	14	103.29	13.21	108.15	8.315	0.043*
	C.	26					
Spelling	*D.*	14	92.29	5.823	113.15	8.774	0.000**
	C.	25					

6.4 Discussion - two tone discrimination (semitone difference)

Dyslexics performed significantly worse than the controls in the discrimination of a semitone difference between two tones.

The correlations depicted in Table 6-3 were all with tasks strongly linked to deficits in dyslexia. However the correlations were mostly dependent on general IQ. After controlling for IQ the majority of the correlations ceased to be significant but a trend correlation was maintained between the task performance and the number of errors

made when reading non-words. Therefore this implies a correlation between tone discrimination performance and phonological skills.

To examine if the difference in performance between dyslexics and controls seen in this task was due to poor memory of the test stimulus, a roving difference was used to uncover the smallest frequency difference individuals could discriminate. If the dyslexic deficit was a short-term memory deficit rather than limited by the size of the frequency difference in comparison to the controls it may be suggested that the discrimination difference was due to the memory deficit rather than a frequency discrimination deficit in isolation.

Another problem with this experiment was that attention was not measured. For this reason we cannot be sure that the effects were due to dyslexia rather than attentional deficits during the task procedure. For this reason assessment of participants' attentional abilities will be recorded to assess any group differences or any attentional effects.

The results of this task were very close to ceiling given the detection requirement of a semitone difference. In future, quarter tone differences should be used to give a larger variation in the scores, pulling the mean performances away from the ceiling.

6.5 Task 2: Methods - discrimination of incremental frequency differences

6.5.1 Design

I aimed to assess the initial tone encoding ability of four groups to assess the differences between university dyslexics versus university controls; university versus non-university students; and non-university dyslexics versus non-university controls. A simple two tone frequency discrimination task analysed the frequency gap threshold required to detect differences between two tones. The frequency difference between the two tones on the 'different' trials was varied during the task.

Performed alongside this task was an extensive battery of psychometrics, to analyse the difference between dyslexics and controls, and their educational backgrounds.

6.5.2 Participants

Four groups of individuals (amounting to 83) participated in this study:

- A group of 21 current or previous university students, diagnosed by an educational psychologist as dyslexic. Henceforth ‘university dyslexics’ (UD).
- A group of 22 current or previous university students who did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties. Henceforth ‘university controls’ (UC).
- A group of 21 adults who did not attend tertiary education with no plans to attend in the future. These adults had been diagnosed by an educational psychologist as dyslexic or else had a distinct dyslexic profile in the psychometric battery and had a history of learning difficulties. Henceforth ‘non-university dyslexics’ (NUD).
- A group of 19 adults who did not attend tertiary education with no plans to attend in the future. They did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties. Henceforth ‘non-university controls’ (NUC).

Table 6-5 Participant descriptive statistics

Participant Group	Total Number	Male/Female	Age Range	Mean Age	SD	Median Age	IQR
UD	21	12 / 9	18 – 44	25.9	7.5	22.5	5
UC	22	7 / 15	19 – 42	25.4	6.0	24.5	9
NUD	21	13 / 8	17 – 44	30.0	9.8	26.5	20
NUC	19	5 / 14	18 – 48	28.8	9.6	23.0	18

6.5.3 Exclusion criteria

Three control participants were removed from the study and not included in the numbers above. Two were removed due to a failure to detect tones at less than 20dB during the audiometric assessment and one for having had a distinct pattern of symptoms in the psychometrics which would indicate another learning disorder, in this instance ‘non-verbal processing disorder’.

6.5.4 Materials

The participants completed four of the batteries questionnaires; the Connors’ adult ADHD rating scale (CAARS), Adult Dyslexia Questionnaire (ADO), the Annett Handedness Questionnaire and the Musicality Questionnaire.

The full details of the tasks computer programme can be seen in Appendix A2.1.

6.5.5 Measures of cognitive ability

Each participant was administered an extensive battery of psychometrics. These included: the 12 subtests of the Wechsler Adult Intelligence Scale - Third edition (WAIS III UK) required for the four ability indices and the Random Automatised Naming task (RAN).

6.5.6 Measures of literacy ability

Participants were given the Single Word Reading and Spelling subtests of the Wide Range Achievement Test (WRAT) and all three of the Castles and Coltheart (C&C) single word reading lists.

6.5.7 Procedure

In their own time, participants were played in random order 72 pairs of tones and asked to detect whether the two were the same or different. One of three target tones was played, followed by a silent interstimulus interval of 2000ms before a comparison tone. 50% of the comparison tones were identical to the target, 25% differed by one of 6 higher frequency tones and 25% differed by one of 6 tones of a lower frequency.

Table 6-6 Target and comparison tone frequencies

Difference	Target tone	Comparison tone	
		UP	DOWN
Whole tone	**293 Hz**	295.1356	261.617
Semi tone		296.6307	277.1702
1/4 tone		299.6437	285.2902
1/8 tone		302.2507	289.4389
1/16 tone		311.1054	291.5359
1/32 tone		329.6006	292.59
Whole tone	**369 Hz**	371.8293	329.6006
Semi tone		373.713	349.1954
1/4 tone		377.5089	359.4254
1/8 tone		380.7933	364.6523
1/16 tone		391.949	367.2941
1/32 tone		415.2504	368.6222
Whole tone	**659 Hz**	662.4432	587.2096
Semi tone		665.7991	622.1192
1/4 tone		672.562	640.3448
1/8 tone		678.4133	649.6568
1/16 tone		698.2881	654.3635
1/32 tone		739.8014	656.7296

The 6 fixed frequency intervals ranged from 1/32 of a tone difference to a whole tone incrementing in logarithmic steps. After each stimulus the participant indicated whether the target and comparison tones were the same or different using the 'S' or 'D' key respectively before initiating the next trial.

6.6 Results - discrimination of incremental frequency differences

The results from this task were not normally distributed. The results for each of the six trial types were truncated, as four of the trial types produced floor and ceiling results. For this reason non-parametric tests were used for the analysis. As the procedure was a two way forced choice paradigm, those scores below 50% have been levelled to the floor of 50%. To work around the floor and ceiling results analysis has been performed with those trials which were a quarter tone different where indicated.

The majority of all four groups improved equally in performance as the frequency difference between target and comparison grew. During the trials with the two smallest differences (1/32 & 1/16), performance was restricted to chance level across all the groups (below 50% accuracy). As seen in Figure 6-4 the university controls fell slightly behind the others when discriminating at a quarter tone difference. When the frequency difference was ½ tone or more the performance was mostly at ceiling level.

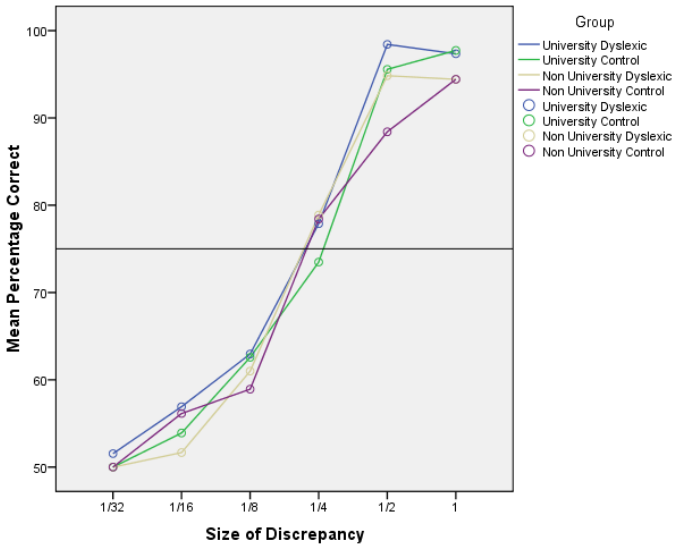


Figure 6-4 Group mean plots: Performance improves as frequency gap widens

The difference in group performance was widest at a quarter tone difference (Figure 6-4). By singling out these trials an individual analysis was performed. At this stage

the variance of the groups is too wide to see a significant difference in performance between the groups (Figure 6-5).

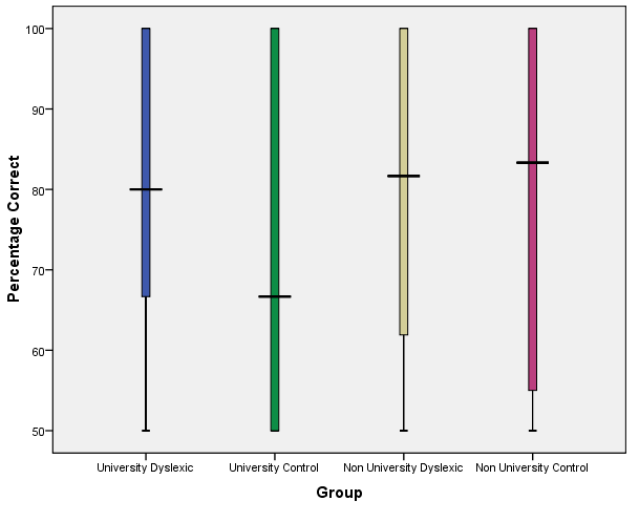


Figure 6-5 Group differences discriminating a quarter tone difference

6.6.1 Dyslexia's effect on tone discrimination thresholds

There were no significant differences in the total performances of the dyslexics versus the controls. Even when control outliers were removed the group differences remained insignificant (Figure 6-6).

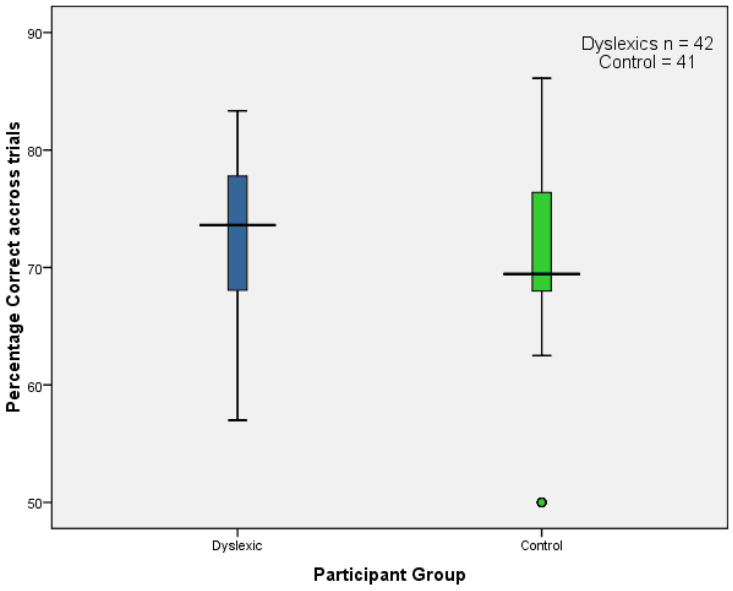


Figure 6-6 Performance of dyslexics vs. controls

When the calculation was performed using only those trials with a quarter tone difference, to avoid the ceiling and floor results, the difference remained insignificant,

however the box plots indicate a smaller variability in the dyslexic results and higher performance (Figure 6-7).

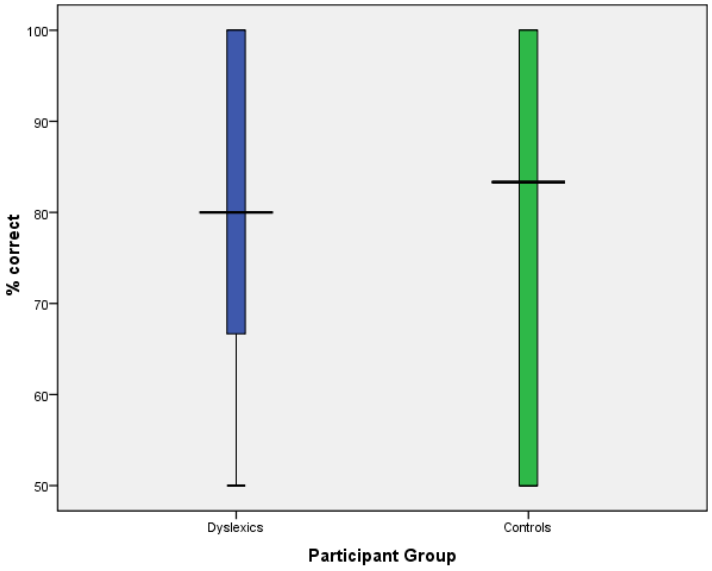


Figure 6-7 Performance of dyslexics vs. controls with 1/4 tone difference

6.6.2 Education's effect on tone discrimination thresholds

There were no discernible differences between the two educational groups in either the total results (Figure 6-8) or those with quarter tone differences (Figure 6-9). The two educational groups had significantly different IQ scores. The university educated participants had higher Full Scale IQ's than their counterparts who had not received tertiary education ($t = 4.904$, $df = 81$, $p < 0.000$). However, despite the difference in IQ scores and the high correlation between IQ and the task performance ($R= 0.289$, $p= 0.015$), the difference was not enough to produce any significant differences between the educational groups in the Discrimination task.

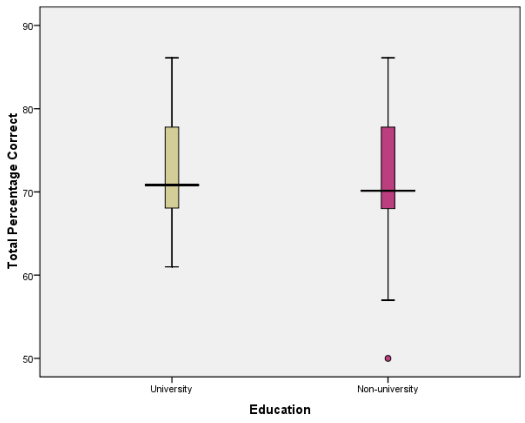


Figure 6-8 Total performance of university vs. non-university

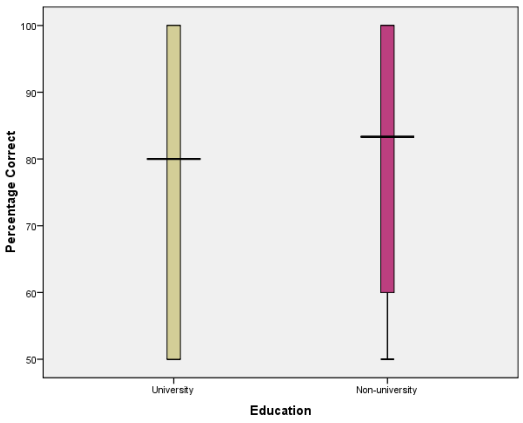


Figure 6-9 Performance of university vs. non-university with 1/4 tone difference

6.6.3 Correlations between the tasks

The combined result over all six trial types was subjected to Spearman's rho two-tailed correlations with the ability measures. The total number of correct responses correlated strongly with both the full scale IQ (R = 0.289, p = 0.015) and the literacy scores (R = 0.234, p = 0.000). The task also correlated with the musical ability and experiences of the participants (R = 0.234, p = 0.000).

When looking at the results from those trials with a quarter tone difference, the percentage correct correlates significantly with all IQ Index measures, except the Processing Speed Index (R = 0.138, p = 0.240), and all literacy measures. When controlling for the full scale IQ the ¼ tone performance maintains correlation trends with both reading (R= 0.173, p= .064) and spelling (R=0.153, P=0.089).

6.6.4 Memory

In those trials which differentiated between quarter tones, we see strong positive correlations with the WAIS Working Memory Index (R = 0.255, p=0.025) implying that the better their memory skills, the better their performance in this task. However this correlation is not maintained when controlling for IQ.

6.6.5 Psychometric group differences

The four different groups' performances in the attainment and ability tasks are compared in Table 6-7. This table makes it possible to see how much dyslexia can affect ability and then the effect education can have on the participants' psychometric performance. Luckily the groups show no differences in musical ability or handedness so any other group differences are not driven by these factors.

Table 6-7 Psychometric group differences

** = $p \leq 0.01$, * = $p \leq 0.05$, · = Trend $p \leq 0.1$, N.S. = Not significant $p \geq 0.1$.

Test	UD		UC		NUD		NUC		Between Group Differences	DvC	Uv NU	UD v NUD
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Sig.	Sig.	Sig.	Sig.
WAIS scores												
Vocabulary	14	2.3	14.82	2.6	11.4	3.4	10.89	2.2	.000**	-	.000	.004
Similarities	13.86	2.8	13.68	2.6	11.3	2.6	10.58	3.2	.000**	-	.000	.018
Arithmetic	11.91	3.1	12.68	2.9	9.15	3.2	10.47	3.1	.002**	-	.001	.024
Digit Span	9.86	3.1	11	3.4	8.4	2.0	9.84	2.9	.046*	.049	-	-
Information	14.09	2.0	14.18	2.1	12	2.1	10.89	2.8	.000**	-	.000	.002
L-N Sequencing	10.05	2.4	11.55	3.3	8.15	2.4	10.37	2.6	.001**	.003	.055	-
Picture Completion	11	3.3	10.5	2.8	10.65	2.5	9.58	2.3	.420	-	-	-
Digit Symbol Copy	9.95	2.5	11.36	3.0	7.75	2.4	10.11	2.8	.001**	.003	.005	.006
Block Design	12.82	1.5	12.14	2.9	12.85	2.9	10.53	1.9	.009**	.008	-	-
Matrix Reasoning	13.23	1.7	13.36	2.6	11.55	2.8	11.53	2.8	.020*	-	.004	.058*
Symbol Search	11.14	2.3	11.55	3.3	9.1	2.8	9.74	2.6	.017*	-	.001	.006
IQ scores												
Verbal IQ	117.0	13.4	121.2	14.3	103.8	12	103.4	11.8	.000**	-	.000	.002
Performance IQ	111.6	12.7	112.8	15.3	105.8	14.9	101.5	12.2	.037*	-	.005	-
Full scale IQ	117.2	13.1	118.9	14.7	105.0	11.1	102.7	10.9	.000**	-	.000	.006
WAIS Index scores												
VCI -Verbal Comprehension Index	123.4	12.2	124.0	13.5	109.0	12.8	104.0	12.2	.000**	-	.000	.001
POI - Perceptual Organisation Index	114.1	12.3	112.1	14.1	110.0	14.6	102.6	11.9	.043*	-	.023	-
WMI – Working Memory Index	104.2	14.7	110.7	17.9	91.0	12.1	100.8	13.5	.001**	.020	.005	.048
PSI – Processing Speed Index	103.5	11.7	107.3	15.8	91.1	12.2	99.3	13.4	.002**	.059	.001	.001
Literacy scores												
Reading	102.7	8.8	109.1	9.5	95.1	18.0	98.8	8.5	.002**	.059	.001	.067
Spelling	98.8	10.4	111.8	9.8	91.7	15.3	102.6	10.3	.000**	.000	.008	-
Questionnaire Percentages												
CAARS	43	11.3	37.91	13.4	47.25	14	34.21	14.8	.016*	.003	-	-
Music	39.91	23.6	47.41	29.4	41.15	24.2	39.58	20.8	.706	-	-	-
ADO	45.55	20.4	17.14	14.8	64.30	18.3	25.53	27.0	.000**	.000	.023	.011
Handedness	85.14	18.6	82.14	26.1	78.25	21.4	90.21	21.0	.466	-	-	-

6.7 Discussion - discrimination of incremental frequency differences

It was anticipated that the dyslexics would show a requirement for larger frequency gaps to adequately discriminate between two tones. However there were no significant group differences across the board.

There were however correlations. It seems that memory skills play a significant role in participants' abilities to perform the discrimination task during the intermediary trial types.

The weakness of this task was to use fixed frequency differences. Due to limitations of time the trial differences were limited to logarithmic reductions in frequency. This proved too large a difference as floor and ceiling effects skewed the data. For this reason many of the results were calculated using the quarter tone difference trials with the intermediary frequency difference. However, using this limited number of trials has meant that the variance in the scores is too wide for truly useful data. Thus it has been inconclusive as to whether the dyslexic deficit seen in the Simple Tone Discrimination Task is due to procedural effects or lower discrimination thresholds.

6.8 Discussion - psychometrics

The results Table 6-7 exhibits the group differences between the four groups. These psychometrics are the same as those in Tasks 4 and 6.

The groups were controlled to have equal musical experience (as assessed by a questionnaire; see Appendix A1.4) and numbers of left and right handers (handedness also assessed by questionnaire; see Appendix A1.3). Despite large effects of education on IQ scores the groups were balanced so that the dyslexics and control group did not differ in total IQ.

Diagnosis of dyslexia in adults relies upon deficits in the Working Memory Index (WMI) and the Processing Speed Index (PSI). Between the dyslexic and control groups the WMI is a significant difficulty for the dyslexics but the PSI shows only a trend difference. Reading and spelling performances are also anticipated to be more

difficult for the dyslexics. Interestingly reading shows only a trend difference whilst the spelling performance indicates a clear difficulty.

Spelling performance shows no significant differences between those dyslexics who have received a university education and those dyslexics who have not. This means that the difference seen between the university and non-university groups (dyslexics and controls combined) is driven by the differences between university and non-university controls. It seems that even those dyslexics who attend university cannot acquire the skills required for competent spelling despite almost achieving competent reading skills.

6.9 Conclusions - pure tone discrimination

In these studies we have two apparently contradictory findings. The initial two tone task found a dyslexia deficit whereas Task 2, discrimination of incremental frequency differences, did not. Having achieved such ceiling and floor results in the majority of the trial types of the second task, it was unsurprising that no distinguishable differences were seen. Having looked at the quarter tone differences alone there was too wide a variance between the results to see any significant differences although the control mean was slightly higher than that of the dyslexics.

Despite the inconclusive findings in the second task the first does show robust, significant differences between the two groups. These results support the theory that dyslexics do have more difficulties discriminating between two tones than their control counterparts at discriminating semitone differences. There is the possibility that the reduced memory skills seen in dyslexia may be playing a causal role.

7 Interstimulus interval length effects

7.1 Rationale for tasks

These tasks were created to see what difference interstimulus lengths would have on dyslexics' performance of tonal discrimination, whether they would benefit from a longer consolidation time than the controls, or whether temporal processing deficits would inhibit the processing of tones with short intervals. Task 3 was performed only on university educated participants, assessing discrimination across three different long interstimulus intervals. The second, Task 4, was performed on four groups with dyslexics and controls both with and without tertiary education. This second interval task analysed logarithmic increases in interval times, starting with much shorter intervals than used in Task 3. It was predicted that dyslexics would have increased problems with very short intervals.

7.2 Task 3: Methods - testing three long ISI lengths

7.2.1 Design

This task was designed to assess the encoding ability of dyslexics in comparison to that of controls when exposed to three different long interstimulus interval lengths. A simple two tone frequency discrimination task detects their ability to tell the difference between the two tones under three different time conditions.

7.2.2 Participants

In total 46 individuals participated in this study, all participants of this study had reached a university education:

- A group of 24 current or previous university students, diagnosed by an educational psychologist as dyslexic. Henceforth 'dyslexics'.
- A group of 22 current or previous university students, who did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties. Henceforth 'controls'.

Table 7-1 Participant discriptive statistics

Participant Group	Total Number	Male/Female	Age Range	Mean Age	SD	Median Age	IQR
Dyslexics	24	12/12	19-26	21.25	1.78	21	2
Controls	22	10/12	18-23	19.91	1.07	20	1

7.2.3 Materials

The participants completed four of the batteries' questionnaires: the Connors' adult ADHD rating scale (CAARS), Adult Dyslexia Questionnaire (ADO), the Annett Handedness Questionnaire and the Musicality Questionnaire.
The experimental programme was designed in Borland C++ to run under DOS, and the stimuli individually created using Praat. For full details of the programme see Appendix A2.2.

7.2.3.1 Measures of cognitive ability

Participants performed the 12 subtests of the Wechsler Adult Intelligence Scale - Third edition (WAIS III UK) required for the four ability indices.

7.2.3.2 Measures of literacy ability

The participants were administered the Single Word Reading and Spelling subtests of the Wide Range Achievement Test (WRAT 3) and the three Castles and Coltheart (C&C) single word reading lists. With this task an additional passage comprehension task Woodcock Reading Mastery Tests – Revised (WRMT-R) was included to investigate whether dyslexic adults manage to attain competent passage comprehension despite accuracy problems.

7.2.4 Procedure

In their own time, participants heard 180 pairs of 150ms tones and were asked to detect whether the two tones were the same or different. The stimuli were made with two tones. A fixed initial target tone of 880Hz was followed by a silent interval of varying length; 1000, 2000 or 3000ms. After the interval the comparison tone stimulus was presented, either the same frequency or, with equal probability, a semi-tone higher or lower than the target tone.

The order of the same or different trials was randomised on a subject-by-subject basis. To indicate whether the target and comparison tones were the same or different participants used the 'Y' key to indicate 'yes they were the same' or 'N' key to indicate 'no they were different' before initiating the next trial. The participants read the instructions along with the administrator who answered any questions they may have had (Figure 7-1).

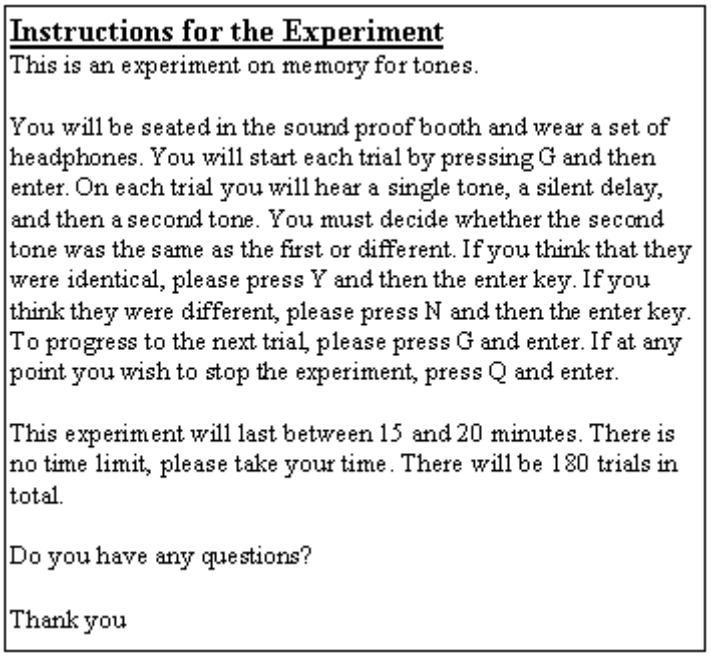


Figure 7-1 Instructions

7.3 Results - three Long ISI Lengths

7.3.1 Descriptive statistics

The Kolmogrov-Smirnov tests of normality indicated that none of the experimental data sets from this task were normally distributed. Thus nonparametric tests have been used in these analyses, with the exception of the analysis of variance which is sufficiently robust to be used with this data set.

7.3.2 Analysis of variance

This analysis revealed a trend difference between dyslexics and controls ($F = 3.034$, $p = 0.084$). The differences between the interstimulus interval lengths were not enough to show any differences and the strength of the dyslexia effect was not maintained when the three intervals were combined.

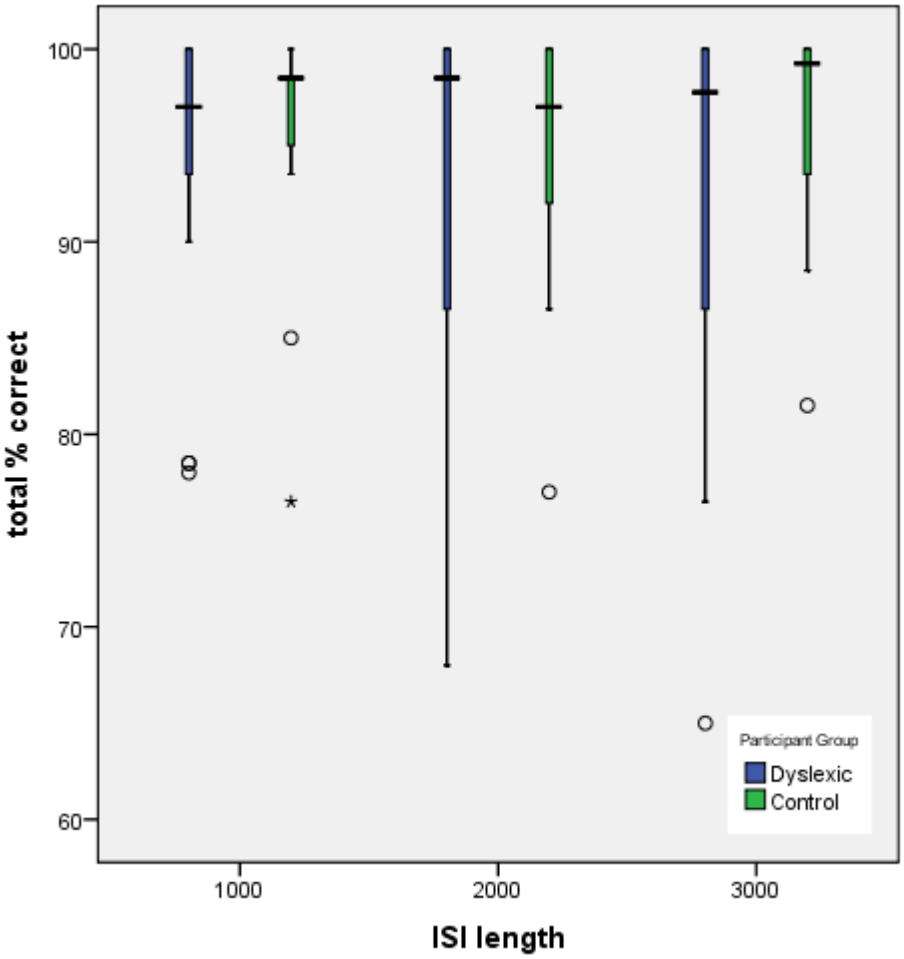


Figure 7-2 Group differences at three different long intervals

7.3.3 Correlation analysis

The overall pitch task results correlated with those elements of the psychometric battery renowned for being the least affected by dyslexia. There was a significant correlation between the results and the Block Design task, the Matrix Reasoning task and the picture arrangement task.

After controlling for FSIQ the strength of the correlations was reduced leaving trend correlation between the total performance and the Spelling task ($p = 0.064$); but a strong negative correlation between total performance and the memory task, Arithmetic, appeared ($R = -0.496$, $p = 0.002$).

Table 7-2 Correlations
** = Correlation p ≤ 0.01, * = Correlation p ≤ 0.05, ・= Trend p ≤ 0.1, N.S. = Not significant p ≥ 0.1.

Experimental	Task	Correlation Coefficient	Two Tailed
Overall correct correlates with	Block Design	0.351	0.028*
	Matrix Reasoning	0.496	0.001**
	Picture Arrangement	0.332	0.036*
ISI = 1000 correlates with	Spelling	0.263	0.088・
	Irregular reading (orthographic skills)	0.305	0.049*
	Non-word reading (Phonological skills)	0.313	0.043*
	Block Design	0.444	0.005**
	Matrix Reasoning	0.495	0.001**
	Picture Arrangement	0.356	0.024*
	Vocabulary	0.311	0.054・
	Digit Span	0.278	0.086・
	Comprehension	0.341	0.027*
ISI = 2000 correlates with	Matrix Reasoning	0.536	0.000**
	Vocabulary	0.270	0.097・
	Digit Span	0.273	0.093・
ISI = 3000 correlates with	Non-word reading (phonological skills)	0.296	0.057・
	Matrix Reasoning	0.451	0.004**
	Picture Completion	0.368	0.020*
	Picture Arrangement	0.368	0.020*

The three different interstimulus interval lengths all correlate significantly to each other and to the overall result.

Table 7-3 Internal correlations
** = Correlation p ≤ 0.01, * = Correlation p ≤ 0.05, (two-tailed)

	% Correct ISI 1000	% Correct ISI 2000	% Correct ISI 3000	Total % correct
% Correct ISI 1000	-	0.735 **	0.741**	0.365*
% Correct ISI 2000		-	0.735**	0.573**
% Correct ISI 3000			-	0.487**

7.3.4 Psychometrics

The ability and attainment differences between the two groups are portrayed in the table below.

Table 7-4 Group differences
** = p ≤ 0.01, * = p ≤ 0.05, ° = equal variances' not assumed.

Test	University Dyslexic		University Control		T-test significance
	Mean	***S.D.***	***Mean***	***S.D.***	
WAIS Scores					
Picture Completion	13.11	2.279	12.5	2.445	Not Significant
Digit Symbol	10.59	3.306	12.41	2.053	°0.001**
Block Design	13.47	3.568	13.73	3.041	Not Significant
Matrix Reasoning	13.24	2.534	13.5	2.501	Not Significant
Picture Completion	11.06	2.804	10.95	2.984	Not Significant
Symbol Search	10.56	3.124	11	2.614	Not Significant
Object Assembly	10.78	2.062	11.77	2.486	0.020*
Vocabulary	14.71	2.935	14.86	2.688	Not Significant
Similarities	15.56	2.478	13.73	2.109	0.000**
Arithmetic	13.05	2.936	13.91	1.895	0.054
Digit Span	10.18	2.840	12	3.696	°0.003*
Information	14.58	2.434	14.82	1.889	Not Significant
Comprehension	14.90	2.468	15.09	2.467	Not Significant
Letter-Number-Sequencing	9.67	3.120	12.62	3.149	0.000**
Literacy Scores					
Reading	104.14	12.331	111.59	7.932	°0.000**
Spelling	102.71	16.724	114.64	6.513	°0.000**
Passage Comprehension	60.67	5.058	62.37	2.273	°0.026*

7.4 Discussion - three long interstimulus interval lengths

The dyslexics discriminated a semitone difference worse than the controls when the results of the three interval lengths were combined. Their performance varied more widely and they produced more of the lower scores than controls. Both groups had such high mean averages that no significant mean differences could be seen.

All participants had received higher education, the majority of whom had attended the University of Oxford and represent the highest of academic achievers. It can be seen in the psychometric differences that the cognitive scales, especially the verbal

subtests, were well above the national averages. What we can see is that the dyslexics performed significantly worse than the controls in the literacy tasks, processing speed subtests and working memory subtests. Interestingly the dyslexics performed significantly better on the verbal test, Similarities. This task requires participants to find the association between seemingly dissimilar items. This subtest may give insight into the skills used by dyslexics to perform at the highest levels, despite their literacy deficits.

As the task was performed using a semitone difference, as was Task 1 in Chapter 5, it may be advisable that if the task was re-performed a quarter tone difference should be used to give a larger variation in the scores, pulling the mean performances away from the ceiling, which may enable the detection of mean differences in addition to variance differences.

7.5 Task 4: Methods - effects of incremental interval length increases

7.5.1 Design

This task was designed to investigate the effects of shorter intervals on tonal discrimination in dyslexics, comparing university educated participants against non-university participants. It was anticipated that this task would reveal the optimal duration between the exemplar and test tones for the participants to detect whether they were the same or different. In response to Tallal's theories it is anticipated that dyslexics will show the largest deficits in comparison to controls with the shortest intervals. As a semitone difference gave near ceiling effects in the last task the differences have been reduced to quarter tones.

7.5.2 Participants

Four groups of individuals (amounting to 81) participated in this study;. This is the same body of participants who participated in Task 2, the roving two tone discrimination task in the second half of Chapter 5:

- A group of 20 current or previous university students, diagnosed by an educational psychologist as dyslexic, henceforth 'university dyslexics' (UD).

- A group of 22 current or previous university students who did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties, henceforth ‘university controls’ (UC).
- A group of 20 adults who did not attend tertiary education with no plans to attend in the future. They had been diagnosed by an educational psychologist as dyslexic or else had a distinct dyslexic profile in the psychometric battery and had a history of learning difficulties, henceforth ‘non-university dyslexics’ (NUD).
- A group of 19 adults who did not attend tertiary education with no plans to attend in the future. They did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties, henceforth ‘non-university controls’ (NUC).

Table 7-5 Participant descriptive statistics

Participant Group	Total Number	Male / Female	Age Range	Mean Age	S.D.	Median Age	I.Q.R.
UD	20	11 / 9	18 – 44	25.9	7.7	22.5	6
UC	22	7 / 15	19 – 42	25.4	6.1	24.5	9
NUD	20	13 / 7	17 – 44	29.9	10.0	26.5	20
NUC	19	5 / 14	18 – 48	29.0	10.2	23.0	18

7.5.3 Exclusion criteria

Three control participants were removed from the study and not included in the numbers above. Two were removed due to a failure in the audiometric assessment and one for having had a distinct pattern of symptoms in the psychometrics which would indicate another learning disorder, in this instance ‘non-verbal processing disorder’.

7.5.4 Materials

The participants completed four of the batteries’ questionnaires: the Connors’ adult ADHD rating scale (CAARS), Adult Dyslexia Questionnaire (ADO) the Annett Handedness Questionnaire and the Musicality Questionnaire.
Full details of the programme, designed in Borland C++ to run under DOS, can be seen in Appendix A2.1.

7.5.4.1 Measures of cognitive ability

Each participant was administered an extensive battery of psychometrics. These included: the 12 subtests of the Wechsler Adult Intelligence Scale - Third edition

(WAIS III UK) used to ascertain the four ability indices and the Random Automatised Naming (RAN) tests.

7.5.4.2 Measures of literacy ability

The participants performed the Single Word Reading and Spelling subtests of the Wide Range Achievement Test (WRAT 3) and Castles and Coltheart (C&C) single word reading lists.

7.5.5 Procedure

Participants carried out 70 trials during which one of three target tones was played, followed by a silent interstimulus interval of varying length before a comparison tone. 50% of the comparison tones were identical to the target, 25% differed by a quarter tone higher and 25% differed a quarter tone lower.

Table 7-6 Target and comparison tone frequencies

Target tone	Comparison tone	
	UP	**DOWN**
261 Hz	269.28	254.17
369 Hz	380.79	359.43
587 Hz	604.41	570.50

The six varying intervals ranged from 50ms to 1600ms incrementing in logarithmic steps. The participants read the instructions along with the administrator who answered any questions they may have had (Figure 7-3). In each trial after the stimulus the participant indicated whether the target and comparison tones were the same or different using the ‘S’ or ‘D’ key respectively before initiating the next trial.

Varying Interstimulus Interval Task

In this task your role is to indicate, for each trial, whether two target tones are the same or different.

In this task the two tones are always either identical or a quartertone different. The silence between the two tones varies in length.

To start each trial you press 'C'. Listen to the two target tones then if you think they are the same hit 'S' or hit 'D' if you think they are different. To continue to each next trial press 'C'.
At the end of any trial you can hit 'E' instead of 'C' to exit the experiment if you so wish.

There are 70 trials in total and the experiment should take around 4 minutes. Half of the trials are the same and half of them are different.

Do you have any questions?

Figure 7-3 Instructions

7.6 Results - effects of incremental interval length increases

The results were not normally distributed. For this reason non-parametric tests were used for the majority of the analysis. However parametric analysis of variance was performed as it is sufficiently robust to use with these data sets. The psychometric performance of these participants can be seen in the results of Task 2, the simple two tone discrimination task in Chapter 5.

7.6.1 Different interstimulus intervals effect on dyslexics

There was a trend difference between the groups in when combining the effects of dyslexia and educational differences ($f = 3.222$, $p = 0.073$). The largest differences were from the increased performance in the dyslexics who had received higher education. There were no significant differences between the group scores of any of the four participant groups.

The discrimination performance correlated with the participants' IQ scores ($R = 0.417$, $p < 0.000$) and also with their literacy scores ($R = 0.429$, $p = 0.000$) and participants' musical experience ($R = 0.493$, $p = 0.000$). The performance negatively correlated with the CARS questionnaire results ($p < 0.041$) and in the longer intervals there were correlations with the ADO questionnaire results, at 400ms ($R = -0.248$, $p =$

0.025), 800ms (R = -0.221, p = 0.047) and a trend correlation at 1600ms (R = -0.201, p = 0.072).

Table 7-7 Correlations,
** = Correlation $p \leq 0.01$, * = Correlation $p \leq 0.05$, ・ = Trend $p \leq 0.1$, N.S. = Not significant $p \geq 0.1$, ۞ = *correlations that remain significant when controlling for IQ.*

	Task	Rho	Two tailed
Combined Results correlate with:	FSIQ	.417	.000**
	VCI	.376	.001**
	POI	.337	.003**
	WMI	.432	.000**
	Literacy	.429 ۞	.000**
	Reading	.491 ۞	.000**
	Spelling	.299 ۞	.007**
	Music Experience	.493 ۞	.000**
	ADO Questionnaire	-.198	.040*

All the correlations above were performed with the total performance over the task. There were no interesting differences between the individual trial interstimulus interval lengths; however it was very clear that all the above correlations were driven by the correlation between the task in question and the results from those trials where there was a difference between the tones. When the target and comparison tones were the same the results evoked no correlations.

When the correlations were performed on only the university educated participants, IQ only correlated with the two shortest intervals of 50 (R = 0.311, p =0.048) and 100ms (R =0.392, p = 0.011).The correlations with literacy scores was only seen in the two longest intervals. The negative correlations with the ADO score were lost and the correlation between the results and the CARS was only seen at the 50ms (R = -0.326, p = 0.037) and the 1600ms (R = -0.37, p = 0.017) intervals. The non-university participants however maintained a strong correlation with IQ ($p < 0.05$) and literacy scores ($p < 0.05$) and continued to show negative correlations with the ADO questionnaire and also the CARS questionnaire at the longer intervals.

7.6.2 Short interstimulus interval effect on discrimination

There were no differences in the performance or variance between the different time intervals. Correlations between the attentional attributes questionnaire and the discrimination performances were only significant in the trials with the longer

interstimulus intervals. As shown in Figure 7-4 it appears that the performance of the groups is less erratic at the longer interstimulus lengths. At the shorter intervals (<200ms) it appears that the university dyslexics perform better than the other groups however this is not a statistically significant finding.

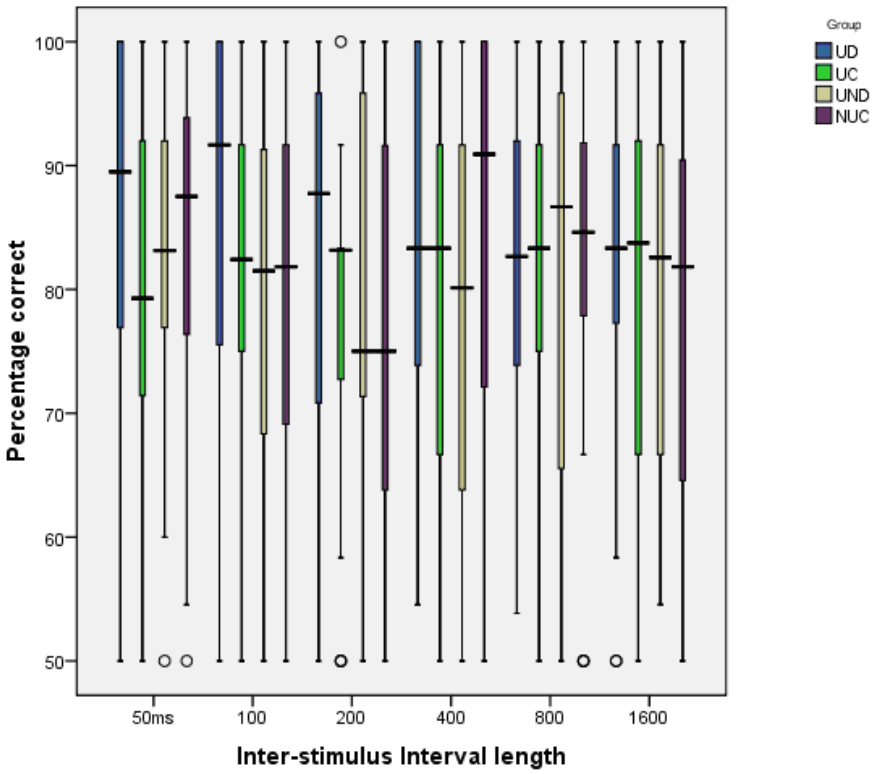


Figure 7-4 Box plots of group perfromance differences

When the performance in the six different interstimulus lengths are combined it can be seen that the two participant groups did not differ in performance. The variances within the scores for the two groups are also too similar for any distinguishable differences.

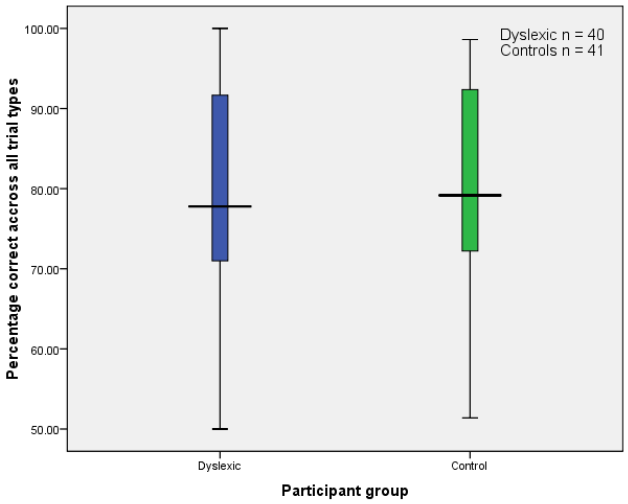


Figure 7-5 Boxplots of dyslexic and control differences

7.7 Discussion - effects of interval length increases

There were no significant differences in the abilities of the groups when discriminating a quartertone difference at each of six different interval lengths. There did seem to be a slight university dyslexic advantage at the shorter intervals; however this was not significant. If the task were to be re-administered it would be interesting to have more of the shorter intervals as Tallal works with intervals below 100ms and it would have been interesting if we had had more trials of this type. A more recent paper by Lewandowska *et al.* (2008) report that temporal order deficits are only indistinguishable if interstimulus intervals are as little as 30ms.

The task did show correlations with literacy scores independent of total IQ. This implies that the basic auditory discrimination skills may be a prerequisite skill for learning to read and write. Also, it does appear that using a quartertone difference rather than the semitone difference has enabled the mean performance to be drawn away from the ceiling effects seen in the last chapter.

7.8 Conclusions - interval effects

The dyslexics showed more low scores than the controls at the longer interstimulus lengths. This indicates a reduced performance in at least a subgroup of the dyslexics, though it is still unclear if this subgroup is definable in any other way. A similar conclusion was made by Hill *et al.* (1999) and Lachmann *et al.* (2005) after they found frequency discrimination deficits in a subgroup of dyslexic listeners. Roach and colleagues point out how many dyslexic psychophysical differences have been found

to be driven by just a small group of under-performing dyslexics. They claim that those studying perceptual deficits should place more emphasis on differences at the level of the individual observer (Roach *et al.*, 2004).

At the shorter interstimulus intervals equal to or less than one second, the university dyslexics appeared to be performing better than the other three groups. The cognitive strategies required for dyslexics to achieve tertiary education may develop compensatory skills during the fast encoding of information. This may imply that Tallal's temporal processing theories of dyslexia only apply to a small subgroup of dyslexics; from these results one would expect that the subgroup is likely to be closest to the non-university dyslexic group. However Tallal performs the majority of her studies on children and is unclear on the educational backgrounds of her adult participants.

It may prove interesting to test at more of the shorter intervals than were used here, to further investigate the differences between the educational groups within the dyslexic group. It would suggest that only those who do not achieve tertiary education may support Tallal's views of fast speed deficits in dyslexia.

However both Tasks 3 and 4 showed IQ independent correlations with literacy skills. This adds further support to the view that auditory discrimination abilities are indeed essential for developing reading and spelling skills.

8 Distraction during tonal discrimination

8.1 Rationale for tasks

Thus far tasks have used a simple two tone comparison paradigm. In this chapter the memory function of the encoding of the initial target tone is investigated. Distractor tones were used to interrupt the encoding process.

It is predicted that dyslexics should be affected more by distractors during the discrimination task. Because of their tonal discrimination problems I predicted that they would experience more problems than the controls with the disrupted memory encoding. In the first task (Task 5) there were five distracting tones at a fixed time location during the interstimulus interval. In the second task (Task 6) a single interrupting tone was played at one of three different time positions during the interstimulus interval. The position of this interruption is anticipated to do less damage if the participant is given more time to encode the target tone before the interruption.

Again, for the second of the two tasks the participant groups distinguished between those who stayed in education for a university degree and those who were not university educated. In this way I hoped to see how the different groups developed.

8.2 Task 5: Methods - pitch discrimination with five distractor tones

8.2.1 Design

This task was created to assess the abilities of dyslexics and controls, to distinguish one tone from another, when interrupted by a sequence of irrelevant distracting tones. A simple two tone frequency discrimination task used a roving exemplar tone to analyse the frequency gap threshold required to detect differences between the two tones. I hypothesised that dyslexics' discrimination ability would be more disrupted than that of controls.

8.2.2 Participants

In all, 33 individuals with mixed educational achievements participated in this study; this was the same group (with the exception of two control participants) who participated in Task 1, the two tone discrimination task in Chapter 6:

- A group of 26, diagnosed by an educational psychologist as suffering from the learning difficulty dyslexia, henceforth ‘dyslexics’.
- A group of 30 who did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties, henceforth ‘controls’.

Table 8-1 Participant descriptive statistics

	Total Number	Male/Female	Age Range	Mean Age	SD	Median Age	IQR
Dyslexics	26	13/13	18-41	23.9	6.4	21.5	3
Controls	30	12/18	16-30	20.1	2.8	19	6

8.2.3 Measures of cognitive ability

Each participant was administered a limited battery of psychometrics. These included; six subtests of the Wechsler Adult Intelligence Scale - Third edition (WAIS III UK); Vocabulary, Similarities, Block Design, Symbol Search, Digit Span and Picture Arrangement. Also included were the Random Automatised Naming (RAN), object and digit tests.

8.2.4 Measures of literacy ability

Participants performed the Single Word Reading and Spelling subtests of the Wide Range Achievement Test (WRAT) and Castles and Coltheart (C&C) single word reading lists.

8.2.5 Procedure

In their own time, participants undertook 50 trials in a fixed sequence. In total each trial was 3500ms long. The 150ms target tone was followed by a 2000ms silent delay before five irrelevant tones interrupted the interval before the comparison tone. The irrelevant tones were all 150ms spaced at 50ms intervals. After the five interrupting tones there was a further 250ms silence before the final comparison tone. For 26 of the trials the comparison tones were identical to the target, 12 differed by a frequency one semitone up and 12 differed by a frequency one semitone down. Participants were asked to detect whether the two tones were the same or different. The five intervening

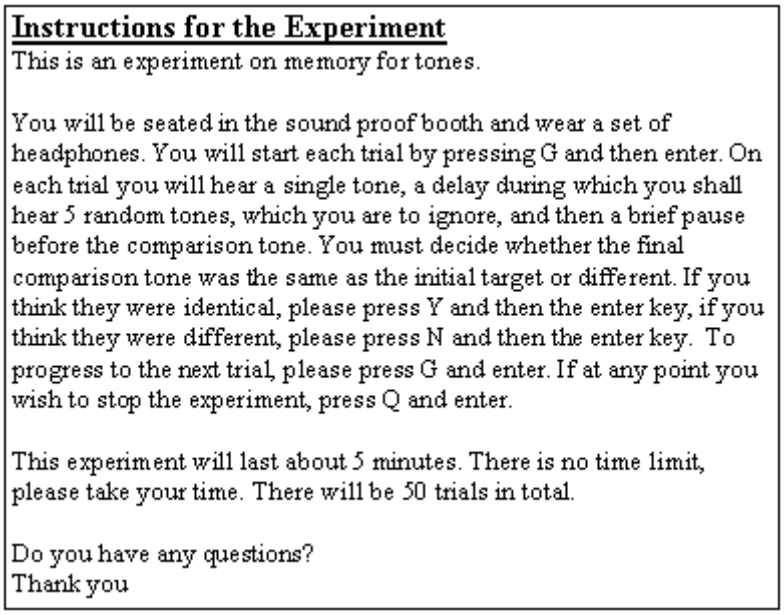
tones were taken at random from a pool of tones controlled so as never to include the target tone or any frequency a tone higher or lower.

Table 8-2 Target and comparison tone frequencies

Target tone	Comparison tone	
	DOWN	UP
440	415	466
523	494	554
622	587	659
740	698	784
880	831	932

Participants controlled the initiation of each individual trial with a key press. The participants were asked to attend to the first and last tones ignoring the five intervening tones. After each stimulus the participant indicated whether the target and comparison tones were the same using the 'Y' key to indicate 'yes they were the same' or the 'N' key to indicate 'no they were different' before initiating the next trial.

The participants read the instructions along with the administrator who answered any questions they may have had (Figure 8-1). The participants performed the task in their own time initiating each trial independently.



Instructions for the Experiment

This is an experiment on memory for tones.

You will be seated in the sound proof booth and wear a set of headphones. You will start each trial by pressing G and then enter. On each trial you will hear a single tone, a delay during which you shall hear 5 random tones, which you are to ignore, and then a brief pause before the comparison tone. You must decide whether the final comparison tone was the same as the initial target or different. If you think they were identical, please press Y and then the enter key, if you think they were different, please press N and then the enter key. To progress to the next trial, please press G and enter. If at any point you wish to stop the experiment, press Q and enter.

This experiment will last about 5 minutes. There is no time limit, please take your time. There will be 50 trials in total.

Do you have any questions?
Thank you

Figure 8-1 Instructions

8.3 Results - discrimination through five distracting tones

The Kolmogrov Smirnov test of normality showed that the results from the discrimination task were normally distributed. Therefore a parametric analysis was performed on this data. The results of the psychometrics are the same as those in Task 1, the two tone discrimination task in Chapter 5, detailed in Table 6-4.

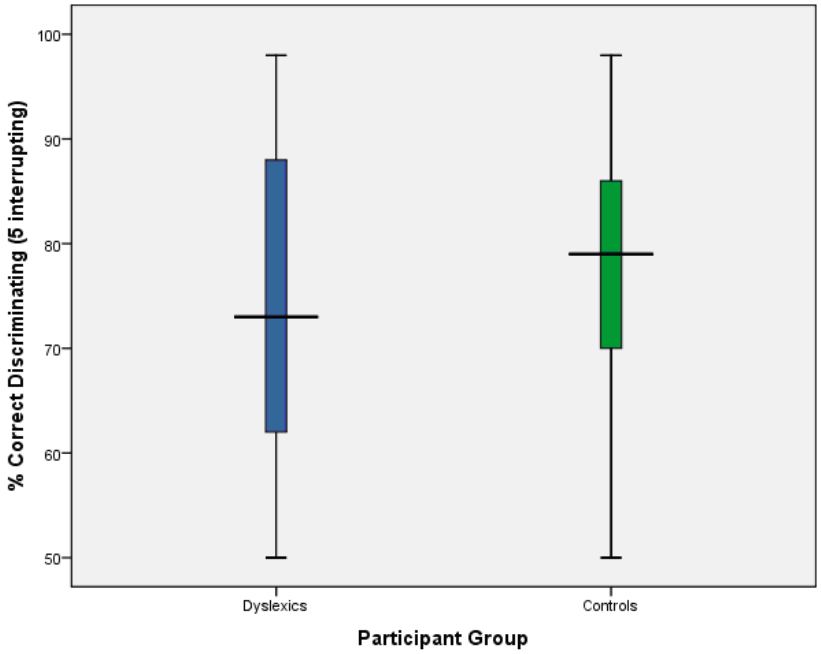


Figure 8-2 Group differences in discrimination task with five interrupting tones.

Although the difference was not statistically significant, dyslexics showed worse discrimination than controls during the distraction paradigm.

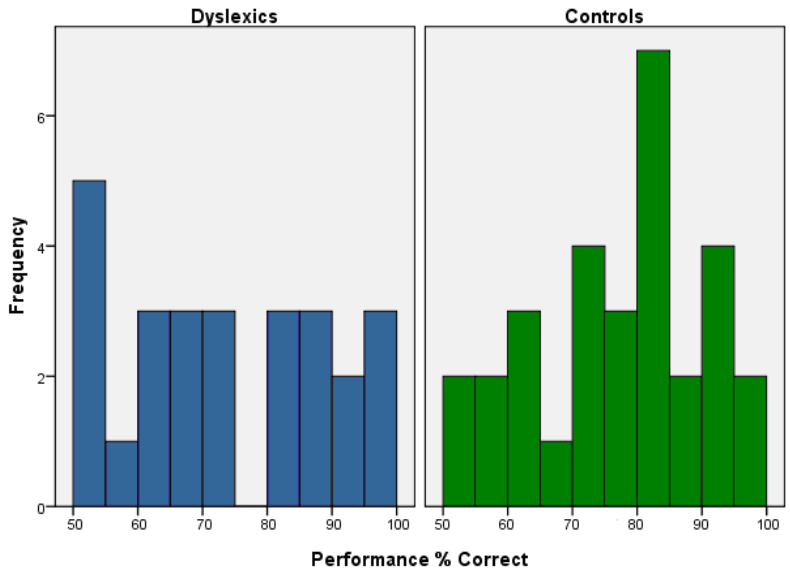


Figure 8-3 Group performance frequencies

Looking at the discrimination performance we can see that the controls' distribution was closer to normal whereas the dyslexics showed poorer performances. Despite the limited number of psychometrics performed on these participants clear correlations were found.

Table 8-3 Correlations
** = Correlation $p \leq 0.01$, * = Correlation $p \leq 0.05$, · = Trend $p \leq 0.1$, N.S. = Not significant $p \geq 0.1$.

Task Performance correlated with	Task	Correlation	Two tailed
	Musical ability	0.557	0.006**
	Similarities	0.402	0.010*

However neither of the above correlations remained significant after controlling for IQ.

8.4 Discussion - discrimination through five distracting tones

Though Figure 8-2 shows dyslexics as demonstrating a poorer performance in this task the results did not reveal any significant difference between the dyslexics and the controls. However there is an interesting observation in the differences between this task and Task 1, two tone discrimination of a semitone, detailed in the first half of Chapter 6.

The paradigms were very similar with the only variant being the inclusion of interfering tones. The presence of these distracting tones removed the significant

difference found in the initial simpler task, probably because the task was harder for both dyslexics and controls.

However the two tasks do correlate significantly with each other. Spearman' rho correlation indicates the two tasks correlate together with a correlation coefficient of 0.626** (two-tailed; $p \leq 0.000$). This correlation is still maintained as a trend, after controlling for IQ ($p = 0.065$).

Table 8-4 Correlations

** = Correlation $p \leq 0.01$, * = Correlation $p \leq 0.05$, · = Trend $p \leq 0.1$, N.S. = Not significant $p \geq 0.1$.

	Two-tailed		
	Pearson's	**N**	**Sig.**
Dyslexics	0.617	26	0.001**
Controls	0.529	30	0.003**

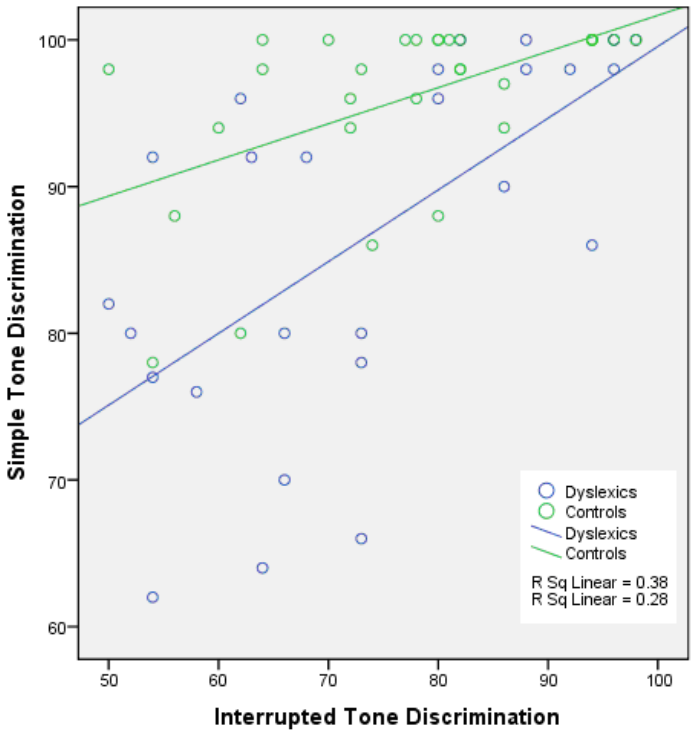


Figure 8-4 Correlations for simple and interrupted discrimination

This difference in performance between the two different tasks implies that dyslexics coped relatively better with the distracting tones than the controls. This may be because dyslexics have to apply more effort to acquire the same literacy skills than controls have to. This may require more effort in sustained attention during education and thus mean dyslexics have more practice at blocking unhelpful stimuli.

8.5 Task 6: Methods - single roving distractor

8.5.1 Design

This task was designed to investigate abilities in tone discrimination when the process was interrupted by a single irrelevant tone, comparing university educated with non-university participants. It was anticipated that dyslexic groups would be more distracted by the interrupting tone than the control group and that the more educated groups would better withstand the distraction.

The distracting tone was positioned in one of three places to further investigate possible forwards and backwards masking effects, anticipating increased backwards masking effects in the dyslexic participants.

8.5.2 Participants

Four groups of individuals (amounting to 81) participated in this study; this is the same body of participants who participated in Tasks 2 and 4:

- A group of 20 current or previous university students, diagnosed by an educational psychologist as dyslexic. Henceforth ‘university dyslexics’ (UD).
- A group of 22 current or previous university students who did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties. Henceforth ‘university controls’ (UC).
- A group of 20 adults, who did not attend tertiary education with no plans to attend in the future. These adults had been diagnosed by an educational psychologist as dyslexic or else had a distinct dyslexic profile in the psychometric battery and had a history of learning difficulties. Henceforth ‘non-university dyslexics’ (NUD).
- A group of 19 adults who did not attend tertiary education with no plans to attend in the future. They did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties. Henceforth ‘non-university controls’ (NUC).

Table 8-5 Participant descriptive statistics

Participant Group	Total Number	Male/Female	Age Range	Mean Age	SD	Median Age	IQR
UD	20	11 / 9	18 – 44	25.9	7.7	22.5	6
UC	22	7 / 15	19 – 42	25.4	6.1	24.5	9
NUD	20	13 / 7	17 – 44	29.9	10.0	26.5	20
NUC	19	5 / 14	18 – 48	29.0	10.2	23.0	18

8.5.3 Materials

The participants completed four questionnaires: the Connors' adult ADHD rating scale (CAARS), Adult Dyslexia Questionnaire (ADO), the Annett Handedness Questionnaire and the Musicality Questionnaire.

The experimental programme was designed in Borland C++ to run under DOS, and the stimuli individually created using Praat, for full details of the programme see Appendix A2.1.

8.5.4 Measures of cognitive ability

Each participant was administered an extensive battery of psychometrics. These included; the 12 subtests of the Wechsler Adult Intelligence Scale - Third edition (WAIS III UK) used to ascertain the four ability indices, and the Random Automatised Naming (RAN) tests.

8.5.5 Measures of literacy ability

As in the full assessment battery, participants were given the Single Word Reading and Spelling subtests of the Wide Range Achievement Test (WRAT) and all three of the Castles and Coltheart (C&C) single word reading lists.

8.5.6 Procedure

Participants were exposed to 129 auditory stimuli, each consisting of three tones; a target, comparison and one distractor tone. 50% of the comparison tones were identical to the target, 25% differed by a quarter tone higher and 25% differed a quarter tone lower.

Table 8-6 Target and comparison tone frequencies

Target tone	Comparison tone	
	DOWN	UP
261 Hz	-	269.28
293 Hz	285.29	302.25
329 Hz	320.22	339.96
369 Hz	359.43	380.79
415 Hz	403.43	427.42
466 Hz	452.83	479.75
523 Hz	508.27	538.48
587 Hz	570.50	604.41
659 Hz	640.34	678.41
739 Hz	718.75	761.47
830 Hz	806.74	-

The distractor tone was chosen from the same pool of tones as the target and comparison tones, excluding the target itself or either of the tones one higher or one lower. All the tones included in this task were 50ms in duration.

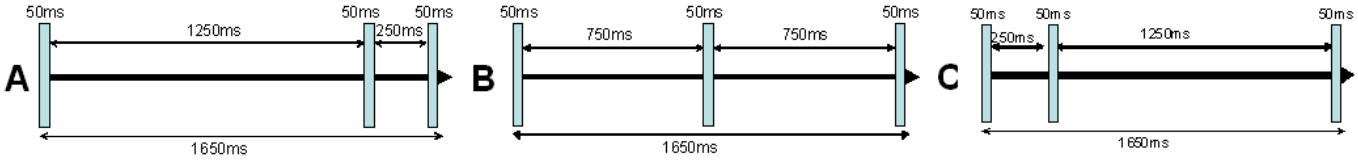


Figure 8-5 Stimuli profiles

The distractor tone interrupted the 1550ms interval between the target and comparison tones after 1250ms, 750ms or 250ms (Figure 8-5). The analysis was performed individually for the three distracting positions to detect any forward or backward masking effects. The participants read the instructions along with the administrator who answered any questions they may have had (Figure 8-6). The participants performed the task in their own time initiating each trial independently.

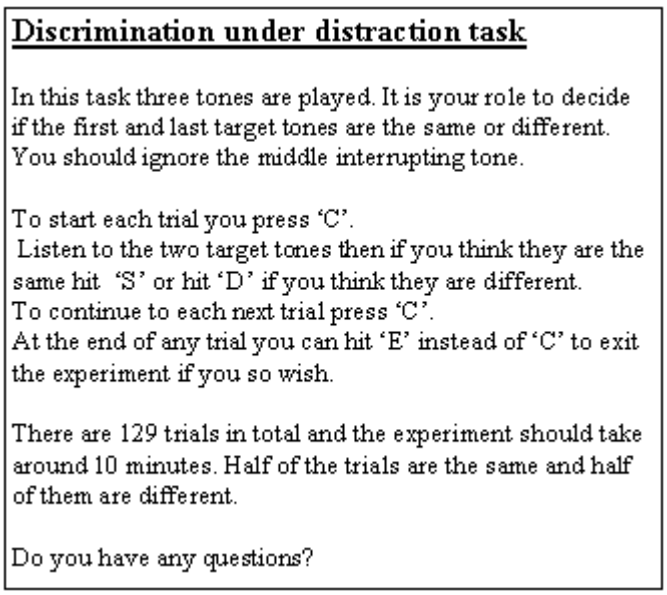


Figure 8-6 Instructions

8.6 Results - single roving distractor

The results were not normally distributed, but truncated to the left, as 20% of participants performed at floor. For this reason non-parametric tests were used for the majority of the analysis. Only parametric analysis of variance was performed as it is robust enough to use with these data sets. The results for the psychometric analysis of these participants are the same as that detailed in Chapter 5 as it is the same participant group.

8.6.1 Dyslexia's effect on tone discrimination during distraction

There was a significant difference between the performance of dyslexics and controls. Analysis of variance showed a significant difference between dyslexics and controls ($f = 4.398$, $p = 0.037$). Interestingly however, the group difference was driven by a superior dyslexic performance in comparison to the controls (see Figure 8-7).

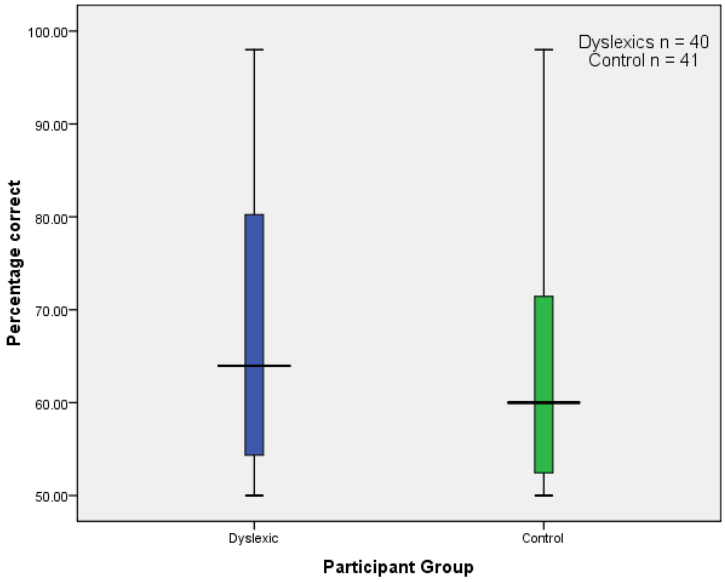


Figure 8-7 Group performance differences in task

Correlations between participants' discrimination performance and their literacy skills support the developing idea that tone discrimination skills are involved in the development of literacy skills. The data combined over the three trial types subjected to a Spearman's rho correlated with both phonological accuracy ($R = 0.328$, $p < 0.000$) and speed ($R = 0.735$, $p = 0.001$) in Castles and Coltheart's non-word reading test. The correlation analysed individually was stronger with the dyslexics than with the controls.

For each participant a discrepancy score was calculated using the literacy skills against general ability. The discrepancy scores showed no relationship to the total percentage correct; however after controlling for IQ negative trend correlations were found between discrepancy scores and the total percentage correct ($R = -0.186$, $p = 0.099$) and between the third trial type ($R = -0.194$, $p = 0.085$) where the distraction occurred after 1250ms, the shortest consolidation interval.

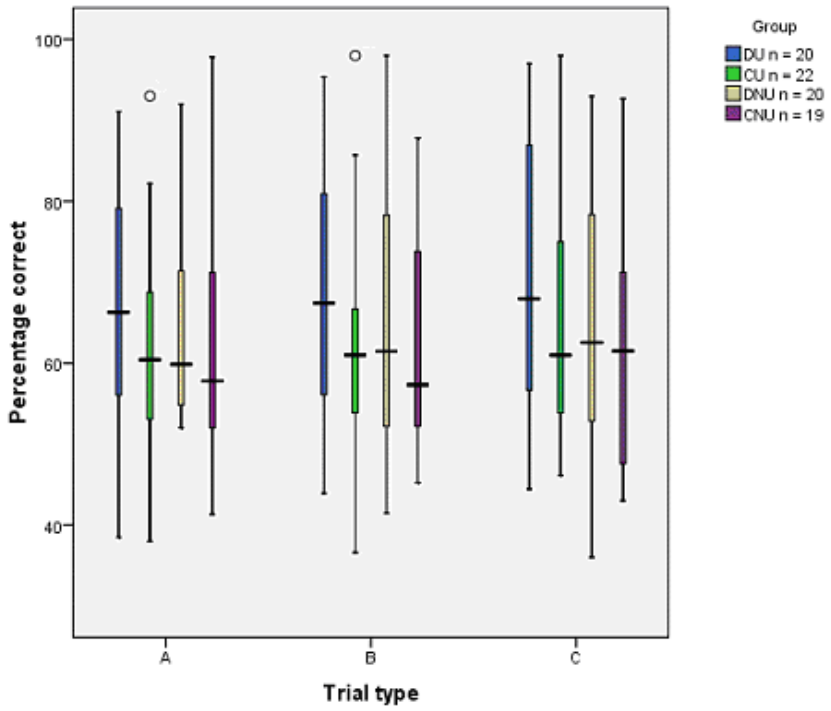


Figure 8-8 Performance of subgroups by trial type

8.6.2 Education's effect on tone discrimination during distraction

There were no differences in the performance between the university educated and the non-university groups, when the dyslexics and controls were combined. However when looking at the educational differences in relation to the significantly worse performance by the dyslexics over controls, it was the university participants who maintained trend differences between dyslexics and controls ($p = 0.073$) when analysed separately from the non-university group. There were no significant differences between the IQ scores of the dyslexics and controls (see Figure 8-9).

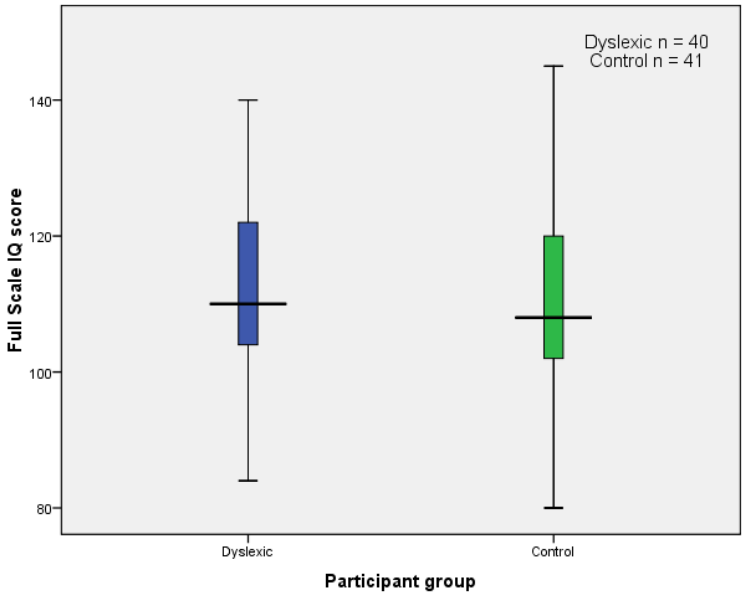


Figure 8-9 IQ scores of dyslexics vs. controls

8.6.3 Effect of distractor position on tone discrimination

There were three trial types during this task, each analysed individually. There were no significant differences in performance between any of the three trial types in relation to each other or the total performance (see Figure 8-10). This was true for all the four participant groups.

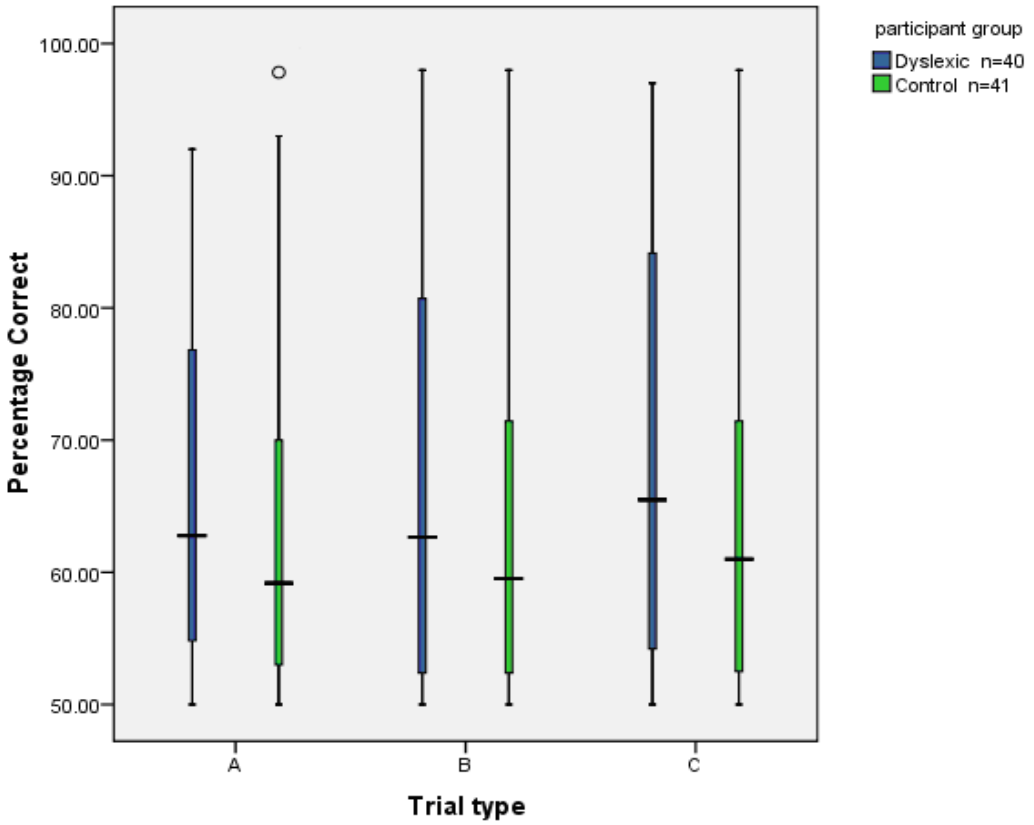


Figure 8-10 Performance of dyslexics vs. controls by trial type

8.6.4 Correlations – distraction effects

The three trial types correlated strongly positively with each other and with the total performance across all three, the Spearman's rho significance level never being higher than $p < 0.000$. The trial types also correlated with the ability scales, three of the IQ indices correlated significantly at the 5% level. One index however did not correlate; the Processing Speed Index did not significantly correlate with any of the three trial types except for trial type B when there is a negative correlation when controlling for the Full Scale IQ ($r = -0.234$, $p = 0.045$).

When the results from the trial types were combined, the performance in the distraction task correlated with three of the IQ indices (all but Processing Speed) and all literacy measures. After controlling for IQ the correlations with the different IQ indices disappeared. However the correlations between total performance and the literacy measures (with the exception of spelling and regular word reading) were independent of IQ, see Table 8-7.

Table 8-7 Correlations
** = Correlation $p \leq 0.01$, * = Correlation $p \leq 0.05$, ・ = Trend $p \leq 0.1$, N.S. = Not significant $p \geq 0.1$.
⯎ = correlations that remain significant when controlling for IQ.

	Task	Two tailed	
		Rho	Sig.
Combined results correlate with:	Music ability	0.542⯎	0.000**
	VCI	0.352	0.001**
	WMI	0.364	0.001**
	POI	0.307	0.006**
	PSI	-0.238	N.S.
	Reading	0.393⯎	0.000**
	Spelling	0.288	0.009**
	Regular word reading	0.253	0.024*
	Irregular word reading	0.364⯎	0.001**
	Non-word reading	0.373⯎	0.001**
	Arithmetic	0.345⯎	0.002**

8.6.5 Masking effects

The lack of any significant differences in performance across the three different trial types provides no evidence of masking effects during this task. However correlations between the IQ indices and the performances on the experimental task showed different results for the three distraction positions. The correlations of the Working

Memory and Perceptual Organisation indices increased as the distracting tone got closer to the initial target tone (see Table 8-8). When controlled for the Full Scale IQ both the WAIS-III Verbal and Performance IQs show significant correlations only in the distraction positions A and C.

Table 8-8 IQ indices correlation differences by trial type
** = Correlation $p \leq 0.01$, * = Correlation $p \leq 0.05$, ‧ = Trend $p \leq 0.1$, N.S. = Not significant $p \geq 0.1$.
۞ = correlations that remain significant when controlling for IQ.

Index	Trial Type A		Trial Type B		Trial Type C	
two-tailed	rho	Sig.	rho	Sig.	rho	Sig.
WMI	0.274	0.015*	0.311	0.005**	0.403	0.000**
POI	0.256	0.024*	0.274	0.015*	0.279	0.013*

8.7 Discussion - single roving distractor

The dyslexics seem to be performing better than the controls at each of the interval lengths. The better performance is driven by the high performance of the university dyslexics. It seems that either their experience in education while coping with their dyslexia have lead to them being better practiced in the rejection of unimportant material; or, it is those dyslexics who could reject interruptions who were able to acquire the literacy skills required to get into university. This leads to a ‘chicken or egg’ dispute when trying to apply the findings to compensatory skills in university dyslexics. The other groups do not appear to show any performance differences.

There were no performance differences influenced by the positions of the distractions, or the type of distraction used. There has been no evidence to support Bailey and Snowling's theory (2002) that dyslexics are more susceptible to backwards masking. However two of the WAIS-III IQ indices, Working Memory Index and Perceptual Organisation Index, both showed increasing correlations with task performance as the interval before the distraction increased.

8.8 Conclusions - distraction

It appears that the in both tasks dyslexics were less affected by the distracting stimuli. In the second task we can see that the increased performance was driven by the university dyslexics. This is an interesting finding as it implies that the route to success in academic pursuits in dyslexia is mediated by the ability to focus on the task in hand.

Dyslexics' performance on the distraction tasks indicated that they could better cope with distraction than the controls. Perhaps this could be related to a sluggish temporal processing. It is suggested that dyslexics' attentional dwell time is prolonged by up to 30% (Hari *et al.*, 1999b). This could suggest that as the distracting tone was being played out, the dyslexic's attention was still captured by the initial stimulus thus reducing its effect.

The findings of Conway *et al.* (2001) are in direct contradiction to these findings. They claim that those with higher memory spans were better at 'rejecting' distracting information. It seems that despite dyslexics having reduced memory capacities their ability to ignore was not impaired in this task. However there was a positive correlation between the task performance and the Working Memory Index which increased as the time interval before the distraction increased. The university dyslexics were significantly better than the non-university dyslexics and non-university controls at the Working Memory Index but overall the combined dyslexics were still worse than the combined controls (results can be seen in Table 6-4 of psychometric differences between the groups).

Keppel and Underwood (1962) predicted that their replication of the Brown–Peterson short-term memory interference paradigm would show decreased performance in the presence of interference during the memory task. However they found that the interference effect did not hold for the first and second trials in an experiment – only once the interference had built up. Only once there was too much going on to automatically retrieve the information, was the effect of the interference shown. Perhaps by allowing the participants to initiate each trial themselves allowed them to prevent the build up of interference.

9 Verbal and non-verbal auditory memory spans

9.1 Rationale for tasks

The purpose of this chapter was to replicate and extend the findings of Rose and Rosner: for review see 1.4.2 Auditory working memory. Using a recognition staircase paradigm the phonological loop could be assessed without the need for overt retrieval. Baddeley *et al.* (2002) found that serial recognition tasks were less affected than recall tasks by word length, similarity or lexicality effects (Gathercole *et al.*, 2001). Thus by using a recognition staircase paradigm the risks of word length effects can be reduced.

The Rose and Rosner (2005) study was complicated by the differing performances of those with and without a higher education. By assessing these two groups separately I hope to shed some light on the differences between compensated and uncompensated dyslexics, a little studied area. Shaywitz *et al.* (2003) comment that 'in comparison to compensated dyslexics the environmentally influenced poor readers rarely attend university and may not readily come to the attention of investigators'. Often diagnosed as dyslexic in primary or secondary education, many dyslexics choose not to even attempt to attend university, while others manage to acquire the competent literacy skills to allow them to perform academically. As a small subset of Rose and Rosner's (2005) participants, their non-university dyslexics, appeared to skew their findings. I hope, by investigating university and non-university groups of dyslexics separately I can determine whether either group has under-developed auditory memory.

9.2 Tasks 7 and 8: Methods - sequence recognition

9.2.1 Participants

Four groups of adults, ages 17-60 years, were classified as:

- A group of 19 current or previous university students, diagnosed by an educational psychologist as dyslexic. Henceforth 'university dyslexics' (UD).
- A group of 14 current or previous university students who did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties. Henceforth 'university controls' (UC).

- A group of 14 adults who did not attend tertiary education with no plans to attend in the future. These adults had been diagnosed by an educational psychologist as dyslexic or else had a distinct dyslexic profile in the psychometric battery and had a history of learning difficulties. Henceforth 'non-university dyslexics' (NUD).
- A group of 16 adults who did not attend tertiary education with no plans to attend in the future. They did not have a dyslexic profile in the psychometric battery and had no history of learning difficulties. Henceforth 'non-university controls' (NUC).

Table 9-1 Participant descriptive statistics

Participant Group	Total Number	Male/Female	Age Range	Mean Age	SD	Median Age	IQR
UD	16	9/7	18-60	31.38	6.2	26.3	9
UC	14	7/7	19-52	23.86	4.5	21.4	8
NUD	14	8/6	20-53	32.93	8.6	29.0	15
NUC	16	5/11	18-55	25.88	7.2	25.2	12

9.2.2 Design

The stimuli were exactly the same as those used in the Rose *et al.* study (2007). The different tasks used separate stimuli each run though the same Borland custom computer software 'staircase recognition paradigm' created by Burton Rosner (Rose *et al.*, 2007).

9.2.2.1 Stimuli

In the digit recognition task the stimuli consisted of the digits 0 through 9. Recorded in a male southern English accent, each digit was recorded as a 16-bit digitised audio file and edited to as near as 500ms as possible. For the tonal recognition task 10 triangular waveform tones were created, raising in frequency from 262 to 741Hz in whole tone steps. The tones are 500ms each with rise and fall times of 20ms.

9.2.3 Procedure

All tasks were performed in replication of the Rose, et al (2007) study. The two experimental tasks were alternated in presentation order for each participant, each which lasted between 5 and 15 minutes. The number of trials ranged from 20-58 in the tonal task (mean = 33.66) and 20 - 49 in the digit task (mean = 34.24).

The custom computer software controlled the sequence length in a two-up-one-down staircase. Participants are initially presented with two sequences of four stimuli (either tones or digits). The participant was asked to indicate by keyboard whether the two sequences were identical or different. After each error the number of stimuli in the sequence was reduced by one. After two correct answers in a row, the number was increased by one. Each time an error stopped a climb up the staircase the length of the sequence was recorded as a turning point. Equally the turning point is recorded when two correct trials cease a descent.

In this study ten turning points were recorded in each run; the first two were ignored. The number of stimuli in the sequence at each of the remaining eight turning points was averaged to compute the individual's memory span.

9.2.4 Measures of cognitive ability

Each participant was administered an extensive battery of psychometrics. These included; the 12 subtests of the Wechsler Adult Intelligence Scale - Third edition (WAIS III UK), and the Random Automatised Naming (RAN) tests.

9.2.5 Measures of literacy ability

As in the full assessment battery, participants were administered the Single Word Reading and Spelling subtests of the Wide Range Achievement Test (WRAT) and all three of the Castles and Coltheart (C&C) single word reading lists.

9.3 Results - sequence recognition

ANOVAs were used on the data sets having confirmed normality in Kolmogrov-Smirnov tests. Levene's test confirmed homogeneity of the variances.

9.3.1 Group differences

Table 9-2 Group differences
** = p ≤ 0.01, * = p ≤ 0.05, ‧ = Trend p ≤ 0.1, N.S. = Not significant p ≥ 0.1, ° = equal variances' not assumed.

Subtests (WAIS in scaled scores; WRAT in standard scores)	**Means & S.D.**								**Significance p value**
	UD		**UC**		**NUD**		**NUC**		
Vocabulary	13.87	3.5	13.77	4.6	11.36	2.1	11.6	2.7	0.069 ‧
Similarities	14.2	3.0	11.54	4.9	12.29	3.3	10.6	3.0	0.052‧
Arithmetic	11.77	2.9	11.92	4.8	8.85	3.9	11.36	2.5	N.S.
Digit Span	9.31	2.7	11	4.8	8.54	2.6	10.21	2.5	N.S.
Information	13.46	2.8	12.58	4.7	12.23	1.9	11.93	2.4	N.S.
Comprehension	14.46	2.9	13.42	4.7	12.38	1.9	12.86	2.5	N.S.
Letter-Number Sequencing	9.08	3.3	10.92	4.5	9.46	2.1	11.21	1.8	N.S.
Picture Completion	11.62	3.4	10.08	4.0	11.31	2.4	9.5	3.3	N.S.
Digit Symbol Coding	10.75	2.9	10.69	4.5	7.79	2.4	10.5	2.7	N.S.
Block Design	12.85	2.8	12.0	5.0	11.23	3.9	11.07	3.2	N.S.
Matrix Reasoning	13.15	2.0	13.25	4.5	12.08	3.2	12.0	2.9	N.S.
Picture Arrangement	11.31	3.1	9.67	3.8	9.69	3.5	8.14	1.6	N.S.
Symbol Search	9.8	2.2	10.69	4.1	7.71	3.0	10.2	2.7	0.063‧
Object Assembly	11.31	1.9	9.0	3.4	10.00	2.9	9.86	2.2	0.09‧
WRAT Reading	106.53	11.4	107.38	8.1	93.36	17.0	103.6	10.1	0.013*
WRAT Spelling	99.07	18.4	108.85	4.4	91.07	17.1	100.53	9.1	0.011*
Tone recognition (mean number of tones)	6.45	1.6	6.20	3.0	5.23	1.1	6.92	1.3	0.004** (outliers removed)
Digits recognition (mean number of digits)	6.45	1.4	7.07	1.6	5.75	1.8	6.28	1.5	0.022* (outliers removed)

The ANOVAs revealed between group differences in both the Reading (f = 3.949, df =3, p = 0.013) and Spelling (f = 4.014, df = 3, p = 0.011) subtests. Post hoc tests showed that the differences in reading ability were driven by significant differences between both the university dyslexics and non-university dyslexics (p = 0.037), and university controls and non-university dyslexics (p = 0.042). The differences in the spelling were driven by a significant difference between the university controls and non-university dyslexics (p = 0.012).

The trend differences in the vocabulary scores were driven by the superior performance of the university attendees over the non-university participants, whereas the Symbol Search's trend group differences were driven by the poor performance of the dyslexics in comparison to the controls.

Verbal skills such as the vocabulary and similarity subtests from the WAIS-III were dominated by the differences between those with and without a university education, as seen with independent samples' t-tests. Interestingly there was a trend for both dyslexic groups to outperform their controls in the Similarities test.

The differences between the dyslexic and control groups focused more on the working memory subtests of the WAIS-III, significantly the Digit Span and the Letter-Number Sequencing tasks.

Table 9-3 Post hoc t-tests
** = $p \leq 0.01$, * = $p \leq 0.05$, ⋆ = Trend $p \leq 0.1$, N.S. = Not significant $p \geq 0.1$, ° = equal variances' not assumed.

	Subtests where differences were found	**Means & S.D.**				**P value**
		Dyslexic		**Control**		
Dyslexics Vs Controls	Digit Span	8.97	2.5	10.69	3.5	0.031*
	Letter-Number Sequencing	9.17	2.6	11.18	3.2	0.011*
	Spelling	95.94	17.6	104.97	8.5	0.015*
University Vs Non-university		**Uni**		**Non-Uni**		
	Vocabulary	13.77	3.8	11.5	2.3	0.008*
	Reading	106.53	9.6	98.73	14.3	0.016*
	Spelling	103.97	14.0	96.63	14.4	0.05**

9.3.2 Tone and digit span performance

In the tonal recognition task the means suggested that the differences were mainly driven by poor non-university dyslexics' performance. There were no significant differences between dyslexics and controls overall, or between university and non-university participants. Post hoc t-tests showed that neither the differences between, university dyslexics and university controls, nor between non-university dyslexics verses university dyslexics were significant; whereas there were highly significant

differences between the non-university dyslexics and the non-university controls (p=0.005), and the university controls (p< 0.001).

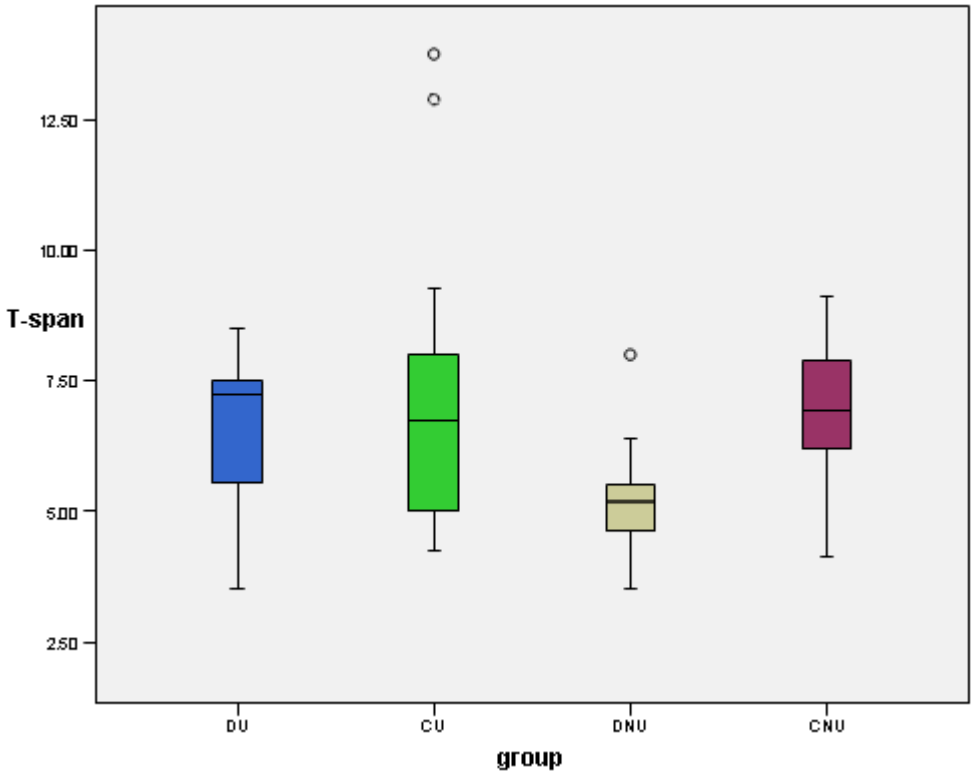


Figure 9-1 Group performances on tonal recognition span

In tonal sequence recognition, the performance of the control readers was equal regardless of university education. However non-university dyslexics showed poorer performance than controls despite the university dyslexics performing on a par with the two control groups.

In the digit recognition task the only significant difference was between the university controls and the non-university dyslexics (p= 0.036). Prior to the removal of the four outliers seen in Figure 9-2 there were no significant differences between the groups.

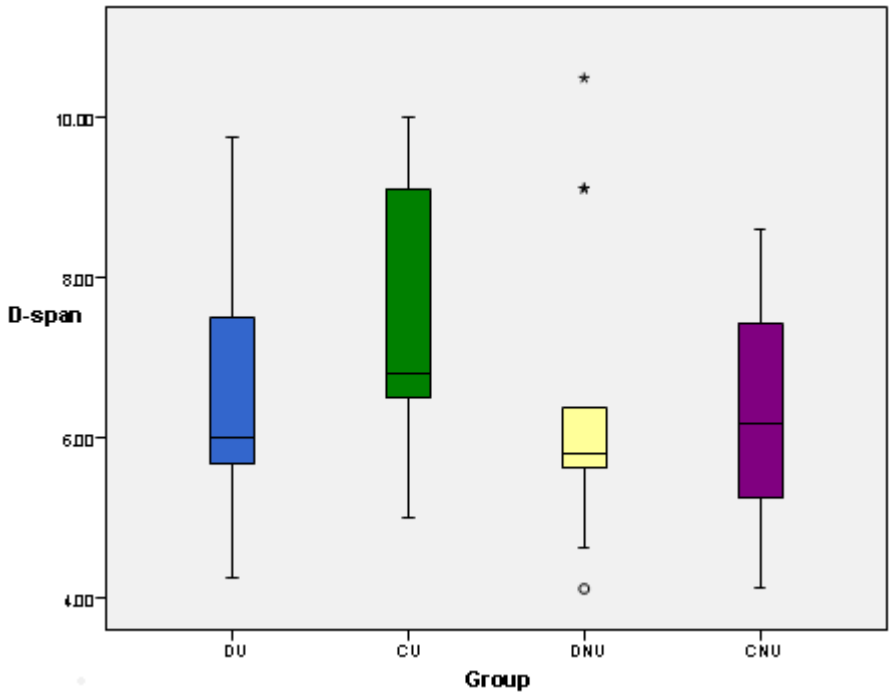


Figure 9-2 Group performances on digit recognition span

It seems in this task that the university educated controls perform above the three other groups. The university dyslexics do show higher scores than the non-university dyslexics, however it is insignificant.

Looking at the Pearson correlations between the two memory tasks there was a significant correlation taking the groups together ($p < 0.000$). The correlations were also significant when the groups were split into university versus non-university attendees or dyslexics versus controls. When looking at each group individually the two extreme groups drove the significant correlations; for the university control group the Pearson correlation ($r = 0.7$, $p = 0.005$, two-tailed) and for the non-university dyslexics ($r = 0.59$, $p = 0.045$, two-tailed). Neither for the non-university controls nor the university dyslexics groups were the correlations significant.

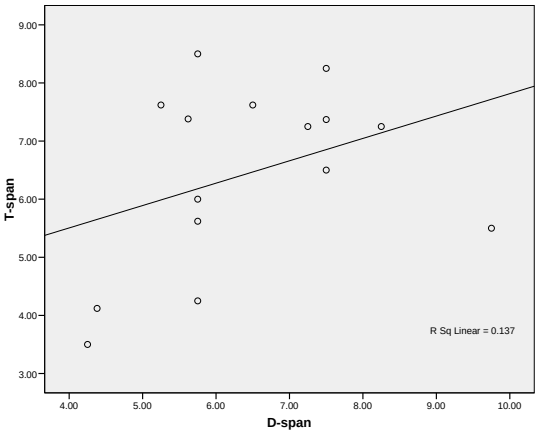


Figure 9-3 University dyslexic tone and digit recognition correlation

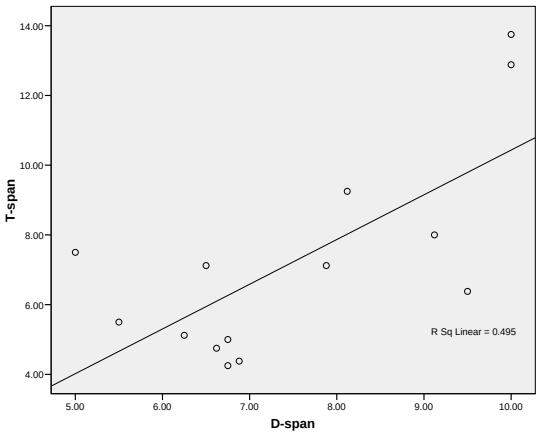


Figure 9-5 University control tone and digit recognition correlation

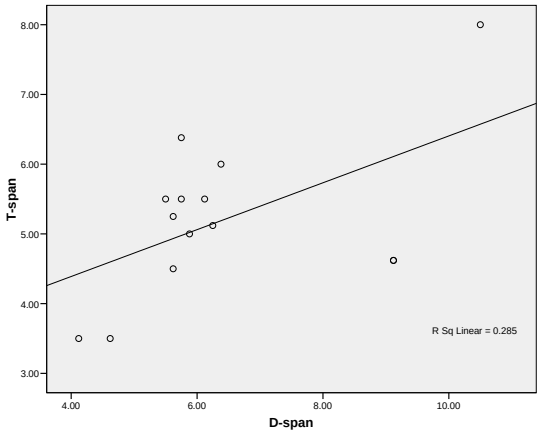


Figure 9-4 Non-university dyslexic tone and digit recognition correlation

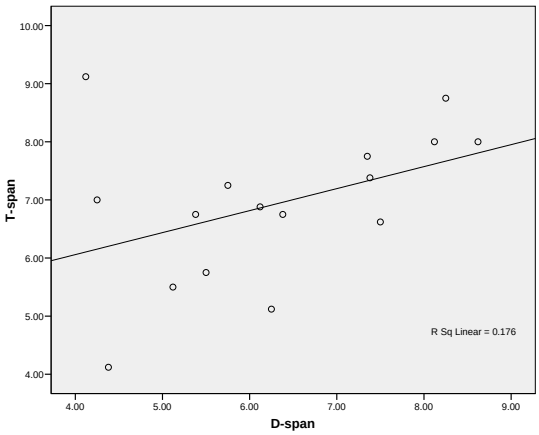


Figure 9-6 Non-university control tone and digit recognition correlation

9.4 Discussion - sequence recognition

In the tonal recognition task the university dyslexics were better than the non-university dyslexics and did not show the significant weaknesses that the non-university dyslexics showed. This finding emphasises the need to control for educational differences when collecting participant groups, as without due care they could skew results. It is important that more research is undertaken to further understand these differences; most such research has been carried out using university students.

A high correlation between digit and tonal memory spans was seen only in control university and dyslexic non-university groups. This suggests that the university dyslexics may have been able to find a better strategy for improving their tonal

memory than their digit memory in comparison to the non-university dyslexics. It is probable that they use a different strategy for remembering the tones and the digits. On an everyday basis we have more practice remembering digits, such as phone numbers and PIN codes. Tonal recognition however would require a new strategy. Previous studies have found tones to be encoded in an abstract form making them harder to remember (Deutsch, 1972a, b).

Thus the compensated university dyslexics seem to have been able to improve their ability to remember digits, whereas the uncompensated non-university dyslexics are as poor at digit recognition as at tonal recognition. A university education exposes students to a more academically challenging environment, one where memory is challenged and stretched in frequent exam conditions, although it is likely these skills are already in place when they reach university. It is likely that those university dyslexics are more adept at creating effective strategies to cope with new situations.

A recent study by Cohnen-Mimran and Sapir (2007) found that when the Digit Span subtest from the WAIS was performed, analysing the digit recall forwards and backwards separately, both dyslexic and control Hebrew students found the backwards recall harder than the forwards. However the differences between the groups' performances were larger in the forwards recall task. This, together with Hulme's (1984) hypothesis that digit span naturally increases with age, supports Rose's theory that dyslexia includes an under developed auditory memory capability for maintaining or processing auditory information in both a verbal and non-verbal setting.

9.4.1 Memory tasks

Having performed a battery of psychometrics in each of the studies, I thought it important to utilise the large number of WAIS-III assessments I had conducted over the course of this thesis to investigate different aspects of the memory recall tasks. Having used a digit recognition task in this thesis it feels important to assess the other tasks in replication of an element of the study by Cohnen-Mimran and Sapir (2007), who found backwards digit span was harder for dyslexics as it involved greater central executive processing.

One hundred and eighty assessments (31 university dyslexics, 58 university controls; 24 non-university dyslexics and 29 non-university controls) were combined to assess performance on the WAIS-III Digit Recall and Letter-Number Sequencing tasks. In addition to this the raw scores of the two Digit Recall subtests, forwards and backwards recall, were evaluated separately in accordance with the Cohnen-Mimran and Sapir study. The backwards and forwards scores are raw score data and are not normalised, so results should be regarded with caution.

Table 9-4 Group performances on each memory task

Task	UD		UC		NUD		NUC	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Digit Recall	9.74	3.24	11.55	3.26	8.12	2.13	10.00	2.69
Forwards	8.90	2.68	10.93	2.36	8.08	1.82	10.03	2.01
Backwards	6.77	2.59	8.52	2.64	6.62	2.04	7.10	2.21
L-N Seq.	9.94	2.95	11.79	3.17	8.33	2.41	10.72	2.34

I wanted to know which method of testing memory was best for detecting the dyslexic deficit, independent of educational differences. All of the memory elements showed significant differences between the dyslexic and control groups (all $p<0.002$) and between the university and non-university groups (all $p<0.026$).

Table 9-5 ANOVA; between group differences

Task	F	df	Sig
Digit Recall	8.13	3	0.000**
Forwards Recall	11.14	3	0.000**
Backwards Recall	5.35	3	0.002**
L-N Sequencing	9.03	3	0.000**

When analysing the ANOVA post-hoc, interestingly the two tasks with the largest ‘F’ differences, the forwards recall subtest and Letter-Number Sequencing, were also the tasks which show the least differences attributable to education. In the Digit Span task the difference seen between the groups is mainly attributable to the only significant difference between university controls and non-university dyslexics. In the backwards recall task educational trend effects appear between the university and non-university controls ($p=0.097$).

These results may imply that the memory skills which are reduced in both the university and non-university dyslexic population may not be those required to achieve a high academic performance. Dyslexics seem to be using different skills to the controls to develop their academic skills.

From this brief analysis I can conclude that the WAIS Letter-Number Sequencing tasks may be more reliable than Digit Span when choosing tests for diagnosis of dyslexia. This task is less affected by the educational differences within the groups than the Digit Recall task. These results do not support Cohnen-Mimran and Sapir's theory that dyslexics show more substantial deficits on memory tasks which are more taxing. The large deficit seen in the Letter-Number Sequencing task does suggest that central executive is involved. Requirement of long-term memory recall of the alphabet implies that the episodic buffer is important as well (Baddeley, 2003), in addition to the central executive which Cohnen-Mimran and Sapir predict may be the cause of the dyslexic deficit (Cohen-Mimran and Sapir, 2007).

9.5 Conclusion - sequence recognition

The results of the digit and tone sequence recognition tasks suggest that dyslexics who have not gone to university have shorter tone and digit memory spans than dyslexics who have received university education or controls. Therefore studies of dyslexic undergraduates need to be interpreted with caution due to their superior auditory memory compared with developmental dyslexics who did not attend university. Analysis of the memory subtests of the WAIS suggest that the WAIS Letter-Number Sequencing tasks may be more reliable than Digit Span when choosing tests for diagnosis of dyslexia as it is affected by the educational differences within the group.

The ability to learn accommodating strategies does seem to play a role in the development of verbal memory skills; however the tonal memory skills were not as advanced as the verbal memory skills when the university dyslexics were compared to the dyslexics who did not attend university.

10 Discussion and conclusions

10.1 Global discussion

This thesis describes auditory processing in dyslexia and the effects of education. In each of the auditory tonal discrimination tasks (with the exception of Task 5; discrimination with five distractor tones) all performance in the tasks correlated with literacy independently of IQ. This finding suggests that tonal discrimination ability is one of the underpinning, prerequisite skills of literacy learning.

These results suggest that dyslexics do suffer discrimination difficulties with non-verbal general auditory stimuli. Dyslexics achieved more of the lower scores than controls when discriminating at the combined different interstimulus intervals - they seem to do especially worse at longer lengths. Those who attended university actually performed better at shorter interstimulus intervals. This is in direct contradiction to the predictions based on Tallal's theories.

The group of university dyslexics seemed to be less affected by distraction than all other groups, which may hold the key to their academic success. With tertiary education the dyslexics' memory for tonal sequences increases capacity but the improvement is not replicated in the ability to recognise numerical sequences. In controls, the university and non-university groups differed only in the digit recognition performance. The two control groups performed equally well on tonal recognition.

I do not believe that these group differences imply that three years at university enabled the dyslexics to learn effective strategies. Probably individuals with the ability to learn the new strategies to compensate for their dyslexia are the only ones who can get to university. Those differences seen in the studies of this thesis are skills which the individuals may have always had or have acquired at any stage of their development. To deduce which compensatory skills are actually developed only as a result of three years at university it would require a longitudinal study: this would take too long for a DPhil thesis.

This further support for a basic auditory processing deficit in dyslexia should help researchers to look into developing an auditory non-verbal assessment for dyslexia. Due to the increasing numbers of children using English as a second or third language being educated in the UK, a general auditory diagnosis tool would be of great assistance to educational psychologists. It would also create a global tool, as often the diagnostic tools for dyslexia are created in the UK or US; there are limited tools available in other countries. A general auditory non-verbal tool would also be unaffected by verbal IQ which, as the psychometric results in this thesis have shown, may be increased with education.

The differences in the dyslexics' performance at different intervals may imply that education may have a confounding effect on the results. Tallal's theory that dyslexics are poor at processing small interval changes did not seem to be upheld, especially for those who had received tertiary education who seemed to perform better at the shorter intervals. But the number of trials at the short intervals (<100ms) was not sufficient to be certain of this finding.

The two recognition tasks confirmed the existence of a verbal deficit in dyslexia; however in the non-verbal tone sequence recognition task it seemed that the deficit was restricted to those dyslexics who did not attend university. This implies that the university educated dyslexics may have been able to find a strategy to cope with the novel task better than the non-university group.

The extensive psychometrics performed in some parts of this thesis has proved to be a worthwhile investment. They have revealed that the dyslexics could sometimes reach a stage where their reading ability was indistinguishable from the controls, but their spelling still remained deficient. It was also found that the two WAIS subtests which revealed the most differences between the controls and dyslexics were the working memory subtest, Letter-Number Sequencing, which is often overlooked and skipped by both researchers and educational psychologists, together with the processing speed subtest of Digit Symbol Copy.

The psychometrics also demonstrated that the university dyslexics' performance on the verbal subtest, similarities, was significantly better than that of university controls. This high performance in the similarities test may reflect the theories that dyslexics

use semantic inference as one of their compensatory mechanisms (Goulandris *et al.*, 2000; Chiappe *et al.*, 2004). The high performance also suggests that the required skills for associating between seemingly dissimilar items may give insight into how the dyslexics can perform at the highest levels, despite their literacy deficits.

Now that an extensive comprehensive battery has been performed, the results can be used for further studies to choose a battery with only the most discriminating tests in order to restrict the time required for each participant's research visit. A review of the memory tasks in Chapter 9 sheds some light on the educational factors on the results. A small battery would leave more time for the psychophysical tasks, enabling better research. Hatcher and colleagues (2002) claim to be able to achieve 95% diagnosis accuracy in higher education students with only five literary tests. However I feel that a detailed analysis of psychometrics and the subjects' history are more important for assessing adult dyslexics (or confirming controls in research) to accommodate any compensatory skills acquired.

10.1.1 Limitations

The largest regret I have about this thesis was the use of fixed intervals. It would have been preferable to use a staircase paradigm throughout as was used in the final chapter. Using this method it may have been possible to find discrimination limens.

Having to control for IQ and balancing musical experience between the groups meant there were many factors coming into play. However the musical experience of the four groups turned out to be well matched and there were no significant differences between them. Musical experience did seem to have a strong correlation with all the tasks and its effects may be interesting to study in greater detail in the future. Even age effects have been found in memory tasks with auditory stimuli (Aine *et al.*, 2005); perhaps therefore the age window for the participants should be limited in further studies.

The ADHD symptom questionnaire did show significant differences between the dyslexics and controls. This may have caused an effect on the results due to the nature of the tasks. The length of the tasks was limited as much as possible to avoid the effects of any attentional difficulties; however the length of the tasks was unavoidable due to the number of trials required.

When White *et al.* (2006) investigated the sensory motor impairments in dyslexic children they found little evidence that auditory, motor or any other visual impairments had any causal role in dyslexia. However the commentaries in rebuttal to their paper claimed that the auditory tasks were too hard, as floor affects were seen (Tallal, 2006, Nicolson & Fawcett, 2006). In the current thesis the argument may have been that some of the tasks were too easy and hit ceiling levels. However in some of the simplest tasks basic auditory deficits were still present.

The link between the auditory deficit and dyslexia is still not certainly causal but the evidence for the existence of such a deficit is undeniable. When dyslexics' reading difficulties were compared to those of prelingually deafened readers, each group's difficulties were found to have different sources, though neither were causally linked to a phonological deficit (Miller, 2005), indicating that the causal deficit lies deeper than phonemes.

10.1.2 Future work

These results raise some important issues. The use of participant groups in studies without controlling for their educational background differences seems to be inadvisable. It is important that research takes educational experience into account rather than just matching for IQ.

Secondly, in the final chapter both verbal and non-verbal sequence recognition tasks were performed. However both tones and digits have a direction. Tones can be higher or lower, digits have a numerical order. For this reason participants may have been able to visualise the patterns, memorising only 'up' or 'down'. In a future study it would be preferable to use a selection of short CVC (consonant-vowel-consonant) words for a verbal task and a collection of noises which have no tonal hierarchy. Using this method it may be possible to rule out the assistance of visual memory.

Another study looking at tonal discrimination in compensated dyslexics found that the frequency range at which dyslexics show impaired frequency discrimination can be extended by 20% if a dichotic presentation of the stimuli is employed (Sebastian and Yasin, 2008). I also plan to perform a discrimination task with more of the shorter intervals (<30ms).

The findings taken from this study should be considered in future research. The backgrounds of participant groups have to be more carefully matched than they are in the majority of papers. Despite controlling for the IQs of the dyslexics and the controls in the studies, when the groups were also split by education it was seen that differences could be driven by just a subgroup (as was seen in Tasks 1 and 6).

10.2 Conclusions

Task Number	Task Name	Aim	Conclusions
5.1 Task 1	Discrimination of a semitone difference.	Do dyslexics discriminate a semitone difference as well as controls?	• Dyslexics differentiated two tones separated by a semitone worse than controls. • Performance correlated independently with phonological skills.
5.5 Task 2	Discrimination of incremental tone differences.	Do dyslexics have a lower threshold? Is it affected by education?	• No differences were seen as the logarithmic steps were too large to produce useful information. • Performance correlated independently with literacy.
6.2 Task 3	Three long interstimulus interval effects.	Do university dyslexics need longer to consolidate the memory of a tone?	• University dyslexics achieved a wider range (more lower scores) than the university controls. • This was widest at 2000 and 3000ms. • Dyslexics' performance was closest to that of controls at 1000ms. • Performance had a trend correlation with spelling ability.
6.5 Task 4	Effects of incremental interval length increases.	Do incremental increases in interval effect tonal discrimination? Is it affected by education?	• There were differences between the groups, the university dyslexics performing the best. • Performance correlated independently with literacy skills.
7.2 Task 5	Pitch discrimination with five irrelevant tones.	Do dyslexics react differently to interruption while discriminating a semitone?	• There were significant differences between the groups. • The controls advantage at simple discrimination had reduced as the dyslexics were less affected than controls.
7.5 Task 6	Single distraction in different positions	Does the position of the distraction have different effects on dyslexics and controls? Is it affected by education?	• University dyslexics obtained more of the higher scores than the other groups. • Performance correlated independently with literacy.
8.2 Task 7	Non verbal Sequence recognition.	Do dyslexics have a non-verbal memory deficit? Is it affected by education?	• Education had no effect on controls. • University dyslexics achieved scores equal to the controls. • Non-university dyslexics underperformed.
8.2 Task 8	Verbal Sequence recognition.	Do dyslexics have a verbal memory deficit? Is it affected by education?	• There were no significant differences between the educational groups. • Correlations between the two sequence tasks were significant in both the university controls and the non-university dyslexics.

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Appendices

Appendix 1 *Questionnaires*

A1.1 British Dyslexia Association Adult Dyslexia Checklist

	Yes	No
1. Do you find difficulty telling left from right?		
2. Is map reading or finding your way to a strange place confusing?		
3. Do you dislike reading aloud?		
4. Do you take longer than you should to read a page of a book?		
5. Do you find it difficult to remember the sense of what you have read?		
6. Do you dislike reading long books?		
7. Is your spelling poor?		
8. Is your writing difficult to read?		
9. Do you get confused if you have to speak in public?		
10. Do you find it difficult to take messages on the telephone and pass them on correctly?		
11. When you say a long word, do you sometimes find it difficult to get all the sounds in the right order?		
12. Do you find it difficult to do sums in your head without using your fingers or paper?		
13. When using the telephone, do you tend to get the numbers mixed up when you dial?		
14. Do you find it difficult to say the months of the year forwards in a fluent manner?		
15. Do you find it difficult to say the months of the year backwards?		
16. Do you mix up dates and times and miss appointments?		
17. When writing cheques do you frequently find yourself making mistakes?		
18. Do you find forms difficult and confusing?		
19. Do you mix up bus numbers like 95 and 59?		
20. Did you find it hard to learn your multiplication tables at school?		

A1.2 CARRS-Self Report: Long Version (CAAR-S:L) Questionnaire

Participant Code:.....…. Date of Birth:.....…. Today's Date: .....….
Sex: M / F

Instructions: Listed below are items concerning behaviours or problems sometimes experienced by adults. Read each item carefully and decide how much or how frequently each item describes you recently. Indicate your response for each item by circling the number that corresponds to your choice. Use the following scale. 0 = Not at all, never; 1 = Just a little, once in a while; 2 = Pretty much, often; 3 = Very much, very frequently.

		Not at all, never	Just a little, once in a while	Pretty much, often	Very much, very frequently
1.	I like to be doing active things.	0	1	2	3
2.	I lose things necessary for tasks or activities (e.g. to-do lists, pencils, books or tools).	0	1	2	3
3.	I don't plan ahead.	0	1	2	3
4.	I blurt things out.	0	1	2	3
5.	I am a risk-taker or a daredevil.	0	1	2	3
6.	I get down on myself.	0	1	2	3
7.	I don't finish things I start.	0	1	2	3
8.	I am easily frustrated.	0	1	2	3
9.	I talk too much.	0	1	2	3
10.	I am always on the go, as if driven by a motor.	0	1	2	3
11.	I'm disorganised.	0	1	2	3
12.	I say things without thinking.	0	1	2	3
13.	It's hard for me to stay in one place very long.	0	1	2	3
14.	I have trouble doing leisure activities quietly.	0	1	2	3
15.	I'm not sure of myself.	0	1	2	3
16.	It's hard for me to keep track of several things at once.	0	1	2	3
17.	I'm always moving even when I should be still.	0	1	2	3
18.	I forget to remember things.	0	1	2	3
19.	I have short fuse/hot temper.	0	1	2	3
20.	I'm bored easily.	0	1	2	3
21.	I leave my seat when I am not supposed to.	0	1	2	3
22.	I have trouble waiting in line or taking turns with others.	0	1	2	3
23.	I still throw tantrums.	0	1	2	3
24.	I have trouble keeping my attention focused when working.	0	1	2	3
25.	I seek out fast paced, exciting activities.	0	1	2	3
26.	I avoid new challenges.	0	1	2	3
27.	I feel restless inside even when I am sitting still.	0	1	2	3
28.	Things I hear or see distract me from what I am doing.	0	1	2	3
29.	I am forgetful in my daily activities.	0	1	2	3
30.	Many things set me off easily.	0	1	2	3

31.	I dislike quiet, introspective activities.	0	1	2	3
32.	I lose things that I need.	0	1	2	3
33.	I have trouble listening to what other people are saying.	0	1	2	3
34.	I am an underachiever.	0	1	2	3
35.	I interrupt others when talking.	0	1	2	3
36.	I change plans/jobs midstream.	0	1	2	3
37.	I act okay on the outside, but inside I'm unsure of myself.	0	1	2	3
38.	I am always on the go.	0	1	2	3
39.	I make comments/remarks that I wish I could take back.	0	1	2	3
40.	I can't get things done unless there's an absolute deadline.	0	1	2	3
41.	I fidget (with my hands or feet) or squirm in my seat.	0	1	2	3
42.	I make careless mistakes or have trouble paying close attention to detail.	0	1	2	3
43.	I step on people's toes without meaning to.	0	1	2	3
44.	I have trouble getting started on a task.	0	1	2	3
45.	I intrude others' activities.	0	1	2	3
46.	It takes a great deal of effort for me to sit still.	0	1	2	3
47.	My moods are unpredictable.	0	1	2	3
48.	I don't like homework or job activities where I have to think a lot.	0	1	2	3
49.	I'm absent-minded in daily activities.	0	1	2	3
50.	I am restless or overactive.	0	1	2	3
51.	I depend on others to keep my life in order and attend to details.	0	1	2	3
52.	I annoy other people without meaning to.	0	1	2	3
53.	Sometimes my attention narrows so much that I am oblivious to everything else; other times it's so broad that everything distracts me.	0	1	2	3
54.	I tend to squirm or fidget.	0	1	2	3
55.	I can't keep my mind on something unless it's really interesting.	0	1	2	3
56.	I wish I had greater confidence in my abilities.	0	1	2	3
57.	I can't sit still for very long.	0	1	2	3
58.	I give answers to questions before the questions have been completed.	0	1	2	3
59.	I like to be up and on the go rather than being in one place.	0	1	2	3
60.	I have trouble finishing job tasks or schoolwork.	0	1	2	3
61.	I am irritable.	0	1	2	3
62.	I interrupt others when they are working or playing.	0	1	2	3
63.	My past failures make it hard for me to believe in myself.	0	1	2	3
64.	I am distracted when things are going on around me.	0	1	2	3
65.	I have problems organising my tasks and activities.	0	1	2	3
66.	I misjudge how long it takes to do something or go somewhere.	0	1	2	3

A1.3 Handedness Questionnaire

Handedness Questionnaire (after Annett, 1972)

Name: DOB: Date:
Age: Sex:

Please indicate right (R), left (L) or either (E) to each of the following questions. Act out the movement in question if there is any doubt about your answer.

Which hand do you use:			
1. To write a letter legibly?	R	L	E
2. To throw a ball to a target?	R	L	E
3. To hold a racquet in tennis, squash or badminton?	R	L	E
4. To hold a match while striking it?	R	L	E
5. To cut with scissors?	R	L	E
6. To guide a thread through the eye of a needle (or guide a needle onto thread)?	R	L	E
7. At the top of a broom while sweeping?	R	L	E
8. At the top of a shovel while moving sand?	R	L	E
9. To deal playing cards?	R	L	E
10. To hammer a nail into wood?	R	L	E
11. To hold a toothbrush while cleaning your teeth?	R	L	E
12. To unscrew the lid of a jar?	R	L	E

If you use the right hand for all of these actions, are there any one-handed actions for which you use the left hand? If so, please record them here.

Which eye do you prefer when looking through a telescope?	R	L	E
Which foot do you prefer kicking with?	R	L	E

How many immediate relatives (parents, siblings, children) do you have in all? _____
Are there any left-handers in your immediate family (i.e. parents, siblings, children)?
YES / NO If yes, please give details:

Has it ever been suggested that you or a member of your immediate family might be dyslexic?
YES / NO If yes, give details:

A1.4 Musical Ability Questionnaire

MUSICAL ABILITY & EXPERIENCE

	(PLEASE DELETE AS APPROPRIATE)		
1	Have you ever sung in a band or played a musical instrument	0= No, never 1= Sometimes / minimal skill 2= Often / moderate skill 3= Regularly / skilled, professional	
2	(a) Have you ever had any formal musical training? (b) If yes: any problems sight-reading music?	0 = None at all 1= A little / to a minimal level 2= Quite a lot / to a moderate level 3= Extensive / skilled, professional ---------- None / Slight / Moderate / Severe	
3	Can you sing in tune (or tell whether an instrument is in tune)?	0= No: have real problems 1=Just about, but not very well. 2=Reasonably well 3=Very well	
4	How is your sense of rhythm? (in playing music, or dancing)	0= Poor: have real problems 1= OK, but not good 2=Reasonably good 3=Very good	

Appendix 2 *Programmes*

A2.1 Task 2, Task 4 and Task 6, auditory programme for 3 studies

This programme was created by the author for this thesis.

```
     /*
     This programme plays on of three tasks. The task is selected in the first
     screen. They are; ISI (tonal discrepancy with a changing interstimulus
     interval), TDisc (a simple tone discrimination task with a changing Hz
     discrepancy between the two tones) and Dist (a simple tone discrimination
     task with a interpolating intervening tone on one of three positions;
     250ms, 750ms  or 1250ms after the initial tone).

     In both TDisc and Dist the ISI is always 1500ms and 2000ms between the
     initial and final tones respectively.

     In ISI and Dist the Hz discrepancy between the initial and final tone
     is fixed at one quarter tone.

     In all tasks the tones are selected between 239 - 830Hz in quarter tone
     intervals.

     All programmes run in the same format and are administered in the sound
     booth, run in DOS.

     There are three run types for formatting help.
     Run-Variable can be set to one of three functions
     =0 - the task is just run though without playing stimuli or asking
     for responses
.
     =1 - plays out the stimuli files without asking for response.
     =2 - plays the whole task as normal.
                                                                          */
//Includes
#include <stdio.h>
#include <iostream.h>
#include <stdlib.h>
#include <conio.h>
#include <string.h>
#include <math.h>
#include <dos.h>
#include <ctype.h>
#include <time.h>
#include <process.h>
#include <sys\stat.h>
//#include <Windows.h>
#include <stdlib.h>

const int MAX=150;
const int NAM_L = 30;
int flag=0,t_type;

char **file_name_array;
unsigned int key_pause, number_files, trial, trial_pause;
char fname [ NAM_L ];
int randSeq [MAX]; //Assuming nuber of files dont exceed MAX
short result_indic[MAX];// [ 2 ] ;
int runVarianble;

void init_screen();
void isi();
void td();
void distract();

FILE * open_data_file(int);
void get_subj_info( FILE *);
void get_run_info( FILE * );
int get_params (FILE * );
void get_trial_info(int , int);
int run_trial(int , FILE*);
void get_results(FILE *);

void main()
{
        runVarianble = 2;
       file_name_array = new char*[MAX];
       for(int i= 0; i<MAX; i++)
```

```
                file_name_array[i] = new char[NAM_L];
        init_screen();
}

void init_screen()
{
        clrscr();
        cout<<"\n\n\n\tWelcome\n"
                <<"\n Please enter the index for the test you want to take:\n\n"
                <<"\t 1). ISI - varying interstimulus interval \n"
                <<"\t 2). TD - tone discrimination task with varying tone freq. discrepancy \n"
                <<"\t 3). Distraction task - tone discrimination with an interpolating tone \n"
                <<"\t 4). Exit \n\n"
                <<"\t Enter # here:";
        int a;
        cin>>a;
        flag=a;
        switch(a)
        {
        case 1:
                isi();
                break;
        case 2:
                td();
                break;
        case 3:
                distract();
                break;
        case 4:
                exit(0);

        default:
                cout<<"Wrong Option! Please Enter from 1 - 3, Thank you."<<endl;
                init_screen();
                break;
        }
}

void isi()
{
        clrscr();
        cout<<"Starting ISI - varying interstimulus interval..."<<endl;

        FILE *datPtr;
        for(int i=0;i<MAX;i++)
        {
                strcpy(file_name_array[i],"");
                result_indic [ i ]=0;
        }

        datPtr=open_data_file(1);
        get_subj_info(datPtr);

        get_run_info(datPtr);
        int a=get_params(datPtr);
        int h=1;
        for (trial = 0; trial < number_files ; trial++)
        {
                get_trial_info(trial, a);
                h=run_trial(trial, datPtr);
                if(h==0)
                {break;}
    }
        cout<<"\n\n\t\t Experiment Over!!! Thank You.\n";
        get_results(datPtr);
        cout<<"\n\n Press any key to go back to main menu...";
        getch();
        init_screen();
}

void td()
{
        clrscr();
        cout<<"Starting TD - tone discrimination task with varying tone freq.
discrepancy..."<<endl;

        FILE *datPtr;

        for(int i=0;i<MAX;i++)
        {
```

```
                strcpy(file_name_array[i],"");
                result_indic [ i ]=0;
        }
        datPtr=open_data_file(2);
        get_subj_info(datPtr);
        get_run_info(datPtr);
        int a=get_params(datPtr);
        int h=1;
        for (trial = 0; trial < number_files ; trial++)
        {
                get_trial_info(trial, a);
                h=run_trial(trial, datPtr);
                if(h==0)
                {break;}
    }
        cout<<"\n\n\t\t Experiment Over!!! Thank You.\n";
        get_results(datPtr);
        cout<<"\n\n Press any key to go back to main menu...";
        getch();
        init_screen();
}
void distract()
{
        clrscr();
        cout<<"Starting Distraction Task - tone discrimination task with interupted
varying tone freq. discrepancy..."<<endl;

        FILE *datPtr;

        for(int i=0;i<MAX;i++)
        {
                strcpy(file_name_array[i],"");
                result_indic [ i ]=0;
        }

        datPtr=open_data_file(3);
        get_subj_info(datPtr);

        get_run_info(datPtr);
        int a=get_params(datPtr);
        int h=1;
        for (trial = 0; trial < number_files ; trial++)
        {
                get_trial_info(trial, a);
                h=run_trial(trial, datPtr);
                if(h==0)
                {break;}
    }
        cout<<"\n\n\t\t Experiment Over!!! Thank You.\n";
        get_results(datPtr);
        cout<<"\n\n Press any key to go back to main menu...";
        getch();
        init_screen();
}

FILE * open_data_file( int prj_typ )
{
        // clrscr( );
        char datf_name[ NAM_L ];
        char dname[ 8 ];
        FILE *datPtr;
//      while ( open_indic == 0 )
        {
          switch(prj_typ)
          {
          case 1:
                  strcpy( datf_name, ".\\ISI\\data\\" );
                  break;
          case 2:
                  strcpy( datf_name, ".\\TDisc\\data\\" );
                  break;
          case 3:
                  strcpy( datf_name, ".\\Dist\\data\\" );
                  break;
          }
          cout << "\n\n\nType name for data file without extension: ";
          cin >> dname;
          strcat( datf_name, dname );
          strcat( datf_name, ".dta" );
          datPtr = fopen( datf_name, "a+t" );
```

```
          if ( datPtr == NULL )
          {
                cerr << "\n Error opening file " << datf_name << endl;
                cerr << " get another name." << endl;
                cerr<<" Starting again.. Press any key to continue...\n";
                getch();
                init_screen();
          }
        }
        return datPtr;
}

void get_subj_info( FILE * datPtr )
{
          char s_name[ 25 ];
          // Subject demographics
        //  clrscr( );
          cout << "\n\nEnter subject's last name:";
          cin >> s_name;
          fprintf( datPtr, "\n\n Name: %s, ", s_name );
          cout << "\nEnter subject's first name:";
          cin >> s_name;
          fprintf( datPtr, "%s", s_name );
          cout << "\nEnter subject's date of birth (dd/mm/yy):";
          cin >> s_name;
          fprintf( datPtr, "\n Date of birth: %s", s_name );
          cout << "\n\nEnter subject's status:";
          cin >> s_name;
          fprintf( datPtr, "\n\n Status: %s, ", s_name );
}

void get_run_info( FILE * datPtr )
{
//  clrscr( );
        struct dosdate_t e_date;
        struct time e_time;
        _dos_getdate( &e_date );
        gettime( &e_time );
        fprintf( datPtr, "\n Date : %d-%d-%d", e_date.day,e_date.month, e_date.year);
        fprintf( datPtr, "\n Time: %d.%d \n", e_time.ti_hour, e_time.ti_min );

//      get_params (datPtr );
}

int get_params (FILE * datPtr)
{
        char parf_name [ NAM_L ]; //para file name
        char param_parf [ NAM_L ]; //stimuli
        char dname[ 8 ];
        char d1name[ 8 ];

        FILE * parfilePtr;
//      open_indic = 0;
//      while ( open_indic == 0 )
        {
                switch(flag)
                {
                case 1:
                        strcpy( parf_name, ".\\ISI\\" );
                        break;
                case 2:
                        strcpy( parf_name, ".\\TDisc\\" );
                        break;
                case 3:
                        strcpy( parf_name, ".\\Dist\\" );
                        break;
                }
                                ////////////strcpy( parf_name, ".\\ISI\\" );
                cout << "\nType name of parameter file without extension: ";

                cin >> dname;  //a

                strcat( parf_name, dname );
                strcat( parf_name, ".mcp" );
                parfilePtr = fopen( parf_name, "r" );
                if ( parfilePtr == NULL )
                {
                  cerr << "\n Error opening parameter file " << parf_name << endl;
                  cerr << " \n  Try again!! " << endl;
                  sleep(3);
```

```
                get_params(datPtr);
              }
//            open_indic = 1;
        }
        fprintf( datPtr, "\n From file %s \n", parf_name );
        fscanf( parfilePtr, "%d", &number_files );
        fscanf( parfilePtr, "%d", &key_pause );
        fscanf( parfilePtr, "%d", &trial_pause );
        fprintf( datPtr, "\n Stimuli %d", number_files );
        fprintf( datPtr, "\nKey pause %d ms", key_pause );
        fprintf( datPtr, "\nTrial pause %d ms", trial_pause );
        fclose ( parfilePtr );

        //now open sentence parameter details

//      FILE * sentencePtr;
        int indic;
        char actual_file_name [NAM_L];

//      open_indic = 0;
//      while ( open_indic == 0 ) {

            //strcpy( param_parf, ".\\ISI\\" );
              switch(flag)
              {
              case 1:
                     strcpy( param_parf, ".\\ISI\\" );
                     break;
              case 2:
                     strcpy( param_parf, ".\\TDisc\\" );
                     break;
              case 3:
                     strcpy( param_parf, ".\\Dist\\" );
                     break;
              }

              cout << "\nType name of stimuli parameter file without extension: ";
              cin >> d1name;  //s
              strcat( param_parf, d1name );
              strcat( param_parf, ".mcp" );
              parfilePtr = fopen( param_parf, "r" );

              if ( parfilePtr == NULL )
              {
                     cerr << "\n Error opening parameter file " << param_parf << endl;
                     cerr << " \n  Try Again!! " << endl;
                     sleep(3);
                     get_params(datPtr);
              }
//            open_indic = 1;

        fprintf( datPtr, "\n Sentences from file %s \n", param_parf );
        fprintf ( datPtr," Trial \t  Trial type \t trial name \t responce " );
        indic = 0;
        while (!feof(parfilePtr) ) ///////while end of file is not reached
        {
            fscanf( parfilePtr, "%s", actual_file_name);
            strcat (actual_file_name,".wav");
            strcpy(file_name_array[indic],actual_file_name);
//            printf("%s\n",file_name_array[indic]);
            indic++;
        }
        fclose ( parfilePtr );
        return indic;
}

void get_trial_info (int tr,int indic)
{
        char go_key;
        time_t t;
        srand((unsigned) time(&t));
        int ran=rand()%indic;
        int i=0;
        while(randSeq[i]!=0 && i<indic && i<tr)
        {
              if (ran == randSeq[i])
              {
                     ran=rand()%indic;
                     i=0;
              }
```

```
                i++;
        }
        randSeq[i]=ran;

        strcpy(fname,file_name_array[ran]);
        if(strchr(fname,'s')!=NULL)
          t_type=0;
        else
          t_type=1;

 //      printf("%d = %s\n",ran,file_name_array[ran]);
 //       cin>>go_key;

}
int run_trial( int tr,FILE * datPtr)
{
      char go_key,Resp;
         int order_check;
         char newname[256];
        // char newname2[256];
         go_key = 'Z';

         clrscr( );

         while(1)
         {
                cout<<"\n\n\t Starting test... You will hear two tones\n\n\t\t Press
c to continue, Press E to end session :";
                 if(runVarianble>1)
                      cin>>go_key;
                 else
                       go_key = 'c';

                if(go_key=='E' || go_key=='e')
                {
                       cout <<"Terminating session!!!"<<endl;
                       cout << "Press any key to continue..."<<endl<<endl;
                       getch();
              //       fclose(datPtr);
              //       init_screen();
                       return 0;
                }
                else if(go_key=='C' || go_key=='c')
                break;
         }

         if(go_key=='E' || go_key=='e')
         {
         }
         else
         {
                cout<<"Playing file ... ";
                //cout << fname;

                fprintf ( datPtr, "\n Trial %d ", trial + 1 );
                                        //sleep( key_pause );



                Resp = 'Z';
                                          // clrscr ( );
                cout<<"\n\n\n Respond S (same) if the two tones were identical";
                cout<<"\n     or D (Different) if the two tones differed in
pitch\n\n";
               // sleep(1);
                char name[ NAM_L ],wav[NAM_L],arg[3]="/Q";
                      //     char me[ 8 ];
                FILE * fPtr;
                switch(flag)
                {
                       case 1:
                              strcpy( name, ".\\ISI\\comm.bat" );
                              strcpy( wav, ".\\ISI\\wav.exe" );
                              strcpy(newname,".\\ISI\\");
                              break;
                       case 2:
                              strcpy( name, ".\\TDisc\\comm.bat" );
                              strcpy( wav, ".\\TDisc\\wav.exe" );
                              strcpy(newname,".\\TDisc\\");
                              break;
```

```
                        case 3:
                                strcpy( name, ".\\Dist\\comm.bat" );
                                strcpy( wav, ".\\Dist\\wav.exe" );
                                strcpy(newname,".\\Dist\\");
                                break;
                }


                fPtr = fopen( name, "w+t" );
                if ( fPtr == NULL )
                {
                      cerr << "\n Error opening file " << name << endl;

                      cerr<<"Halting!!!";
                      getch();
                      exit(0);
                }

                strcat(newname,fname);
        //      cout <<"\n\n filename = " << fname;

                fprintf( fPtr, "%s %s %s", wav, newname, arg );

                fclose(fPtr);
              //  system(name);
                if(runVarianble)
                       spawnl (P_WAIT,wav,wav,newname,arg,NULL);

                while ( (Resp != 's' ) && ( Resp != 'D' ) &&   (Resp != 'S' ) && (
Resp != 'd' ) )
                {
                cout <<"\n\n Please respond S or D and Hit Enter : ";
                 if(runVarianble>1)
                      cin >> Resp;
                 else
                       Resp='d';
                }
               clrscr();

         //}


        // decision_ms =  end_resp_t - start_play_t;

                if ( t_type == 0 )
                {      //identical
                      if ( ( Resp == 'S' ) || ( Resp == 's' ) )      //if it is
identical and correct
                      {
                             result_indic [ trial ]/* [ 0 ]*/ = 1;
                             fprintf ( datPtr, "\t  %c", 'S' );

               //            cout<<"crct i"<<endl;
                      }
                      else
                      {
                             result_indic [ trial ] /*[ 0 ]*/ = 2;  //if it is iden
but INCORRECT
                               fprintf ( datPtr, "\t  %c", 'S' );
        //                   cout<<"wrng i"<<endl;
                      }
                }
                else
                {    //different
                      if ( ( Resp == 'D' ) || ( Resp == 'd' ) )    //if it is diff and correct
                      {
                             result_indic [ trial ] /* [ 1 ]*/ = 3;
                             fprintf ( datPtr, "\t  %c", 'D' ); // add if else here to add the S to the
data file??
        //                   cout<<"crct d"<<endl;
                      }
                      else
                      {
                             result_indic [ trial ] /*[ 1 ]*/ = 4;  //if it is diff
but INCORRECT
                               fprintf ( datPtr, "\t  %c", 'D' );
        //                   cout<<"wrng d"<<endl;
                      }
                }
```

```
                //Get response and write in file

                fprintf( datPtr, "\t  %s", fname );
                fprintf( datPtr, "\t  %c", Resp);
               // fprintf( datPtr, "\t  %i, \t %i, \t %i", end_resp_t, start_play_t, decision_ms);
                go_key = 'Z';
        }
        clrscr( );
        return 1;

}

void get_results( FILE * datPtr ) {

  float iden_c = 0, diff_c = 0, total_c = 0, percent_total_c = 0, percent_iden_c = 0, percent_diff_c =
0;
  int i = 0;
  int no_of_rows =  number_files ;
  int no_of_iden_trials = 0;
  int no_of_diff_trials = 0;
  int id_wrng=0,df_wrng=0,idcR=0,dfcR=0;

  cout<<"\nCalculating results...\n";
  if ( result_indic [ i ] != 0)    //check if the trial was run
  {
        for ( i = 0; i < no_of_rows ; i++ ) //for every row in the results table
        {
                switch (result_indic[i])
                {
                case 1:
            iden_c += 1; //result_indic [ i ] [ 0 ];         //count the correct
responses
            no_of_iden_trials++;                        //count the no of trials
            break;
                case 2:
                        //if the trial is WORNG, count the no of trials
            no_of_iden_trials++;
                        id_wrng++;
                        break;

                case 3:
            diff_c ++;
                        no_of_diff_trials++;
            break;
                case 4:
            no_of_diff_trials++;
                        df_wrng++;
                }/////end switch
        }
        if(no_of_iden_trials==0){no_of_iden_trials=1;}
        if(no_of_diff_trials==0){no_of_diff_trials=1;}
  total_c = iden_c + diff_c;
//  idcR = iden_c/(no_of_iden_trials);
//  dfcR = diff_c/(no_of_diff_trials);

  percent_total_c = total_c/( no_of_diff_trials + no_of_iden_trials)*100;

  percent_iden_c = iden_c/ no_of_iden_trials*100;
  percent_diff_c = diff_c/no_of_diff_trials*100;

  fprintf( datPtr, "\n Correct response rate for identical stimuli = \t\t%5.3f", iden_c);
  fprintf( datPtr, "\n Correct response rate for different stimuli = \t\t%5.3f",diff_c);
  fprintf( datPtr, "\n Correct response rate overall = \t\t\t%5.3f", total_c);
  fprintf( datPtr, "\n Percent Correct response rate overall = \t\t%5.3f %", percent_total_c);
  fprintf( datPtr, "\n Percent Identical Correct response  = \t\t\t%5.3f %", percent_iden_c);
  fprintf( datPtr, "\n Percent Different Correct response  = \t\t\t%5.3f %", percent_diff_c);

  cout<<"Correct response rate for identical stimuli="<< iden_c<<endl;
  cout<<"Correct response rate for different stimuli="<<diff_c<<endl;
  cout<<"Correct response rate overall              = "<<total_c<<endl;
  cout<<"Percent Correct response rate overall      ="<<percent_total_c<<" % "<<endl;
  cout<<"Percent Identical Correct response         ="<<percent_iden_c<<" % "<<endl;
  cout<<"Percent Different Correct response         ="<<percent_diff_c<<" % "<<endl;
  fclose( datPtr );
  }///end if
  else
  {
                cout<<"No test taken!!!"<<endl;
  }
}
```

A2.2 Task 1 and Task 5, Discrimination of a semitone difference and pitch discrimination with 5 irrelevant tones

This programme was created by the author in collaboration with Professor Burton Rosner.

```
/* This programme presents stimuli and collects responses for a
   test of consolidation in auditory memory. On each trial, two target stimuli
   occur. They can be the same or differ by a semitone.

   Under condition 'w', five interfering tones occur 2000 ms after the end
   of the first target stimulus. The second target starts 100 ms after the
   end of the last interfering tone. Under condition 'v', there is just
   3050 ms of silence between the target tones. Same (n=26) and different
   (n=24) pairs come in a balanced sequence. The tones range from 416 to
   932 Hz in semitone steps.

   The experimenter selects either condition, with 'v' first for each subject.

   This programme runs under DOS. All file names must adhere to the DOS
   convention.                                                          */

// Includes
#include <stdio.h>
#include <iostream.h>
#include <stdlib.h>
#include <conio.h>
#include <string.h>
#include <math.h>
#include <dos.h>
#include <ctype.h>
#include <time.h>
#include <process.h>
#include <sys\stat.h>

// globals
const int NAM_L = 30;
const short r_order [ 50 ] = { 0, 1, 2, 0,
                               2, 0, 0, 1,
                               2, 0, 0, 1,
                               0, 1, 2, 0,
                               0, 2, 1, 0,
                               1, 0, 0, 2,
                               1, 0, 0, 2,
                               0, 2, 1, 0,
                               0, 1, 2, 0,
                               2, 0, 0, 1,
                               2, 0, 0, 1,
                               0, 0, 1,
                               2, 0, 0 };

short s_indic [ 37 ] = { 0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0 };

short r_indic [ 50 ] = { 0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0, 0, 0, 0, 0, 0, 0,
                         0, 0 };
FILE *datPtr;
short open_indic;
char dname[ 8 ];

char go_key, s_type;
char datf_name[ NAM_L ], fname[ NAM_L ];
short t_type;

unsigned int key_pause, number_files, trial, trial_pause;

// functions
void open_data_file( void );
```

```
void get_subj_info( void );
void get_run_info( void );
void get_params( void );
void get_trial_info( void );
void run_trial( void );
void play_out( char fn[ NAM_L ] );
void get_results( void );

void main( void )
{
 randomize( );
 open_data_file(  );
 get_subj_info(  );
 get_run_info(  );
 for ( trial = 0; trial < number_files; trial++ ) {
  get_trial_info(  );
  run_trial( );
 }
 clrscr( );
 cout << "\n\n\n   EXPERIMENT OVER. THANK YOU. ";
 delay( 2000 );
 get_results( );
 exit( 0 );
}

void open_data_file( void )
{
 clrscr( );

 open_indic = 0;
 while ( open_indic == 0 ) {
  strcpy( datf_name, "c:\\mconsol\\data\\" );
  cout << "\n\n\nType name for data file, no extension-> ";
  cin >> dname;
  strcat( datf_name, dname );
  strcat( datf_name, ".dta" );
  datPtr = fopen( datf_name, "a+t" );
  if ( datPtr == NULL ) {
   cerr << "\n Error opening file " << datf_name << endl;
   cerr << " get another name." << endl;
  }
  else open_indic = 1;
 }
}

void get_subj_info( void )
{

 // Subject information
 clrscr( );
 cout << "\n\nEnter subject's last name->";
 char s_name[ 25 ];
 cin >> s_name;
 fprintf( datPtr, "\n\n Name: %s, ", s_name );
 cout << "\nEnter subject's first name->";
 cin >> s_name;
 fprintf( datPtr, " %s", s_name );
 cout << "\nEnter subject's date of birth (dd/mm/yy)->";
 cin >> s_name;
 fprintf( datPtr, "\n Date of birth: %s", s_name );
 cout << "\n Enter D(yslexic) or C(ontrol)->" ;
 cin >> s_name;
 fprintf( datPtr, "\n Status: %s", s_name );
}

void get_run_info( void )
{
 clrscr( );
 struct dosdate_t e_date;
 struct time e_time;
 _dos_getdate( &e_date );
 gettime( &e_time );
 fprintf( datPtr, "\n Date: %d-%d-%d", e_date.day,
           e_date.month, e_date.year);
 fprintf( datPtr, "\n Time: %d.%d \n", e_time.ti_hour,
           e_time.ti_min );
 s_type = 'z';
 while ( ( s_type != 'v' ) && ( s_type != 'w' ) ) {
  cout << "\nEnter condition v (no interfering tones) or w (interfering tones)-->";
  cin >> s_type;
```

```
 }
 if ( s_type == 'v' )
  fprintf( datPtr, "\n No interfering tones " );
 else fprintf( datPtr, "\n Interfering tones " );
 get_params( );
}

void get_params( void )
{
 char parf_name[ NAM_L ];
 FILE *parfilePtr;
 open_indic = 0;
 while ( open_indic == 0 ) {
  strcpy( parf_name, "c:\\mconsol\\" );
  cout << "\n\n\nType name for parameter file, no extension-> ";
  cin >> dname;
  strcat( parf_name, dname );
  strcat( parf_name, ".mcp" );
  parfilePtr = fopen( parf_name, "r" );
  if ( parfilePtr == NULL ) {
   cerr << "\n Error opening parameter file " << parf_name << endl;
   cerr << " \n  Programme halting!! "; endl;
   delay(3000);
   exit(0);
  }
  open_indic = 1;
 }
 fprintf( datPtr, "\n From file %s", parf_name );
 fscanf( parfilePtr, "%d", &number_files );
 fscanf( parfilePtr, "%d", &key_pause );
 fscanf( parfilePtr, "%d", &trial_pause );
 fprintf( datPtr, "\n Stimuli %d", number_files );
 fprintf( datPtr, "\nKey pause %d ms", key_pause );
 fprintf( datPtr, "\nTrial pause %d ms", trial_pause );
 fclose ( parfilePtr );
}

void get_trial_info( ) {
  int ran0;
  static int ran0l = 13;
  short ran_indic;
  char hold0[ 4 ];
  t_type = r_order[ trial ];
//  cout << "\n Trial number " << trial;
  if ( s_type == 'v' ) strcpy ( fname, "v" );
  else  strcpy ( fname, "w" );
  switch( t_type ) {

    case 0 : ran_indic = 0;
             while ( ran_indic < 1 ) {
              ran0 = random( 13 );
              if ( ( s_indic[ ran0 ] < 2 ) && ( ran0l != ran0 ) ) {
//         cout << "\n\n Random numbers for 0 are "  << ran0 << "  " << ran0l ;
                s_indic[ ran0 ] += 1;
                ran0l = ran0;
                itoa ( ran0 + 1, hold0, 10 );
                strcat( fname, hold0 );
                strcat( fname, "_1s.wav" );
                ran_indic = 1;
              }
             }
             break;

    case 1 : ran_indic = 0;
             while ( ran_indic < 1 ) {
              ran0 = random( 12 ) + 13;
              if ( s_indic[ ran0 ] == 0 ) {
//               cout << "\n\n Random number for 1 is "  << ran0 ;
                s_indic[ ran0 ] = 1;
                itoa ( ran0 - 12, hold0, 10 );
                strcat( fname, hold0 );
                strcat( fname, "_1u.wav" );
                ran_indic = 1;
              }
             }
             break;

    case 2 : ran_indic = 0;
             while ( ran_indic < 1 ) {
              ran0 = random( 12 ) + 25;
```

```
              if ( s_indic[ ran0 ] == 0 ) {
//               cout << "\n\n Random number for 2 is "  << ran0 ;
                s_indic[ ran0 ] = 1;
                itoa ( ran0 - 24, hold0, 10 );
                strcat( fname, hold0 );
                strcat( fname, "_1d.wav" );
                ran_indic = 1;
               }
              }
  }
}

void run_trial( void )
{
 go_key = 'Z';
 while ( (go_key != 'G' ) && (go_key != 'Q' ) &&
          (go_key != 'g' ) && (go_key != 'q' )) {
  cout << "\n\n\n\n  Trial " << ( trial + 1 );
  cout << "\n\n\n\n        Press Q to quit or ";
  cout << "\n\n         Press G to hear a sequence of tones-> ";
  cin >> go_key;
  clrscr( );
 }
 if ( ( go_key == 'Q' ) || ( go_key == 'q' ) ) {
  clrscr( );
  cout << "\n\n\n Quitting !!";
  fprintf ( datPtr, "\n\nEarly quit." );
  exit( 0 );
 }
 fprintf ( datPtr, "\n Trial %d ", trial + 1 );
 delay( key_pause );
// cout << fname;
// delay(5000);
 play_out( fname );

 // Ask for response
 char Resp = 'Z';
 while ( (Resp != 'Y' ) && ( Resp != 'N' ) &&
         (Resp != 'y' ) && ( Resp != 'n' ) ) {
  clrscr( );
//  cout << "  First " << fname;
  cout << "\n\n\n  Respond Y(es) if first and last tones were the same";
  cout << "\n          N(o) if the two tones were different";
  cout << "\n\n  Please respond Y(es) or N(o) and hit Enter-->";
  cin >> Resp;
 }
 // Get response Resp
 fprintf( datPtr, "\n Trial type %d", t_type );
 fprintf( datPtr, "   Response: %c", Resp );

 // Evaluate it

 if ( t_type == 0 ) {
  if ( ( Resp == 'N' ) || ( Resp == 'n' ) )
       r_indic [ trial ] = 1;
 }
 else {
  if ( ( Resp == 'Y' ) || ( Resp == 'y' ) ) r_indic [ trial ] = 1;
 }
}

void play_out( char fn[ NAM_L ])
{
  int order_check;
//  cout << "\n\nIn play_out " << fn ;
  // Play wave
  order_check = spawnl( P_WAIT, "wav.exe", "wav.exe", fn, "/Q", NULL );
  if ( order_check == -1) {
   cout <<  "\n\nError from spawnl; halting";
   exit(1);
  }
}

void get_results( void ) {
  float diff_c = 0, same_c = 0, total_c = 0;
  int i;
  for ( i = 0; i < number_files/2 ; i++ ) same_c += r_indic [ i ];
  for ( i = number_files/2 ; i < number_files; i++ ) diff_c += r_indic [ i ];
  total_c = same_c + diff_c;
  same_c = same_c/(number_files/2);
```

```
  diff_c = diff_c/(number_files/2);
  total_c = total_c/number_files;
  same_c = 1 - same_c;
  diff_c = 1 - diff_c;
  total_c = 1 - total_c;
  fprintf( datPtr, "\n\n Correct response rate for same stimuli = %5.3f", same_c);
  fprintf( datPtr, "\n\n Correct response rate for different stimuli = %5.3f", diff_c);
  fprintf( datPtr, "\n\n Correct response rate overall = %5.3f", total_c);
  fclose( datPtr );
}
```

A2.3 Task 3, three long interstimulus interval effects

This programme was created by the author in collaboration with Professor Burton Rosner.

```
/* This programme presents stimuli and collects responses for a
   test of consolidation in auditory memory. On each trial, two target stimuli
   occur. They can be the same or differ by a semitone up or down.

   The variable nints sets the number of different possible intervals between
   between tones (ITI). At each ITI within a block of trials,
   two same pairs occur, one different pair by a semitone up, and
   one different pair by a semitone down. Over the nints ITIs, there
   are 4 * nints possible trial types. The order within each
   block is independently randomized.
   The input file must have the following structure:
   nints (number of intervals)
   (List of intervals, one per line:)
   I0
   I1
   .
   .
   I(nints -1)
   number of blocks
   names of the stimulus .wav files, one per line, in the following order:
   At I0, same pair repeated on two lines; pair differing by +1 semitone;
   pair differing by -1 semitone
   At I1, same pair repeated on two lines; pair differing by +1 semitone;
   pair differing by -1 semitone
   .
   .
   At I(nints - 1), same pair repeated on two lines; pair differing by +1 semitone;
   pair differing by -1 semitone
   key_pause (interval after key press in ms)
   trial_pause (interval after trial in ms)

   This programme runs under DOS. All file names must adhere to the DOS
   convention.                                                          */

// Includes
// Includes
#include <stdio.h>
#include <iostream.h>
#include <stdlib.h>
#include <conio.h>
#include <string.h>
#include <math.h>
#include <dos.h>
#include <ctype.h>
#include <time.h>
#include <process.h>
#include <sys\stat.h>


// globals
const int NAM_L = 30;
const int MAXINTS = 10;
const int FI_P_INT = 4;
FILE *datPtr, *stimPtr;

short open_indic;
char dname[ 8 ];

char go_key, s_type;
char datf_name[ NAM_L ], fname[ NAM_L ];
char stimuli [ FI_P_INT * MAXINTS ] [ 30 ];

int block, i, j, key_pause, nints, number_blocks, number_files,
          trial, bl_trial, trial_pause;
int iti[ MAXINTS ], response [ MAXINTS ] [ 3 ], trial_seq [ FI_P_INT * MAXINTS ];


// functions
void open_data_file( void );
void get_subj_info( void );
void get_run_info( void );
```

```
void get_params( void );
void set_block_info( void );
void run_trial( void );
void play_out( char fn[ NAM_L ] );
void get_results( void );

void main( void )
{

 randomize( );
 open_data_file(  );
 get_subj_info(  );
 get_run_info(  );
 for ( block = 0; block < number_blocks; block++ ) {
  set_block_info(  );
  for ( bl_trial = 0; bl_trial < number_files; bl_trial++ ) run_trial( );
 }
 clrscr( );
 cout << "\n\n\n   EXPERIMENT OVER. THANK YOU. ";
 delay( 2000 );
 get_results( );
 exit( 0 );
}


void open_data_file( void )
{
 clrscr( );

 open_indic = 0;
 while ( open_indic == 0 ) {
//  strcpy( datf_name, "c:\\mcon_p\\data\\" );
  cout << "\n\n\nType name for data file, no extension-> ";
  cin >> dname;
  strcpy( datf_name, dname );
  strcat( datf_name, ".dta" );
  datPtr = fopen( datf_name, "a+t" );
  if ( datPtr == NULL ) {
   cerr << "\n Error opening file " << datf_name << endl;
   cerr << " get another name." << endl;
  }
  else open_indic = 1;
 }
}

void get_subj_info( void )
{

 // Subject information
 clrscr( );
 cout << "\n\nEnter subject's last name->";
 char s_name[ 25 ];
 cin >> s_name;
 fprintf( datPtr, "\n\n Name: %s, ", s_name );
 cout << "\nEnter subject's first name->";
 cin >> s_name;
 fprintf( datPtr, "%s", s_name );
 cout << "\nEnter subject's date of birth (dd/mm/yy)->";
 cin >> s_name;
 fprintf( datPtr, "\n Date of birth: %s", s_name );
 cout << "\n Enter D(yslexic) or C(ontrol)->" ;
 cin >> s_name;
 fprintf( datPtr, "\n Status: %s", s_name );
}

void get_run_info( void )
{

 struct dosdate_t e_date;
 struct time e_time;
 clrscr( );
 _dos_getdate( &e_date );
 gettime( &e_time );
 fprintf( datPtr, "\n Date: %d-%d-%d", e_date.day,
           e_date.month, e_date.year);
 fprintf( datPtr, "\n Time: %d.%d \n", e_time.ti_hour,
           e_time.ti_min );
 get_params( );
}
```

```
void get_params( void )
{
 char itid[ NAM_L ], parf_name[ NAM_L ];
 FILE *parPtr;

 open_indic = 0;
 while ( open_indic == 0 ) {
 // strcpy( parf_name, "c:\\mcon_p\\" );
  cout << "\n\n\nType name for parameter file, no extension-> ";
  cin >> dname;
  strcpy( parf_name, dname );
  strcat( parf_name, ".mcp" );
  parPtr = fopen( parf_name, "r" );
  if ( parPtr == NULL ) {
   cerr << "\n Error opening parameter file " << parf_name << endl;
   cerr << " \n  Programme halting!! "; endl;
   delay(3000);
   exit(0);
  }
  open_indic = 1;
 }

 fprintf( datPtr, "\n From file %s", parf_name );
 fscanf( parPtr, "%d", &nints );
 for ( i = 0; i < nints; i++ ) {
  fscanf( parPtr, "%s", itid );
  iti [ i ] = atoi( itid );
 }
 fscanf( parPtr, "%d", &number_blocks );
 number_files = FI_P_INT * nints;
 for ( i = 0; i < number_files; i++ ) {
  fscanf( parPtr, "%s", stimuli [ i ] );
  stimPtr = fopen( stimuli [ i ], "rb" );
  if ( stimPtr == NULL ) {
   cerr << "\n The stimulus file doesn't exist; program halting!! " ;
   exit( 0 );
  }
  else {
   fprintf( datPtr, "\n %s", stimuli [ i ] );
   fclose( stimPtr );
  }
 }
 fscanf( parPtr, "%d", &key_pause );
 fscanf( parPtr, "%d", &trial_pause );
 cout << "  Parameter file read " << endl;

 fprintf( datPtr, "\n ITIs %d:", nints );
 for ( i = 0; i < nints; i++ ) fprintf( datPtr, "\n   %d", iti[ i ] );
 fprintf( datPtr, "\n Blocks: %d", number_blocks );
 fprintf( datPtr, "\nKey pause: %d ms", key_pause );
 fprintf( datPtr, "\nTrial pause: %d ms", trial_pause );
 fprintf( datPtr, "\n Stimuli " );
 for ( i = 0; i < number_files; i++ ) fprintf( datPtr, "\n   %s", stimuli[ i ] );
 for ( i = 0; i < nints; i++ )
  for ( j = 0; j < 3; j++ ) response [i ] [ j ] = 0;
 fclose ( parPtr );
}

void set_block_info( )
{
 int i_s, j_s, k_s, s_num;

 for ( i_s = 0; i_s < number_files; i_s++) trial_seq [ i_s ] = -1;
 for ( i_s = 0; i_s < number_files; i_s++) {
  j_s = -1;
  while ( j_s < 0 ) {
   s_num = random( number_files );
   for ( k_s = 0; k_s < number_files; k_s++ )
    if ( trial_seq [ k_s ] == s_num ) break;
   if ( k_s == number_files ) {
    trial_seq [ i_s ] = s_num;
    j_s = 0;
   }
  }
 }
}

void run_trial( void )
{
 int intvl, pr_type, t_num, tt_num;
```

```
 go_key = 'Z';
 t_num = trial_seq [ bl_trial ] ;
 strcpy( fname, stimuli [ t_num ] );
 intvl = t_num / FI_P_INT;
 pr_type = t_num % FI_P_INT;
 if ( pr_type == 0 ) pr_type++;
 // Types now same=1, up=2, down=3
 while ( (go_key != 'G' ) && (go_key != 'Q' ) &&
          (go_key != 'g' ) && (go_key != 'q' )) {
  clrscr( );
  tt_num = block * nints * FI_P_INT + bl_trial + 1;
  cout << "\n\n\n\n  Trial " << tt_num;
  cout << "\n\n\n\n        Press Q to quit or ";
  cout << "\n\n         Press G to hear a sequence of tones-> ";
  cin >> go_key;
 }
 if ( ( go_key == 'Q' ) || ( go_key == 'q' ) ) {
  clrscr( );
  cout << "\n\n\n Quitting !!";
  fprintf ( datPtr, "\n\nEarly quit." );
  exit( 0 );
 }
 fprintf ( datPtr, "\n Trial %d   File %s", tt_num, fname );
 delay( key_pause );
 play_out( fname );

 // Ask for response
 char Resp = 'Z';
 while ( (Resp != 'Y' ) && ( Resp != 'N' ) &&
         (Resp != 'y' ) && ( Resp != 'n' ) ) {
  clrscr( );
  cout << "\n\n\n  Respond Y(es) if first and last tones were the same";
  cout << "\n          N(o) if the two tones were different";
  cout << "\n\n  Please respond Y(es) or N(o) and hit Enter-->";
  cin >> Resp;
 }
 // Get response Resp
 fprintf( datPtr, "\n Trial type %d", pr_type );
 fprintf( datPtr, "   Response: %c", Resp );

 // Evaluate it

 if ( pr_type == 1 ) {
  if ( ( Resp == 'Y' ) || ( Resp == 'y' ) )
   response [ intvl ] [ pr_type - 1 ] += 1;
 }
 else {
  if ( ( Resp == 'N' ) || ( Resp == 'n' ) )
   response [ intvl ] [ pr_type - 1 ] += 1;
 }
}

void play_out( char fn[ NAM_L ])
{
 int order_check;
 //  cout << "\n\nIn play_out " << fn ;
 // Play wave
 order_check = spawnl( P_WAIT, "wav.exe", "wav.exe", fn, "/Q", NULL );
 if ( order_check == -1) {
  cout <<  "\n\nError from spawnl; halting";
  exit(1);
 }
}

void get_results( void ) {

 float diff_c, down_c = 0, num_b, num_b2, same_c = 0, total_c = 0, tt_2, tt_4, tt, up_c = 0;
 float rdata [ MAXINTS ] [ 4 ];
 int i;

 for ( i = 0; i < nints ; i++ ) {
  same_c += response [ i ] [ 0 ];
  up_c   += response [ i ] [ 1 ];
  down_c += response [ i ] [ 2 ];
 }
 total_c = same_c + up_c + down_c;
 // Float the data table and trials
 for ( i = 0; i < nints ; i++ ) {
  rdata [ i ] [ 0 ] = float( response [ i ] [ 0 ] );
```

```
 rdata [ i ] [ 2 ] = float( response [ i ] [ 1 ] );
 rdata [ i ] [ 3 ] = float( response [ i ] [ 2 ] );
 rdata [ i ] [ 1 ] = rdata [ i ] [ 2 ] +  rdata [ i ] [ 3 ];
}
num_b = float( number_blocks );
num_b2 = 2.0 * num_b;
for ( i = 0; i < nints ; i++ ) {
 for ( j = 0; j < 4 ; j++ ) {
  switch ( j ) {
   case 0 : rdata [ i ] [ j ] /= num_b2;
            break;
   case 1 : rdata [ i ] [ j ] = ( rdata [ i ] [ 2 ] + rdata [ i ] [ 3 ] ) / num_b2;
            break;
   default: rdata [ i ] [ j ] /= num_b;
  }
 }
}
fprintf( datPtr, "\n\n           Correct Rate\n  Interval  Same  Different Up   Down"
);
for ( i = 0; i < nints ; i++ )
 fprintf( datPtr, "\n    %4d     %3.2f   %3.2f   %3.2f   %3.2f",
           iti [ i ], rdata [ i ] [ 0 ], rdata [ i ] [ 1 ],
           rdata [ i ] [ 2 ], rdata [ i ] [ 3]);
tt = number_blocks * number_files;
tt_2 = tt / 2;
tt_4 = tt / 4;
diff_c = up_c + down_c;
up_c /= tt_4;
down_c/= tt_4;
same_c /= tt_2;
diff_c /= tt_2;
total_c /= tt;
fprintf( datPtr, "\n\n Correct response rate for up one semitone = %5.3f", up_c);
fprintf( datPtr, "\n\n Correct response rate for down one semitone  = %5.3f", down_c);
fprintf( datPtr, "\n\n Correct response rate for same stimuli = %5.3f", same_c);
fprintf( datPtr, "\n\n Correct response rate for different stimuli = %5.3f", diff_c);
fprintf( datPtr, "\n\n Correct response rate overall = %5.3f", total_c);
fclose( datPtr );
}
```