AUDITORY SELECTIVE ATTENTION IN TYPICAL DEVELOPMENT AND AUDITORY PROCESSING DISORDER

HANNAH J STEWART, BSc., MA, MSc.

Thesis submitted to the University of Nottingham
for the degree of *Doctor of Philosophy*

DECEMBER, 2016

Thesis Abstract

This thesis examines auditory selective attention as a possible cause of Auditory Processing Disorder (APD). APD is a diagnosis based on the clinical needs of the 5% of children who present with listening difficulties but demonstrate normal hearing. This thesis will focus on developmental APD, which affects children with no known infection, trauma or primary cause inducing their listening difficulties. It will seek to address the current lack of understanding of the root causes of APD, which leads to significant variation in clinical referral routes, resulting in inconsistent methods of diagnosis and treatment.

APD has historically been approached via a bottom-up route of assessing auditory processing skills, such as temporal-spatial abilities. The inconsistent results of bottom-up studies has led to debate regarding the diagnosis and treatment of APD, resulting in extensive batteries of tests being conducted on children. However, recent evidence suggests that studies on the causality of APD should be refocused on top-down processes such as auditory attention and memory – hence the focus of this thesis on auditory selective attention.

The thesis begins by assessing a new test of auditory selective attention, the Test of Attention in Listening (TAiL), to ensure that it measures auditory rather than supramodal attention. Having established the modality-specificity of TAiL, the thesis examines the development of auditory selective attention to both spatial and non-spatial auditory stimulus features, across tasks of varying levels of perceptual demand. Finally, the thesis assesses the selective attention ability of children with listening difficulties. Specifically, listeners' selective attention is assessed in both the auditory and visual domains, using both spatially- and non-spatially-based tasks.

If auditory selective attention deficits are found in those with listening difficulties, this will provide a basis for the diagnosis and treatment of APD to be constructed and managed from a psychological viewpoint rather than an audiological one.

Copyright Permissions

- Chapter 3 is adapted from the paper:

  Stewart, H. J., and Amitay, S. (2015). Modality-specificity of Selective Attention Networks. *Frontiers in Psychology, 6*, 1826

- Chapter 4 is adapted from the paper:

  Stewart, H. J., Amitay, S., and Alain, C. (Submitted). Neural correlates of distraction and conflict resolution for nonverbal auditory events.

- Data from Chapter 4 were presented in:

  Stewart, H. J., Amitay, S., and Alain, C. (2015). The Test of Attention in Listening (TAiL): An event-related potential study. *Cognitive Hearing Science for Communication, Linköping, Sweden. Oral presentation.*

  Stewart, H. J., Amitay, S., and Alain, C. (2015). The Test of Attention in Listening (TAiL): An event-related potential study. *Cognitive Neuroscience Society, San Francisco, USA. Poster presentation.*

- Data from Chapters 5 and 6 were presented in:

  Stewart, H. J., Kang, H. J., Barry, J., and Amitay, S. (2015). The Test of Attention in Listening (TAiL): Development of Auditory Attention. *Cognitive Hearing Science for Communication, Linköping, Sweden. Poster presentation.*

- Data from Chapter 7 were presented in:

  Stewart, H. J., Barry, J. G., and Amitay, S. (2016). Selective attention and Auditory Processing Disorder. *British Society of Audiology, Coventry, England. Poster presentation.*

For the parents.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

aANT	Auditory Attention Network Test
ADHD	Attention-Deficit Hyperactivity Disorder
ANOVA	Analysis of Variance
APD	Auditory Processing Disorder
ASA	Auditory stream analysis
ASD	Autism Spectrum Disorder
ASS	Auditory stream segregation
BESA	Brain Electrical Source Analysis
BSA APD SIG	British Society of Audiology APD Special Interest Group
CANS	Central auditory nervous system
CAPD	Central auditory processing disorder
dB	Decibel
DfDL	Different frequency, different location trial
DfSL	Different frequency, same location trial
ECLiPS	Evaluation of Children's Listening and Processing Skills
EEG	Electroencephalography
ERP	Event-related potential
FD	Frequency discrimination
fMRI	Functional magnetic resonance imaging
GSR	Galvanic skin response
HL	Hearing level
Hz	Hertz
ISI	Inter-stimulus-interval

LDN	Listening difficulties in noise
LiSN-S	Listening in Spatialised Noise-Sentences
M	Mean
MAA	Minimum audible angle
ms	Miliisecond
NEPSY	Developmental NEuroPSYchological Assessment
NHS	National Health Service
OME	Otitis media with effusion
RT	Reaction time
SAS	Social Aptitudes Scale
SD	Standard deviation
SEM	Standard error of the mean
SfDL	Same frequency, different location trial
SfSL	Same frequency, same location trial
SLI	Specific language impairment
SPL	Sound pressure level
T1	First tone
T2	Second tone
TAiL	Test of Attention in Listening
TEA	Test of Everyday Attention
vANT	Visual Attention Network Test
WASI	Wechsler Abbreviated Scale of Intelligence
YA	Young adults

CHAPTER 1

Background

The main aim of this thesis is to assess auditory selective attention in children who experience listening difficulties in noise, often diagnosed as Auditory Processing Disorder (APD). This thesis also has the secondary aim of assessing the typical development of auditory selective attention.

This chapter sets out the pathways taken to assess the overarching aims of this thesis. It first explores the shift of focus regarding APD from bottom-up to top-down processes. The chapter then introduces the theory of auditory selective attention used to assess listeners' abilities in the studies presented within this thesis. Finally, this chapter discusses the current methods of assessing auditory selective attention in children, and their suitability for use in this thesis.

1.1 Auditory Processing Disorder

Auditory Processing Disorder (APD), previously known as Central Auditory Processing Disorder (CAPD), refers to a difficulty in processing the auditory world (Campbell, 2011). Its definition, diagnosis, and even its existence have been the subject of debate for more than 30 years (Moore, 2011). Throughout this time, APD has been used as a clinical diagnosis for those who present at audiology services with normal peripheral hearing ability, yet have a deficit in their ability to identify or discriminate sounds. This typically manifests in a poor ability to understand speech in noisy environments, such as following a conversation in a coffee house or listening in a classroom (Dawes and Bishop, 2009; Jerger and Musiek, 2000; Moore et al., 2013). Due to such difficulties in processing the meaning of sound, these listeners are often described as being uncertain about what they hear (Jerger and Musiek, 2000).

The British Society of Audiology APD Specialist Interest Group (BSA APD SIG) (2013) split APD into three categories. First, developmental APD, which initially presents in childhood with normal peripheral hearing and no other causation. Second, acquired APD from, for example, an infection or trauma. Third, secondary APD, which occurs concurrent to, or is caused by, a hearing impairment, such as otitis media with effusion (OME, or glue ear). This thesis will focus on developmental APD.

The BSA APD SIG (2013) suggested that developmental APD is characterised by poor perception and localisation of speech and non-speech sounds. This is not caused by a failure to understand simple instructions or peripheral hearing loss, but impacts the ability to listen and respond appropriately. The BSA APD SIG also discussed APD's origins in impaired neural function of the auditory system and higher-level processing, such as auditory attention and auditory memory. The individuals affected report that these symptoms are exacerbated in noisy environments. These symptoms lead to more time being required to process and respond to auditory information (Campbell, 2011).

At present, APD is identified through a variety of referral routes ranging from audiologists to educational psychologists. This results in inconsistency in the diagnosis and treatment of the symptomatology outlined above. It is therefore vital that the level, or levels, of auditory processing at which the disorder occurs are identified, so that more consistent diagnosis and treatment plans can be made (Moore et al., 2013; Moore, 2006). With an estimated occurrence rate of 5%[1] (Moore et al., 2010, 2013), there is a clear clinical need for further improvement in the science underpinning the diagnosis and management of APD (Moore, 2011).

1.1.1 Theories underlying APD

The theories regarding the underlying causality of APD range from bottom-up theories discussing a deficiency within the central auditory nervous system (CANS) to more recent theories considering top-down contributions to listening difficulties, such as auditory attention and memory.

[1]This estimate is based on the number of children referred to audiology services who report listening difficulties but are found not to have hearing loss.

Bottom-up theories

Until recently, it was widely believed that individuals who present with listening difficulties and perform poorly on behavioural tests assessing speech and non-speech auditory processing (e.g. temporal resolution or spatial discrimination) should be diagnosed with APD (Moore, 2011). Performance on such tests has been found to match that of patients with lesions in the CANS (American Speech-Language-Hearing Association Working Group on Auditory Processing Disorders, 2005), and it has therefore been concluded that these low-performing individuals have CANS pathology[2] (Jerger and Musiek, 2000; Shinn et al., 2009).

Children diagnosed using this method are thought to display a developmental delay or abnormality within the CANS and therefore function as if a lesion exists (Cherry, 1992). However, evidence has shown that some individual children presenting with the classic APD symptoms (e.g. difficulty understanding speech in noisy environments) can demonstrate central auditory processing thresholds at the same level as adults, suggesting that their auditory processing ability is not underdeveloped (Halliday et al., 2008).

Furthermore, a longitudinal developmental study found no causal connection between auditory processing and the ability to recognise speech under difficult conditions (Watson and Kidd, 2006). Similarly, adults with a history of listening difficulties displayed low correlations between speech recognition and auditory processing ability, specifically spectral-temporal acuity (Watson et al., 1996). Instead, they showed stronger correlations between visual speech recognition (i.e. silent lip-reading) and auditory speech recognition. Together these studies suggest that, in both children and adults, higher-level abilities are used to identify speech in difficult circumstances where speech becomes fragmented (Watson and Kidd, 2006).

A closer investigation of the validity of the theory that bottom-up auditory processing causes the listening difficulties of APD was conducted by the Medical Research Council's Institute of Hearing Research (Moore et al., 2010). Rather than testing only children who had been diagnosed with APD through different referral routes, definitions and tests, the study used a population approach. A total of 1,469 children with normal hearing

[2]Often in these cases, the individuals are diagnosed with CAPD due to the anatomy of the CANS.

were recruited from the general population to capture a sample with APD symptoms, based on the estimated prevalence of APD at 5%.

A large test battery was administered to the children, including overall auditory processing performance measures (i.e. speech-in-noise: vowel-consonant-vowel non-words in speech-modulated noise) and individual basic auditory processing tasks (i.e. frequency discrimination (FD) and simultaneous masking). Additionally, measures of speech perception, cognition and communication were included to test the alternate hypothesis that the listening difficulties of APD are instead caused by difficulties in the top-down processing of sound (i.e. cognitive deficits).

Moore and colleagues found no consistent relationship between the overall auditory processing performance scales and individual auditory processing tasks. It was found that the majority of the auditory processing measures were not related to care-giver reports of listening and communication ability – the symptoms considered typical of APD. Instead, the children scoring in the bottom 5% of auditory processing performance tended to have cognitive (non-verbal IQ, memory, language and literacy) rather than sensory difficulties. This suggests that instead of bottom-up auditory processing deficits leading to poor performance on auditory tasks, the classic listening difficulties of APD are caused by top-down cognitive problems (Moore et al., 2010).

Top-down theories

In their 'white paper', the BSA APD SIG state that cognitive difficulties, for example in auditory attention and memory, must be included in the definition of developmental APD (Moore et al., 2013). With neural responses to sound matured by the age of 4 and behavioural responses continuing to mature past the age of 10, the behavioural delay of auditory processing found in APD may occur because hearing involves neural processing beyond the recognised auditory system (Moore, 2012). The ability to listen in noise and in a multi-talker environment is at the juncture of sensory processing and cognition, and comprises interactions between attention, memory and auditory processing.

Hearing has been described as a sensory-based passive process, and listening as a cognitive-based active process (Beck and Flexer, 2011). For example, many auditory processing tasks require a high level of cognitive-ability, such as working memory in a three-alternative frequency discrimination task. However, little research has been conducted on the contribution of higher-order cognitive abilities, such as attention and memory, to APD, despite a call for such work over a decade ago (Bellis, 2003).

With a shift in the focus of research has come a shift in the labeling of these difficulties. Due to varying methods of diagnosis across countries and research institutions, some studies explicitly refer to APD – a disorder – while others refer to listening difficulties in noise (LDN) – a set of symptoms.

Two key studies have examined the top-down abilities of children (aged 10-15) to reorient their attention and inhibit their responses to auditory stimuli (Dhamani et al., 2013; Sharma et al., 2014). Firstly, Dhamani et al. (2013) compared a clinical group of children with persistent LDN, and a history of OME, to typically developing peers and adults on a test assessing the ability to switch attention between auditory syllable targets. Importantly, in clinical tests of hearing sensitivity and auditory processing, the performance of the two groups of children was interchangeable. By asking listeners to identify a target at expected and unexpected times, the paradigm was able to capture the listener's ability to switch their attention between auditory stimuli and their ability to recover from unexpected auditory stimuli. Dhamani and colleagues' (2013) results showed that the control children were slower in switching their attention than the control adults, indicating that this skill was still developing. The results also showed that the children with listening difficulties took significantly longer to reorient their attention to auditory stimuli compared to their control peers. Furthermore, this group of children with listening difficulties responded significantly more to false alarms, demonstrating a reduced control of inhibition and suggesting an increased distractibility.

Secondly, Sharma et al. (2014) used the same paradigm to assess attention switching to auditory stimuli. This study also tested memory, auditory processing skills and a caregiver questionnaire regarding the children's listening abilities. The study compared a group of 10-15 year olds with persistent LDN, who presented with no middle ear pathology, to their typically developing peers. Both the questionnaire and behavioural results showed that the listening difficulty group was consistently worse than their peers in the auditory memory tasks and at switching their attention between auditory stimuli. Together these results suggest that the ability to allocate attention to auditory information is vital for effective listening skills.

Increasing evidence points to a pivotal role for attention in listening skills, especially in children with LDN. This thesis focuses on auditory selective attention, the definition of which is parallel to the main reported shortfall of those experiencing LDN – the ability to listen to specific task-relevant information while inhibiting listening to task-irrelevant information.

1.2 Auditory selective attention

Typically the content and sound sources of a listening experience are dynamic. With a limited amount of perceptual resources available (Lee et al., 2013) the ability to listen in a noisy environment calls upon selective attention. This allows an individual to efficiently focus on information relevant to ongoing goals in order to protect their limited perceptual resources from becoming overloaded (Pashler et al., 2001). Auditory selective attention involves two main processes: first grouping distinct auditory features to the same real-world source (object-formation) and second prioritising one stream or object over others for further processing (object-selection) (Shinn-Cunningham, 2008) (Figure 1.1). Only after identifying auditory objects can selective attention allow orientation to specific information for further processing, while simultaneously suppressing irrelevant or distracting information (Stevens and Bavelier, 2012). Neuronal responses in the auditory cortex can be strongly modulated by attention (Hubel et al., 1959) with influences on event-related potential (ERP) responses a mere 20-50 ms after stimulus onset (P20-P50) (Hillyard et al., 1973; Woldorff and Hillyard, 1991). Therefore to be effective listeners must develop excellent auditory scene analysis (ASA) skills to segregate and group sounds into auditory streams and objects (Carlyon, 2004) and be very proficient in the allocation of their attention to relevant auditory streams and objects for further processing.

ASA is a method of pattern recognition that allows the nervous system to breakdown a complex auditory environment into its simple, separate sources (Bregman and Rudnicky, 1975). The principles of ASA are similar to the Gestalt principles of grouping in vision (Bregman, 1993). In vision perceptual grouping can be based on physical properties such as colour, spatial proximity, or the smoothness of an object's contour. In audition

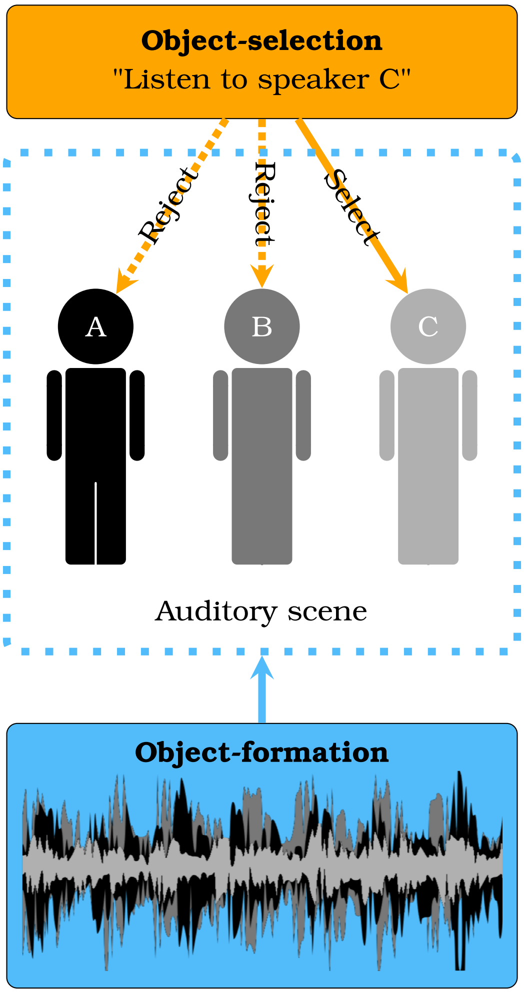

Figure 1.1: The two main processes of auditory selective attention. First, object-formation sorts incoming sound waves into different talkers (A, B and C). Second, object-selection chooses the relevant talker (C) for further processing and rejects the irrelevant talkers (A and B).

grouping can be based on physical properties such as a talker's pitch, spatial proximity, or the speed of talker pitch changes (Bregman, 1990). For example, the auditory system would generally split tones of widely varying frequencies into multiple auditory objects and form individual objects based on a narrower range of frequencies. Importantly, in ASA principles, as in Gestalt, an element cannot simultaneously be part of multiple objects. Thus successful perceptual grouping allows the individual to reject a source as a whole without its elements intruding on another concurrent object which is being accepted (Bregman and Rudnicky, 1975).

Many studies show that listeners can only effectively attend to one auditory object at a time (Shinn-Cunningham, 2008), but the method of selectively attending to a single object has been debated for many years. Dichotic listening paradigms have been widely used to assess auditory selective attention, whereby different talkers are presented to each ear and the listener is asked to shadow a specific channel, defined by the talker and/or ear of presentation. Initial studies reported that listeners were unable to recall the semantic content of the ignored channel and were only able to report its physical features, such as the talker's gender or whether the message was speech or pure tones. This led Broadbent (1956) to introduce the filter theory, whereby, due to limited attentional resources, a listener filters incoming sounds early based on superficial physical features (e.g. location, pitch, intensity) characteristics, leaving semantic processing for only the channel to which the attention was allocated. This theory can be categorised as an early selection theory.

However, Broadbent's filter theory was seriously challenged by dichotic listening studies indicating semantic processing of the unattended channel, as evidenced by a third of the listeners reporting hearing their own names in the unattended channel (Moray, 1959; Wood and Cowan, 1995). This led Deutsch and Deutsch (1963) to introduce a late selection theory which describes how all information, regardless of whether it is attended to or not, is processed for its semantic meaning. This leaves filtering to occur just prior to the listener becoming aware of the information. This theory proposes that listeners would be equally good at identifying key words in both the attended and unattended channels. However, evidence shows that identification is better in the attended channel (Treisman and Geffen, 1967).

An intermediate selection theory was introduced by Treisman (1960) who described auditory selective attention taking place in two phases. First the to-be-ignored channel is attenuated early based on physical features and second only data that reaches a threshold is further processed for identification. While all data from the attended-to channel reach the required threshold, only some of the attenuated data do so. Treisman's attention theory describes how the data are processed in a systematic way, starting with simple information such as physical characteristics, syllabic pattern and individual words, before moving to more complex information such as grammatical structure and meaning. However, this theory has been critiqued for not explaining how the semantic analysis works or the precise nature of the attenuation process (Spence and Santangelo, 2010).

Whereas previous studies had typically used subjective reporting and forced choice recognition, in a critical study by Corteen and Dunn (1974) galvanic skin responses (GSR) were used to determine at what stage of processing auditory selection was made. In their paradigm listeners were asked to shadow a single channel during a dichotic listening paradigm while simultaneously trying to monitor both channels for city names, having been conditioned to expect an electric shock upon hearing specific city names. While the listeners only indicated hearing a city name in less than 1% of occurrences (in both the attended and unattended channels) across participants, 40% of occurrences showed a measurable phasic GSR. Furthermore, the GSR did not just occur in response to the city names associated with conditioning; the effect also generalised to unexpected new city names. Therefore while the listeners were seemingly unaware of the city names, suggesting early selection, the GSR results indicate that the auditory stimuli had been processed to a semantic level, suggesting late selection.

A further development in the theories of selective attention mechanisms was the proposal that selection could occur anywhere along a continuum of auditory information processing from early through to late (Johnston and Heinz, 1978, 1979). This theory suggests that the ease with which the listener is able to discriminate the target from the non-target stimuli determines the depth of processing of non-target stimuli. The idea of selection being determined by the ease of teasing the target from its environment was expanded on by Lavie with her hybrid load theory of selective attention (1995).

Lavie (1995) defined a selection mechanism based on two types of capacity-limited processes: perceptual load and cognitive load. She proposed that if a target is perceptually difficult to discriminate from its surroundings then the task is performed at a high level of perceptual load, and distracting irrelevant stimuli are not processed due to a lack of available capacity – indicating early selection. If the target is easy to separate from the irrelevant stimuli then the task can be performed at a low level of perceptual load, and any remaining perceptual capacity is automatically used to process the irrelevant stimuli – indicating late selection. Under a low perceptual load the processed irrelevant stimuli may interfere with the subsequent processing of the target. Individuals require a cognitive capacity, in particular working memory (WM) and executive control processes (de Fockert et al., 2001; Lavie et al., 2004), in order to maintain the task goals and remain goal-orientated. Lavie proposed that if the individual is performing only the perceptual task then there is a low cognitive load and so they have the capacity to filter out irrelevant stimuli. However, if they are performing a secondary task alongside the primary perceptual task, they will experience a high cognitive load, causing a decrease in their ability to filter our irrelevant stimuli.

The load theory has been critiqued for its circular argument of task load as there is not a clear behavioural method to quantify load. While operational definitions of load are typically used, brain imaging evidence illustrates that increased task processing demands correspond to increased cellular activity in brain regions specific to the task's stimuli (e.g. language – Keller et al., 2001; visual – Carpenter et al., 1999; and speech – Wong et al., 2004). Dual-task paradigms have also illustrated that when the processing load of one task increases (perceptual – Rees et al., 1997; or cognitive – de Fockert et al., 2001) the cortical activity related to the other task significantly reduces.

This thesis assesses auditory selective attention in typical development and in children with LDN. In order to have good listening skills one must not only develop proficient ASA skills but also learn to effectively allocate attention to relevant auditory information for further processing while inhibiting irrelevant auditory information. With its emphasis on a selection mechanism based on different capacity limitations, the load theory of selective attention provides the theoretical underpinning of this thesis.

1.3 Assessing the development of auditory selective attention

Newborns quickly begin visually searching for the source of a sound (e.g. Mendelson and Hath, 1976; Wertheimer, 1961; Muir and Field, 1979), having been able to hear and recognise sounds from within the womb (Partanen et al., 2013). This close relationship between what the child hears and how they direct their visual attention continues throughout development as the child learns how to deal with a multitude of information sources, some of which may be irrelevant and conflict with information to which they should be attending (Smith and Katz, 1996). No matter the modality, to be able to process relevant objects an individual must first be able to differentiate between different objects, select the relevant information and suppress the distracting irrelevant information (Gomes et al., 2000). Auditory processing develops in three main stages: first, the neural mechanisms for coding sound mature; second, children learn how to use finer acoustic details to identify a sound; and third, children develop the ability to flexibly choose the acoustic information they use to identify sounds (Werner, 2007). Behavioural evidence shows that by age 5, children are able to discriminate sounds by basic auditory characteristics (e.g. frequency, duration and intensity) at the same level as adults (Jensen and Neff, 1993). Children then learn how to orient to the aspect of the auditory stimuli that are relevant to the current task (Cherry, 1981).

A wide range of different stimuli and methodologies have informed current understanding of the development of visual selective attention (for reviews see: Enns and Girgus, 1985; Hanania and Smith, 2010; Plude et al., 1994). In comparison, very few studies have attempted to measure auditory selective attention directly (Lee et al., 2014; Shinn-Cunningham, 2008). Instead, the development of auditory selective attention orienting abilities has typically been assessed through dichotic listening paradigms (Broadbent, 1956; Coch et al., 2005), with a focus on differences in perceiving linguistic vs. nonlinguistic targets.

In a dichotic listening paradigm the listener hears multiple talkers simultaneously, typically one talker in each ear, and is given instructions to either shadow or report specific information said by one talker (e.g. repeat the talker in the right ear, or report the numbers said by the female talker). Alternatively, the listener can be asked to switch between talkers throughout the paradigm via visual or auditory cues (e.g. tones) (Sætrevik, 2012). The listener's auditory selective attention abilities are then examined by measuring how quickly they are able to reorient their attention to the new talker or what errors they make (e.g. how many numbers they missed from the female talker or how many numbers they repeated from the male talker). Listeners who struggle to reallocate their attention in accordance with the task instructions are thought to be unable to employ flexible strategies and therefore have poor selective auditory attention (Pearson and Lane, 1991).

Seven year olds have been repeatedly shown to outperform younger children in the presence of distracting auditory and visual information (Bartgis et al., 2008; Ridderinkhof and Molen, 1995). Cross-sectional behavioural and ERP selective listening studies have illustrated improvement in auditory selective attention ability in children aged 5 to 10, and again through to adolescence (e.g. Maccoby and Konrad, 1966; Coch et al., 2005). For a long time it has been thought that with increasing age comes the ability to focus on information designated as relevant by marking it for further activation, while inhibiting the intrusions from the distracting information (e.g. Lane and Pearson, 1982). However, as evidenced by dichotic selective listening paradigms, older children are able to refrain from reporting distracting words despite having processed them, compared to younger children who cannot inhibit the information that they possess (Doyle, 1973). This suggests that the skills that develop with age are the speed of voluntarily orienting attention and the ability to reliably disengage when information is deemed irrelevant – not the marking of relevant information for further processing (Rueda et al., 2004; Coch et al., 2005).

Even after many years of research, the relative contributions of sensory processing, attention and supramodal processes to the performance of dichotic listening tasks are not well understood (Schmithorst et al., 2013). The use of dichotic listening paradigms is heavily reliant on verbal processing, which can cause intelligibility issues due to dichotic syllable pairs fusing (Repp, 1977). With language processing clearly not limited to the bottom-up auditory stream (Moore, 2015), it is vital that a test used to explore the development of auditory selective attention not be dependent on speech stimuli. This is even more important when assessing the ability of clinical groups, such as this thesis' target group of children with APD, which has a high commonality with language-based developmental difficulties such as dyslexia and specific language impairment (SLI) (Dawes and Bishop, 2009; Sharma et al., 2009). Therefore these children's auditory selective attention abilities should be assessed without the complications of potentially atypical language development. This thesis assesses the use of a new non-verbal auditory test of selective attention in order to achieve this goal, the Test of Attention in Listening (TAiL) (Zhang et al., 2012).

1.4 Summary

Listening is a dynamic process due to the constantly changing auditory environment. Selective attention (orienting to the relevant auditory information while inhibiting the irrelevant auditory information) is vital to achieving successful listening in a noisy environment without overloading the limited perceptual resources. It is clear from the discussion above that APD is a prevalent and complicated disorder. Researchers are moving away from a bottom-up approach to understanding APD and are focusing more on the top-down cognitive contributions to APD. Specifically, several researchers state that attention and memory may hold the key to further understanding of APD (e.g. Ahmmed et al., 2014; Moore et al., 2010; Watson and Kidd, 2006). In recent years several studies have investigated switching attention abilities in children with listening difficulties and have shown promising results (Dhamani et al., 2013; Sharma et al., 2014).

This thesis considers developmental APD from the viewpoint of auditory selective attention, as children with LDN present with inability to listen to a specific target in noise – the exact skill that auditory selective attention describes. This thesis is structured around two pathways, which together build towards its main aim (Figure 1.2). First a new auditory selective attention paradigm is evaluated (Chapters 3 and 4), followed by the investigation of the typical developmental trajectory of auditory selective attention using this paradigm (Chapters 5 and 6). This thesis then investigates auditory selective attention in children who, despite having normal audiograms, experience LDN (Chapter 7). It is predicted that children with developmental APD (i.e. listening difficulties with normal peripheral hearing and no known aetiology) have difficulty orienting to the relevant auditory information and lack attentional control to successfully ignore conflicting and irrelevant auditory information.

Re-evaluating the approach to APD could have a transformative effect on the diagnosis and treatment of APD. If deficits are indeed found in cognitive skills such as attention and memory, this could lead to a new approach to diagnosis and interventions. Current interventions are mostly audiological and designed to boost the bottom-up stimuli, or training to maximise the utilisation of what the individual is able to hear. Instead, it may be that cognitive based training such as attention and/or working memory have a bigger impact on improving listening ability.

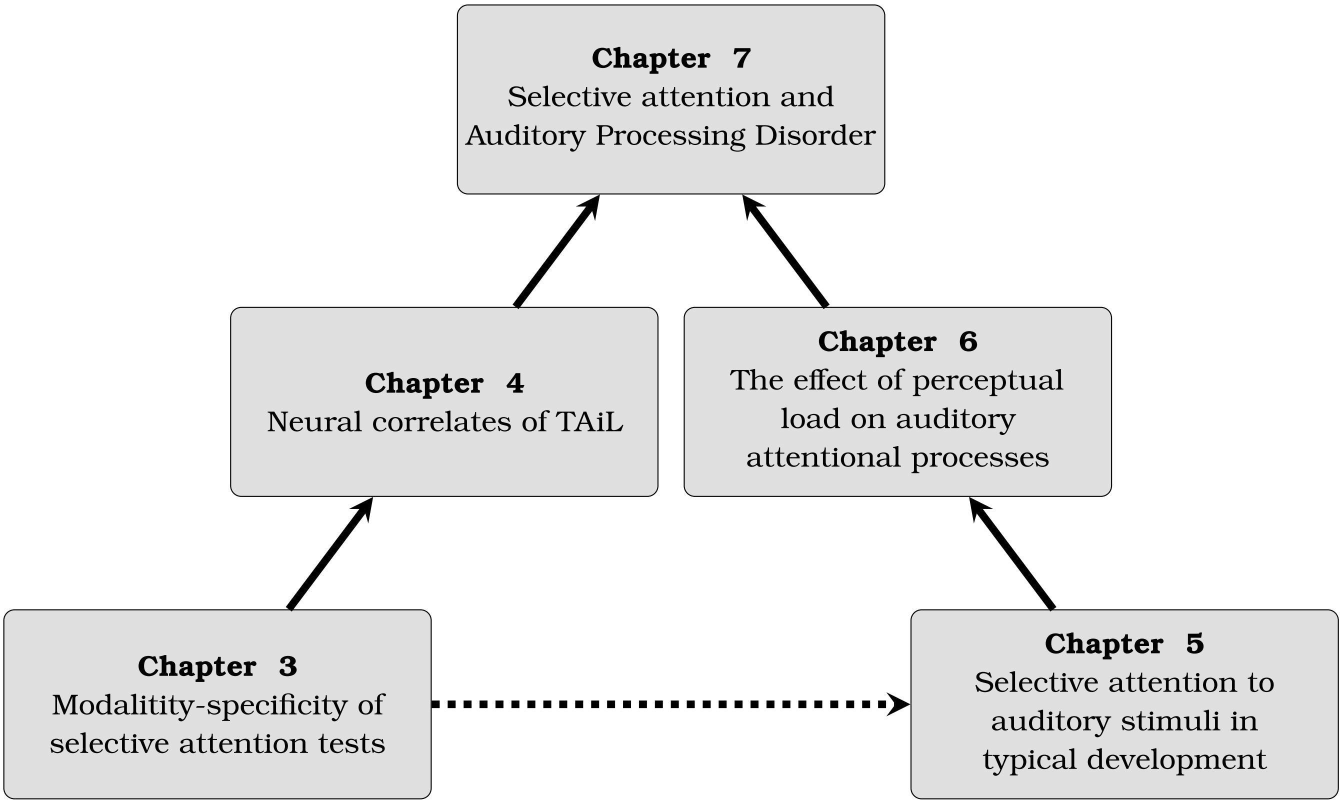

Figure 1.2: Layout of how the chapters feed into the two pathways towards the main aim of this thesis.

CHAPTER 2

General methods

This chapter introduces the paradigm used in this thesis as a method to quantify selective attention to auditory stimuli. The paradigm's outcome measures, parameters and testing environment are described.

TAiL was designed to provide objective measurements of selective attention through the use of auditory stimuli (Zhang et al., 2012), and is used throughout this thesis. TAiL comprises two tasks: attend-frequency and attend-location. Both tasks consist of the same stimuli: simple, sequential, pure tone pairs varying in frequency and/or location. However, in each task the listener is told to attend to only one of these sound features while ignoring the other. The listener then answers whether the sound pair was same or different with respect to the task's relevant sound feature.

	Attend-frequency	**Attend-location**
Relevant	Frequency	Location
Irrelevant	Location	Frequency

Table 2.1: Task relevant and irrelevant sound features.

In the attend-frequency task the listener indicates with a button press whether the frequencies of the two tones (the task-relevant information) were the same or different, while ignoring the location of the two tones (the task-irrelevant information) (Table 2.1). In the attend-location task the listener had to determine whether the location of the two tones (the task-relevant information) was same or different, while ignoring the frequency of the two tones (the task-irrelevant information).

2.1 Measures used in TAiL

Reaction time (RT) measures of distraction, conflict resolution, alerting, and baseline are calculated for each of the two TAiL tasks (Table 2.2). Distraction, based on of Lavie's load theory (1995), provides a measure of how much the listener involuntarily orientates to the irrelevant sound feature. This measure is calculated as the RT difference between trials where the irrelevant sound feature does change and does not change within the sound pair, regardless of the relevant sound feature (e.g. attend-frequency: trials when the location of the two tones was different minus trials when the location was the same). Conflict resolution provides a measure of how the listener is able to deal with conflicting information (i.e. executive control). This measure is a RT difference between trials where the two sound features change congruently and incongruently within the sound pair, similar to a classic flanker task (Eriksen and Eriksen, 1974). Congruent trials are those where the two sound features both change or both do not change, while incongruent trials are those where only one sound feature changes (regardless of its task relevancy). Alerting reflects the RT advantage the listener has when the trial's inter-stimulus interval (ISI) is fixed compared to when it varies randomly. Finally, a measure of baseline is calculated for each of TAiL's tasks as the listener's average RT to trials where both the sound features remain constant (same frequency, same location – SFSL), i.e. where there is no distracting or conflicting information within the trial.

Three of TAiL's measures used throughout this thesis – distraction, conflict resolution, and alerting – map onto the Orientating, Executive Control and Alerting networks, respectively, from Posner and Petersen's (1990; 2012) attentional networks (Zhang et al., 2012). Their relationship with these networks will be further discussed in Chapter 3.

2.2 Stimuli used in TAiL

Tones in all TAiL tasks were sinusoids, each 100 ms in duration (including gated on/off 10 ms cos ramps), with a frequency from within the range of 476.2 and 6187.5 Hz, and presented at 70 dB SPL. The tones within the pair were always at least 2.1 equivalent rectangular bandwidths (≈ 4 semitones)

	Calculation
Distraction	Irrelevant(Different − Same)
Conflict resolution	Incongruent − Congruent
Alerting	Roved ISI − Fixed ISI
Baseline	Same frequency Same location

Table 2.2: Calculations of TAiL's measures.

apart, to be clearly distinguishable from one another for listener's aged 4 and above (Jensen and Neff, 1993). In Chapter 3 the trial's ISI was either fixed at 300 ms or roved between 150 and 450 ms, in all other Chapters the ISI was fixed at 300 ms. Each trial was preceded by 500-1000 ms of silence and listeners were given unrestricted time to respond after the second tone (Figure 2.1). However, responses less than 200 ms and more than 2000 ms (Chapters 3 and 4) or 2500 ms (Chapters 5, 6 and 7) were excluded from further analysis in case of premature responding and lapses of attention or interruption of performance, respectively.

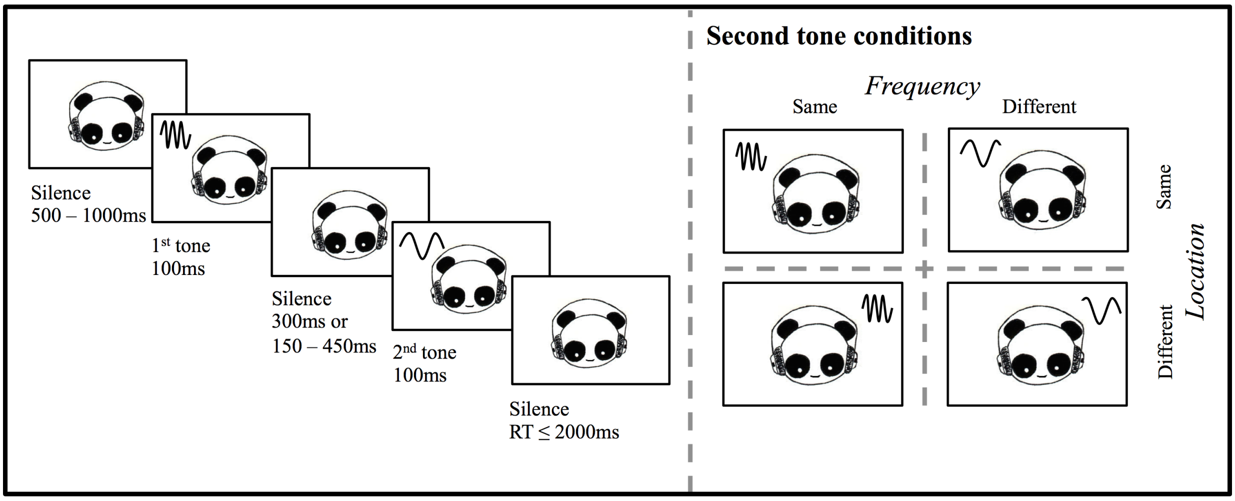

Figure 2.1: Test of Attention in Listening (TAiL) paradigm.

2.3 TAiL interface and paradigm

Two versions of TAiL were used in this thesis. The first version presented auditory stimuli with visual feedback of a happy or sad face after each trial. This version is used in Chapters 3 and 4. A second version used a game-like interface to help make the task more appealing to children. In this second version the listeners were presented with a space scene (Figure 2.2) where they were told that they were lost in space and had to find their way back home. In order to do so they had to work out who else was in deep, dark space – aliens or friendly spaceships. To do this they would hear two sounds and would have to decide if the relevant sound feature (frequency in the attend-frequency task, and location in the attend-location task) was the same or different (full instructions can be found in Appendix A). If the listeners responded correctly that the relevant sound feature was the same they were rewarded with the friendly spaceship shooting up fireworks and cheering, however if they answered same incorrectly they accidentally blew up the friendly spaceship with an accompanying explosion sound. If the listeners responded correctly that the relevant sound feature was different they saw and heard the alien spaceship blowing up, however if they answered different incorrectly then their own spaceship blew up. In both TAiL versions feedback was presented for 500 ms, before the start of the next trial.

Figure 2.2: Game-like interface of TAiL: listener has successfully identified the task-relevant sound feature as different.

With each TAiL block lasting a maximum of two and a half minutes, this interface was able to keep both children and adults entertained and on task. Before each TAiL task listeners completed a practice block of five trials, in which they had to achieve a level of 60% accuracy to proceed with the main TAiL task. Listeners had up to three opportunities to pass the practice, and if they failed to do so they did not continue on to the main TAiL task. Along with equipment details, counterbalancing and the number of trials and blocks of each task will be detailed in each experimental chapter.

Listeners responded using a custom built three-choice button box placed horizontally between the listener and the screen, pressing the right button

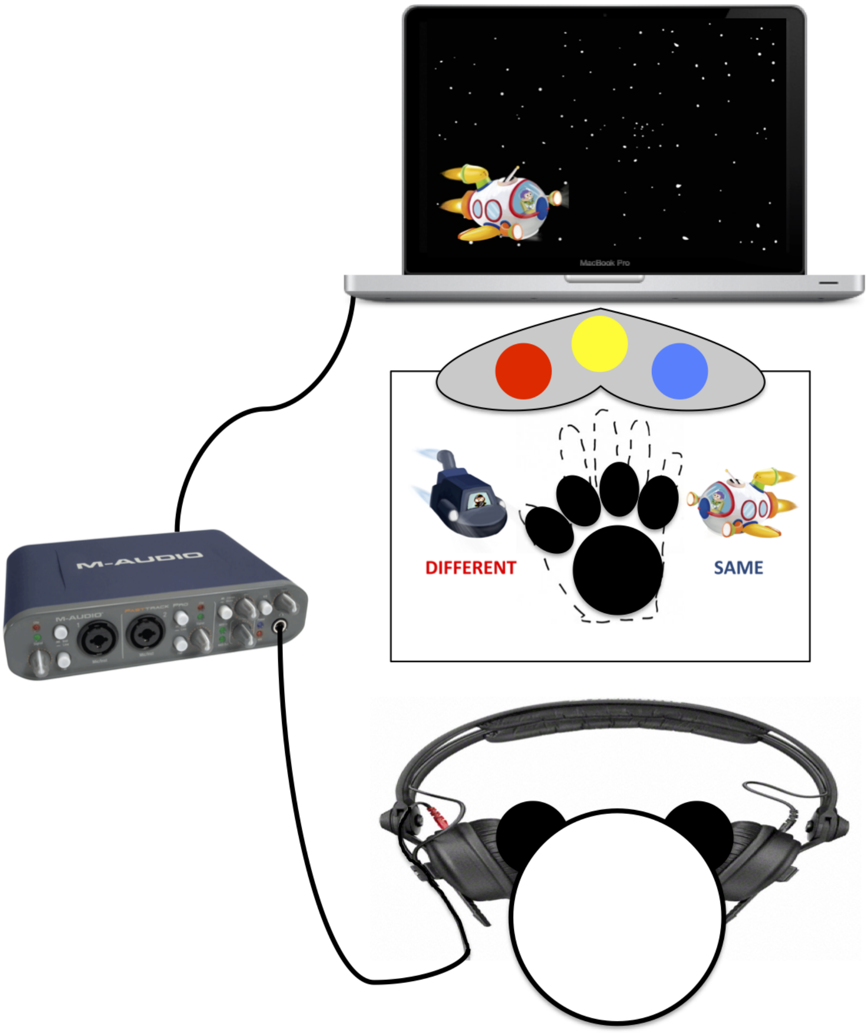

Figure 2.3: TAiL set-up illustrating button box and hand response guide.

for same decisions and left for different. In front of the button box was a hand response guide on which the listener was asked to place their hand between each trial (Figure 2.3). In the majority of studies presented in this thesis (Chapters 3, 4, 6 and 7) TAiL was presented in Matlab 2008a (MATLAB, 2008), using PsychoPhysics Toolbox v3.0.9. Custom built software was used to present TAiL in Chapter 5, with a more experimenter-friendly-interface. However, the stimuli and trial infrastructure were identical to the Matlab version.

2.4 Use of TAiL

In this thesis TAiL is used in three ways. Firstly, TAiL is compared to other tests of selective attention to assess whether it is measuring auditory selective attention rather than supramodal selective attention (Chapter

3). Secondly, it is used with electroencephalography (EEG) to explore the underlying neural pathways of selective attention to auditory stimuli (Chapter 4). Thirdly, TAiL is used to assess auditory selective attention in children aged 4-11 (Chapter 5). The perceptual demands of TAiL is then manipulated to assess how children (aged 4-11) deal with increasing auditory task difficulty (Chapter 6). Finally, TAiL is used to assess auditory selective attention in children with listening difficulties in noise (Chapter 7).

CHAPTER 3

Modalitity-specificity of selective attention tests

In order to assess the auditory selective attention ability of typically developing children and those with LDN, who have a high co-morbidity with developmental disorders (e.g. dyslexia), a non-verbal test of auditory selective attention is required. In this chapter an exploratory factor analysis compares the TAiL to other selective attention tests, all of which are based on the attentional networks framework, using auditory and visual stimuli. The aim of this chapter is to assess whether TAiL can be used as an auditory-specific selective attention measure, rather than a measure of generalized selective attention using auditory stimuli.

3.1 Introduction

With a limited amount of perceptual resource available to complete a given task, the ability to selectively attend to relevant sensory stimuli out of the numerous available is a vital skill (Lee and Choo, 2013). This skill is referred to as selective attention, and although extensively researched in the visual domain throughout the lifespan (for reviews see: Enns and Girgus, 1985; Plude et al., 1994; Hanania and Smith, 2010), very few studies have attempted to measure it directly in audition (Lee et al., 2014; Shinn-Cunningham, 2008). A major reason for this has been the lack of a well-validated measure of auditory attention that is free of language processing. TAiL was developed to meet this need for a non-verbal measure of auditory selective attention (Zhang et al., 2012). However, it remains to be shown that it does indeed capture auditory-specific selective attentional processes rather than general selective attention using auditory stimuli, for which there are already well-established tests (e.g. Test of Everyday

Attention (TEA); Robertson et al., 1996). The study presented in this chapter was designed to establish whether TAiL is such a measure.

TAiL's outcome measures have been shown to be independent from one another, mirroring the attentional networks framework on which the structure of TAiL is based (Posner and Petersen, 1990; updated in Petersen and Posner, 2012). Specifically, TAiL's measures map onto this framework in that: the listener's ability to maintain awareness throughout the task (i.e. the alerting network) is derived from the RT gain the listener achieves from knowing when the tones will occur; distraction is derived from the listener involuntarily orienting to the task-irrelevant information (i.e. the orienting network); and conflict resolution is derived from the change between task-relevant and -irrelevant stimulus features (i.e. the executive control network).

The attentional networks have been used as the foundation of other selective attention tests. Three such tests were used in this study to examine how TAiL relates to different modalities, through the use of exploratory factor analysis. First, a task using only visual stimuli – the visual Attention Network Test (vANT; Fan et al., 2002) uses simple arrow stimuli with a combination of temporal and spatial cues to probe the alerting and orienting networks, and irrelevant flanking arrow stimuli to create conflict to assess the executive control network. Second, an auditory task equivalent to the vANT – the auditory Attention Network Test (aANT; Roberts et al., 2006) uses temporal and spatial cues (alerting and orienting networks, respectively), and auditory pitch-word Stroop stimuli (McClain, 1983) to create conflict between the lexical semantics and pitch in which the words were spoken to assess the executive control network. Third, the Test of Everyday Attention (TEA; Robertson et al., 1996) was selected as it uses both visual and non-verbal auditory stimuli in a series of different sub-tests to assess the three attentional networks.

To illustrate its ability to assess auditory-specific selective attention, TAiL's measures would be expected to group together with those using auditory stimuli and to separate from the visual test measures. However a deeper level of segregation is expected to occur, as it has been proposed that different attentional processes can be either modality-general or sensory-specific. For example, object-based selectivity used to orient attention has typically been considered to be modality-specific due to being affected by stimulus features in a bottom-up manner (Petersen and Posner, 2012). Meanwhile, the executive control required to deal with different stimuli is affected in a top-down fashion, therefore making it a supramodal attentional process (Petersen and Posner, 2012). Each of the three attention networks will be discussed below and specific predictions made regarding the loading of measures onto modality-specific and supramodal factors within the exploratory factor analysis.

Alerting in the real world involves detecting the appearance of an object or a change within an object. This perception can be based on any of the object's features, regardless of whether they are visual or auditory. Therefore an efficient method of monitoring the environment is to do so in a supramodal fashion rather than integrating modality-specific perceptual streams. This has been demonstrated by imaging studies showing the same brain areas being activated when monitoring both visual and somatosensory stimuli (Kinomura et al., 1996), and when utilising auditory and visual temporal cues (Sturm and Willmes, 2001; Roberts and Hall, 2008). However, behavioural studies have found a lack of correlation between auditory and visual alerting measures, which suggests that alerting is a modality-specific network (Roberts et al., 2006; Spagna et al., 2015), potentially due to the greater speed of processing auditory information (see Hillyard, 1993). Therefore it is expected that the TAiL alerting measures will load onto the same factor as other auditory alerting measures, indicating that they are auditory-based. However, it is unclear whether the visual alerting measures will also load onto this one unifying factor. If this were shown to be the case, this finding would provide support for the imaging evidence pointing purporting towards a supramodal alerting network.

Orienting is the ability to select specific objects or object features relevant to the behavioural goal while avoiding distraction by irrelevant features. In both vision (e.g. Fan et al., 2002) and audition (e.g. Roberts et al., 2006) it is usually measured as the advantage given by cueing the target location (see Spagna et al., 2015). However, orienting does not necessarily need to be to a specific location, as a cue can orient to non-spatial object features, such as colour (Lamers et al., 2010) or pitch (Zhang et al., 2012). The orienting network may therefore depend on the modality of the object feature to be selected, and in that sense may be modality-specific. This suggestion is supported by studies showing that attention can be concurrently oriented to different locations in different modalities (Spence and Driver, 1996; Spence, 2001). It is expected that within the exploratory factor analysis TAiL's measures relating to the orienting network (i.e. the distraction measures) will load onto a factor occupied by other auditory orienting measures (from the aANT and TEA), whilst visual orienting measures (from the vANT and TEA) will load onto another separate factor. This would suggest that TAiL can measure auditory-specific orienting abilities.

The executive control network is measured in this study's battery of tests by assessing how the individual can respond correctly to task-relevant object features in the face of conflicting irrelevant feature information. Regardless of the modality of the conflicting features, the resolution process is considered to be supramodal (Donohue et al., 2012). Support for this supramodal network has been illustrated by comparing different conflict paradigms based on various feature types, e.g. visual colour vs. auditory pitch (Roberts and Hall, 2008), and visual spatial vs. auditory spatial and auditory pitch (Spagna et al., 2015). Therefore it is expected that the TAiL conflict resolution measures will load onto a supramodal factor containing their kindred measures from the other three tests of attention regardless of whether they encompass auditory or visual stimulus features.

In summary, the exploratory factor analysis is expected to find either that the auditory alerting measures load onto a single factor along with the visual alerting measures, representing a global alerting network, or that visual alerting measures will group onto a separate factor indicating two modality-specific alerting networks. It is also predicted that the orienting measures will load onto two modality-specific factors representing auditory-specific orienting and visual-specific orienting networks. Finally it is predicted that the conflict resolution measures from both the auditory and visual tests will load onto one factor representing one supramodal network. These results would confirm not only the structure of the attentional networks framework, but also affirm whether TAiL can access auditory-specific selective attention when the attentional networks separate into modality-specific sub-networks.

3.2 Method

3.2.1 Participants

Forty-eight participants aged 19 to 37 (M = 24.2 years, SD = 4.8 years; 30 females and 18 males) were recruited through poster advertisements placed in the University of Nottingham. All participants had normal hearing (pure tone thresholds below or equal to 20 dB HL bilaterally at octave frequencies between 250 and 8000 Hz in accordance with the British Society of Audiology, 2011b). Through self-report none of the participants had a history of language-related or attention-related conditions, autism spectrum syndrome or any auditory system disorder. All procedures were approved by the National Health Service (NHS) Research Ethics Committee East Midlands – Nottingham. Informed written consent was given by each participant prior to the experiment, and they were paid an inconvenience allowance.

3.2.2 Apparatus

Participants were tested individually in a sound-attenuated booth. All tests, except for the TEA, were fully automated and presented on a PC through Matlab v7.6 (The MathWorks, 2008), with a 15 inch flat-screen monitor placed 65 cm in front of the participant. Auditory stimuli were presented through Sennheiser HD 25-II headphones via an ASIO driver controlled custom sound card. Participants responded to all tests, except the TEA, using a custom-made three-choice button box using only the exterior buttons (i.e. ignoring the middle button). In TAiL and the vANT the button box was placed with the buttons arranged from left to right; in the aANT the buttons were arranged from nearest to farthest from the participant. The TEA was completed with the experimenter in the sound-attenuated chamber, with the CD-recorded stimuli presented through laptop speakers and the participant giving verbal responses.

3.2.3 Stimuli & procedure

All four tests of selective attention were administered in a single testing session lasting approximately two hours, including rest breaks between individual tests. A random number generator was used to assign an initial

	Alerting	**Orienting**	**Conflict resolution**
TAiL ^{A}	Fixed ISI − Roved ISI	Irrelevant(Different − Same)	Incongruent − Congruent
vANT ^{V}	Double cue − No cue	Spatial cue − Double cue	Incongruent − Congruent
aANT ^{A}	Double cue − No cue	Spatial cue − Double cue	Incongruent − Congruent
TEA ^{A,V}		Visual elevator ^{V}	Telephone search task ^{V}
		Elevator counting with reversal ^{A}	Elevator counting with distraction ^{A}

Table 3.1: Calculations used for outcome measures in TAiL and the Visual & Auditory ANTs, and tasks from the TEA used for measures of alerting, orienting and conflict resolution. ^{A} auditory task ^{V} visual task

order to the four attention tests, which was then counterbalanced across the participants using a Latin square design.

Test of Attention in Listening (TAiL).
Both of TAiL's tasks were administered, differing only in the relevant feature participants were asked to attend to: (1) the attend-frequency task, in which participants had to decide whether the two sequential tones had the same or different frequencies while ignoring their location; and (2) the attend-location task, in which participants had to decide whether the two sequential tones were presented to the same or different ears whilst ignoring their frequencies (Figure 3.1A). Each task was repeated twice, once with a fixed ISI and once with a roved ISI, with 40 trials per task providing a total of 160 trials for each participant. The order of the blocks was counterbalanced using a Latin square design across participants. Each block was preceded by five practice trials, accompanied by on-screen instructions. No feedback on performance was provided. RTs from correct trials were used in the analysis.

Five outcome measures were calculated from the RT data: alerting was calculated using both the attend-frequency and the attend-location tasks, while distraction (covering the orienting network) and conflict resolution were each calculated separately for the attend-frequency and attend-location tasks (see Table 3.1).

Visual Attention Network Test (vANT).
Participants were first presented with a central fixation cross, followed by a visual temporal or spatial cue (an asterisk), or a blank screen in the

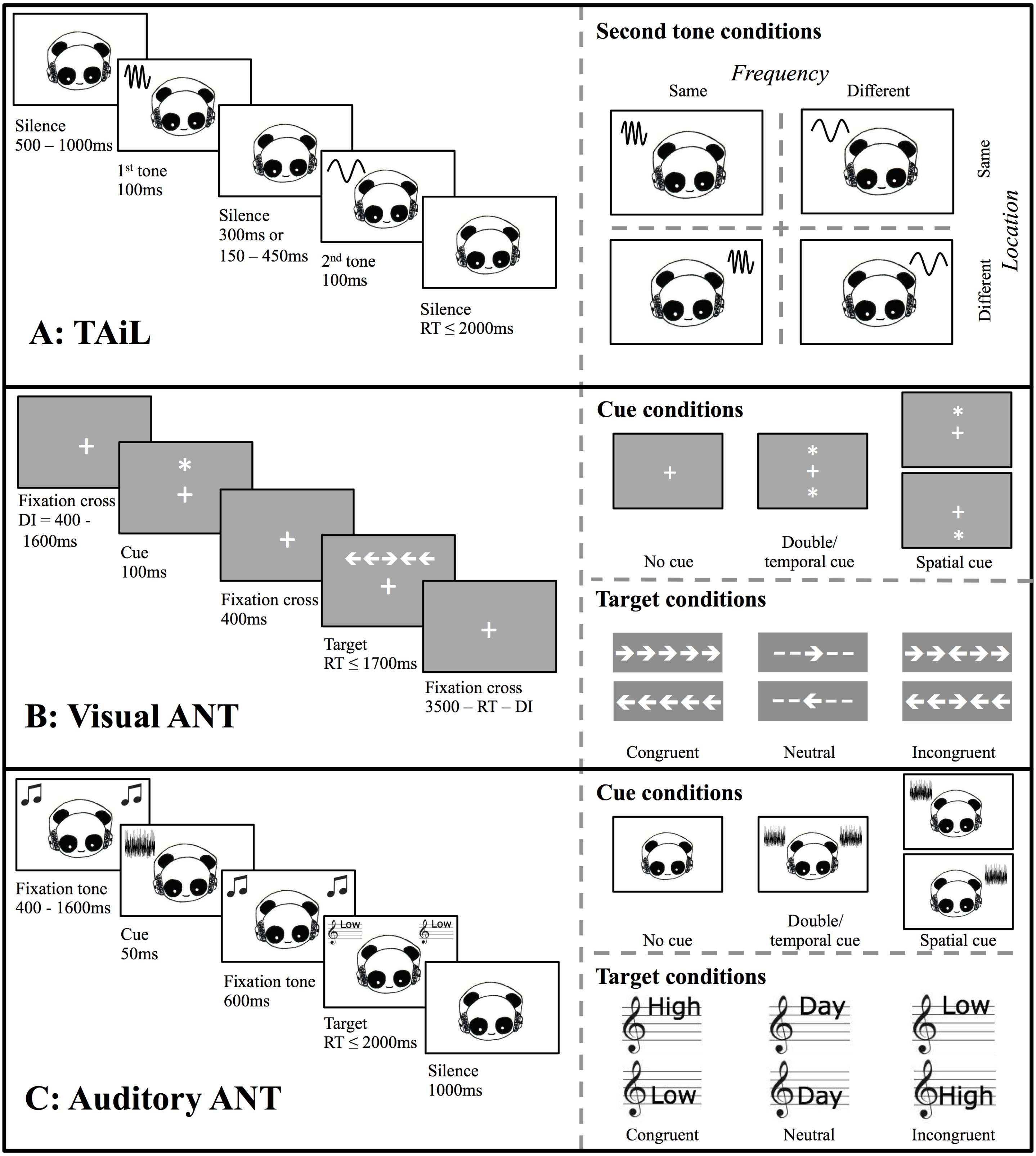

Figure 3.1: Trial paradigm illustrations, including cue and target conditions, for the (A) TAiL, (B) visual ANT and (C) auditory ANT tests.

no-cue condition, to alert participants that the target would occur soon (Figure 3.1B). The target stimulus (an arrow pointing left or right) was then presented either below or above the fixation cross, alone or with conflicting/congruent flankers. The participants' task was to indicate via a button press (far left or far right) the direction the target arrow was pointing (task-relevant information), regardless of the flanker arrows (task-irrelevant information). All stimuli were white in colour and presented on a 60% grey background. Stimulus sizing and timing followed the methodology of Fan et al. (2002).

The test consisted of two blocks of 144 trials where all cue types and flanker conditions were randomised within the blocks (4 cue conditions × 2 target locations × 2 target directions × 3 flanker conditions × 3 repetitions). Prior to the first block, participants were provided with verbal instructions and 8 practice trials with visual accuracy feedback. RTs from correct trials only were used in the analysis.

Measures of alerting, orienting of attention and conflict resolution were calculated from different combinations of cue and flanker trials (see Table 3.1). Alerting was calculated as the difference between trials with a spatial-neutral temporal cue (i.e. a double cue – an asterisk at both possible target locations) and no temporal cue. The participants' orienting of attention was calculated as the difference between trials that provided a valid spatial cue (an asterisk at the location of the future target) and those that displayed a spatial-neutral (double) cue. Finally, conflict resolution was calculated as the difference between trials where the task-relevant and -irrelevant information (target arrow and flankers respectively) were incongruent (pointing in different directions) and trials where they were congruent (pointing in the same direction).

Auditory Attention Network Test (aANT).
The original stimuli from Roberts et al. (2006) were used. The test set-up is very similar to that of the vANT in that temporal and spatial cues were used, but these cues were auditory tones rather than visual stimuli (Figure 3.1C). The participants' task was to indicate via a button press whether the talker's voice was high or low in pitch, whilst ignoring the semantic content (the spoken word "high", "low" or "day") – an auditory Stroop task. As in the vANT the test consisted of two blocks of 144 trials where all cue types and flanker conditions were randomised within the blocks. Prior to the first

block, participants were provided with verbal instructions and 24 practice trials with visual accuracy feedback. RTs from correct trials were used in the analysis.

The measures of alerting, orienting of attention and conflict resolution were calculated as in the vANT (see Table 3.1). Alerting was calculated as the RT difference between trials with a spatial-neutral temporal auditory cue (i.e. a double cue – statistically independent noise in each ear) compared to no temporal cue. Orienting of attention was calculated as the difference between trials with valid spatial cues (noise in the ear of the future target) and those with a spatial-neutral (double) auditory cue. Finally, conflict resolution was calculated as the difference between trials where the task-relevant and -irrelevant information were incongruent (i.e. the word "low" spoken in a high pitch and vice versa) and congruent (with matching word and pitch).

Test of Everyday Attention (TEA).
Four subtests of TEA were used to extract measures of orienting of attention and conflict resolution involving auditory and visual stimuli (see Table 3.1). A short description of these subtests is presented below.

The visual elevator task presents the participant with a series of pictures and rules to work out what floor an imaginary elevator is on. This subtest has been shown to correlate strongly with classic psychological tasks requiring the participant to switch attention to relevant stimuli (e.g. The Wisconsin Card Sorting Test), therefore providing a visual orienting of attention measure (Robertson et al., 1994, 1996). This test was repeated in the auditory domain by the elevator counting with reversal subtest (Robertson et al., 1994, 1996) where the participant counted medium-pitched tones using high and low tones to instruct them when to count the imaginary elevator up and down, respectively. In the telephone search task participants visually searched for matching symbols in a "telephone directory" while ignoring non-matching symbols. This measure has been shown to be strongly correlated with the Stroop task (Bate et al., 2001; Robertson et al., 1996), and so provides a measure of visual conflict resolution. Finally the auditory elevator subtest with distraction was used as an auditory conflict resolution task where the participant had to count the low tones but ignore the high tones to work out what floor the imaginary elevator was on. The TEA subtests were presented and ordered as described in the TEA manual (Robertson et al., 1996).

Normative comparative standards were used to calculate a standardised score for each subtest (Robertson et al., 1996). In addition, an individual standard score was used as a general attention measure, calculated as formulated by Crawford et al. (1997).

3.2.4 Statistical analysis

One participant was excluded from analysis because they did not complete all four attention tests, leaving a total of 47 complete data sets.

Initial analysis of each of the attention tests was conducted in SPSS v20.0 (IBM Corp, released 2011). The exploratory factor analysis was carried out using R 2.15.2 (R Core Team, 2012) with an oblimin rotation, as the attention network framework states each network is independent the input variables were not expected to be orthogonal. The oblimin rotation provided a well-defined factor structure, with items with factor loadings greater than .40 considered appropriate for inclusion in a factor (Fields, 2005). The RT difference measures from the vANT, aANT and TAiL and the standard scores from the TEA were converted to Z-scores prior to factor analysis because they were measured on different scales.

The alerting measure from TAiL was assessed using a paired-sample t-test comparing roving and fixed-gap tasks. Involuntary orienting and conflict resolution for TAiL were assessed using two repeated-measures ANOVAs (one per task-condition) with the task-relevant and task-irrelevant dimension as repeated measures. Involuntary orienting was the main effect of the task-irrelevant dimension, and conflict resolution was the interaction between the relevant and irrelevant dimensions. The RT difference measures of alerting, orienting, and conflict resolution were assessed for the vANT, aANT using one-sample t-tests (test value of 0). Only significant measures were included in the factor analysis.

3.3 Results

3.3.1 Attention tests

TAiL.
There was no significant alerting effect when tasks with fixed ISI were compared to roved ISI (paired t-test: $t(46) = .50, p = .62$). The distraction and conflict resolution measures were examined using a

2×2 repeated measures ANOVA (frequency: same, different; location: same, different) for each TAiL task. Both measures were significant in both the attend-frequency and attend-location tasks. Distraction by the irrelevant feature was significant in both the attend-frequency task ($F(1,46) = 25.97, p < .001, \eta_p^2 = .37$) and the attend-location task ($F(1,46) = 12.09, p = .001, \eta_p^2 = .21$). Conflict resolution, the difference between congruent and incongruent trials, was also significant in both the attend-frequency ($F(1,46) = 14.69, p < .001, \eta_p^2 = .24$) and attend-location ($F(1,46) = 20.42, p < .001, \eta_p^2 = .30$) tasks.

vANT.
Paired t-tests between temporally cued and un-cued trials showed significant alerting ($t(47) = 4.93, p < .001$). A comparison of trials with informative spatial and non-informative cues showed significant orienting ($t(47) = 7.22, p < .001$), and a comparison of congruent and incongruent flankers showed significant conflict resolution ($t(47) = 14.74, p < .001$).

aANT.
Neither alerting (advantage of a temporal cue) nor orienting (advantage of a valid spatial cue) were significant (alerting: ($t(47) = .22, p = .83$); orienting: ($t(47) = .96, p = .34$). Only conflict resolution between semantic content and pitch was significant ($t(47) = 4.13, p < .001$).

TEA.
Standard scores (M and SD) as well as population-comparable percentiles for the TEA subtests used in this study are reported in (Table 3.2).

3.3.2 Exploratory factor analysis

The following 12 measures were included in the factor analysis: the distraction and conflict resolution from both the attend-frequency and attend-location tasks of TAiL; orienting and conflict resolution from the vANT; conflict resolution from the aANT; orienting and conflict resolution using auditory and visual stimuli, and general attention from the TEA. Alerting measures were not included because it was only significant in the vANT, and therefore could not be used to determine modality-specificity/generality in this model.

The factorability of these 12 items was examined. Eight of the 12 items correlated at least .30 with at least one other item; Bartlett's test of Sphericity

Attention measure **TEA subtest**	**M**	**SD**	**M Percentile**
Orienting ^{V} Visual elevator task	12.06	2.04	70.26
Orienting ^{A} Elevator task with reversal	11.13	2.22	57.86
Conflict resolution ^{V} Telephone search task	8.74	3.38	27.69
Conflict resolution ^{A} Elevator task with distraction	11.21	2.56	59.12

Table 3.2: M, SD and mean percentile of the TEA subtests. ^{A} auditory task ^{V} visual task

was significant ($\chi^2(66) = 290.42, p < .001$); and the Kaiser-Meyler-Olkin measure of sampling adequacy was $.57$, over the minimum recommendation of $.50$ (Fields, 2005). However the communality of the visual conflict resolution measure from the TEA (the telephone search subtest) was low at $.43$, suggesting that this variable did not share common variance with the other items. This item was excluded and the factorability of the remaining 11 items was re-examined. Eight of the 11 items correlated at least .30 with at least one other item. Bartlett's test of Sphericity was significant ($\chi^2(66) = 239.65, p < .001$), and the Kaiser-Meyler-Olkin measure of sampling adequacy had increased to $.61$. All communalities were above $.50$ (see Table 3.3).

Given the results from these initial tests, principal components analysis was conducted with all 11 measures, as the aim of the factor analysis was to explore the underlying relationships of the modalities of different attention tests.

Principal components analysis indicated the presence of four factors with eigenvalues greater than Kaiser's criterion of 1 (Kaiser, 1960). This was supported by parallel analysis and Cattell's scree plot test (Cattell, 1966), with the four factors explaining 67.6% of the cumulative proportion of variance.

3.3.3 Factor loading

Principal components analysis yielded a 4-component solution. The factor loading matrix is presented in (Table 3.3) and graphically presented in (Figure 3.2).

All four TEA measures loaded onto the first component: general attention, consisting of both auditory and visual subtest scores; orienting from the visual and auditory (with distraction) elevator task scores; and the conflict resolution measure from the auditory elevator counting subtest (with distraction). This component was named 'general attention'.

The second component consisted of the orienting measure from the vANT and the distraction measure from TAiL's attend-location task. Both of these items are spatially based orienting measures from tasks requiring a direction based decision (i.e. left/right) covering both audition and vision, providing a supramodal 'spatial orienting' component.

Two items loaded onto the third component: both the distraction and conflict resolution from TAiL's attend-frequency task. This component appears to be auditory-specific and was labeled 'auditory attention'.

The final component consisted of three conflict resolution measures from the vANT, the aANT and TAiL's attend-location task. This suggests that this component is also supramodal, and it was therefore labeled 'spatial conflict' as each task involved a directional decision (i.e. left/right or high/low).

3.4 Discussion

The aim of this chapter was to assess how TAiL relates to other tests of attention, using both visual and auditory stimuli, in order to establish whether TAiL can measure auditory-specific selective attention. Contrary to this study's prediction, the distinction was not between attentional networks – orienting being modality-specific and conflict resolution supramodal – but rather depended on the type of stimulus features being processed during the task. Orienting to location and resolving spatial conflict from both modalities loaded onto the same orienting and conflict resolution components, respectively. Only when listeners were asked to selectively attend to non-spatial auditory features did the measures load onto a separate component. It is possible that no equivalent visual-specific component was

Attention measure **Task**	**General attention**	**Spatial orienting**	**Auditory attention**	**Spatial conflict**	**Communality**
General attention [A,V] TEA	**.918**	.052	-.002	-.059	.86
Orienting [A] Elevator task with reversal – TEA	**.901**	.162	.068	-.076	.86
Conflict resolution [A] Elevator task with distraction – TEA	**.836**	-.238	.146	.015	.75
Orienting [V] Visual elevator task – TEA	**.627**	.283	-.305	.100	.67
Orienting [V] vANT	.253	**.746**	.112	.011	.64
Distraction [A] Attend-location – TAiL	.042	**-.712**	.162	.044	.53
Distraction [A] Attend-frequency – TAiL	.216	.077	**.846**	.110	.76
Conflict resolution [A] Attend-frequency – TAiL	-.307	.288	**.576**	-.274	.59
Conflict resolution [V] vANT	.089	-.212	-.047	**.770**	.64
Conflict resolution [A] aANT	-.321	.219	.071	**.688**	.66
Conflict resolution [A] Attend-location – TAiL	-.106	.287	.364	**.584**	.58
Proportion variance	28.0	13.6	13.0	13.0	67.6

Table 3.3: Factor analysis loadings with oblimin rotation. [A] auditory task [V] visual task

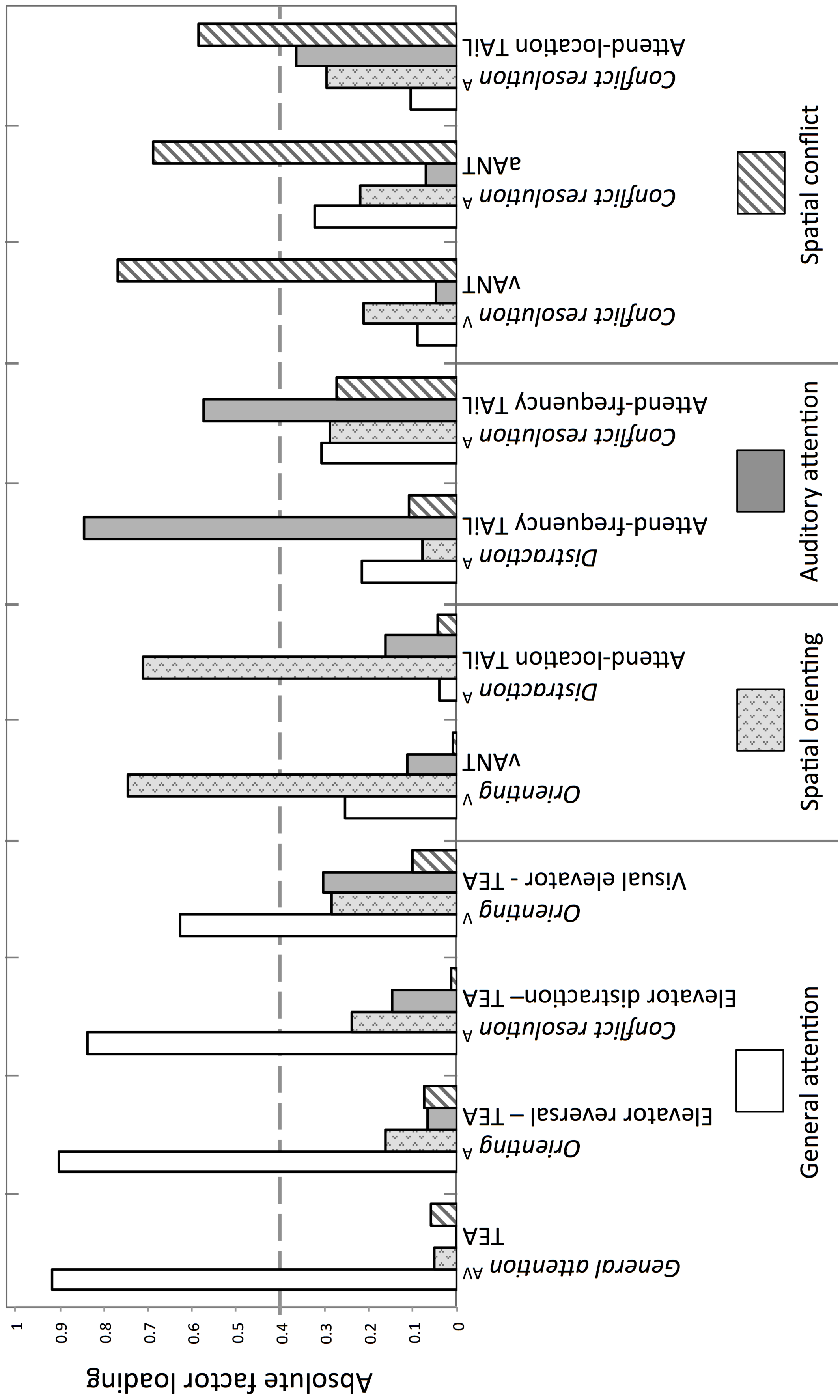

Figure 3.2: A visual represenation of Table 3.3 – the factor analysis loadings with oblimin rotation. Dotted horizontal line indicates the cutoff of item loadings considered for each factor (i.e. .04). ^{A} auditory task ^{V} visual task

found because the visual tests used did not contain task-relevant non-spatial features.

A great strength of TAiL lis that both of its tasks, attend-frequency and attend-location, use an identical set of stimuli – the only difference is in the feature to which the listener is instructed to attend to. Therefore any behavioural differences found in an individual listener reflects differences in the attentional goals of the listener rather than the bottom-up processing of the sensory information (Lee et al., 2013). This study's results suggest that these goals reflect auditory-specific attention within TAiL's attend-frequency task, and supramodal attention in TAiL's attend-location task. This suggests that the TAiL fulfills the purpose of its creation: it is able to measure both auditory-specific selective attention (through the attend-frequency task) and supramodal selective attention (through the attend-location task).

3.4.1 'What' and 'where' pathways in vision and audition

These behavioural results support the theory of dual-pathways (Mishkin et al., 1983; Goodale and Milner, 1992), suggesting that sensory stimuli are processed in two separable pathways: a 'where' pathway processing spatial information and a 'what' pathway processing non-spatial object-related information. This theory is supported by numerous imaging studies in both human (e.g. Haxby et al., 1991; James et al., 2003; Zachariou et al., 2013) and animal (e.g. Baizer et al., 1991; Desimone et al., 1985; Felleman and Van Essen, 1991) vision, corresponding to anatomically separate ventral and dorsal streams processing the 'what' and 'where' features of a visual object, respectively. A similar dual-pathway theory has been proposed for audition (for reviews see Rauschecker and Tian, 2000; Arnott et al., 2004.

Based on the anatomical evidence, this theory suggests that while processing of the spatial features of an object is supramodal, the non-spatial features are processed in a modality-specific fashion (Driver and Spence, 1994, 1998; Turatto et al., 2002). Imaging studies comparing the cortical activation elicited by spatial and non-spatial feature processing in the visual and auditory domains have suggested that selective attention for spatial auditory features engage cortical circuitry similar to that engaged in visual spatial selective attention (e.g. Krumbholz et al., 2009; Smith et al., 2010). This network is referred to as the dorsal stream, consisting of a superior parietal and frontal network of regions that is activated by tasks requiring spatial orienting or conflict resolution in either the visual (Giesbrecht et al., 2003; Slagter et al., 2007) or auditory (Ahveninen et al., 2006; Hill and Miller, 2010; Lee et al., 2013) modality. This study's behavioural results mirror these imaging studies by showing that the spatial-based task measures loaded onto the same two components regardless of modality – one for orienting of attention and one for conflict resolution.

Furthermore, the behavioural results suggest a divide between the processes involved in attending to auditory and visual non-spatial object features. This division is further illustrated by imaging evidence in that orienting to non-spatial object features leads to activation in separate modality-specific sub-networks along ventral regions. In audition it includes areas in the non-primary auditory cortex in the temporal lobe (e.g. the superior temporal sulcus; Arnott and Alain, 2011) activated by non-spatial auditory object features (e.g. pitch), while in vision it includes extrastriatal visual areas in the inferior temporal gyrus (Giesbrecht et al., 2003) activated by non-spatial object features (e.g. colour).

3.4.2 Visual and auditory alerting measures

Evidence of alerting was found only in the visual ANT, and not in either auditory test. In TAiL there was no significant RT advantage for the fixed versus roved ISI, suggesting that knowing when the second tone would be presented did not lead to faster responses. This study also failed to replicate the significant alerting effect Roberts et al. (2006) found in the aANT when comparing RTs in the presence of a temporal cue that indicated when the target will occur to RTs in a no-cue condition. Despite the differences between the types of decision required by the two tasks – discrimination in TAiL and identification in the aANT – the main question here is why there is no apparent auditory alerting effect, whereas a robust visual alerting effect was found in the vANT.

Auditory detection is much more rapid than visual detection; the time from stimulus onset to arrival at primary sensory cortex is considerably shorter at 15-20 ms in the auditory domain compared to 40-50 ms in the visual domain (Hillyard, 1993). It may be that the latency advantage conferred by knowing exactly when an auditory 'target' will occur may be too small to detect with any precision using the RT measures of the aANT and TAiL. Nevertheless, in the absence of a means of measuring alerting to auditory stimuli with existing attention tests, it cannot be concluded whether alerting is a sensory-specific or supramodal function.

3.4.3 Orienting to stimuli and test-relevance

The RT tests used in this study tapped into two different types of orienting: orienting to a non-spatial feature of an object (frequency in TAiL's attend-frequency task), and orienting to the spatial location of an auditory (TAiL's attend-location task) or visual (vANT) object. In the vANT, the location cue was relevant to the task, as knowing where the target will appear on the screen allows covert attention to be moved to that location, reducing target processing time. TAiL, on the other hand, does not measure the benefit afforded by a cue that orients attention to the task-relevant information, but rather the resistance to distraction by task-irrelevant information. When the relevant information is spatial (attend-location), it is a measure of how well participants can orient to location and ignore other stimulus features. Indeed, this measure loaded onto a spatial orienting component together with the vANT orienting measure. With both a visual and an auditory measure loading onto this component, spatial orienting appears to be a supramodal function.

Unlike the vANT, the spatial location cue in the aANT (ear of presentation) is irrelevant to the required decision about the pitch of the word. It is possible that knowing the future location of an auditory object does not help with identifying its features (McDonald and Ward, 1999). Moreover, the well-established right-ear advantage for speech (for a review see Hugdahl, 2011) may have confounded any putative advantage of a spatial orienting cue, resulting in no significant orienting effect in the aANT here or in the Roberts et al. (2006) study.

By comparison, the attend-frequency task of TAiL required orienting to a non-spatial stimulus feature, unlike the vANT which measured only spatial orienting. It therefore follows that this measure did not load on the spatial orienting component. Since the aANT did not have a measure of non-spatial orienting, the results can only suggest that orienting to non-spatial features is modality-specific. This conclusion is supported by Spagna et al. (2015), who showed a significant orienting effect to tone pitch in a non-spatial version of the aANT, which was uncorrelated with the vANT.

Although it has been suggested that the TEA visual and auditory (with reversal) elevator subtests tap into the orienting network (Robertson et al., 1994, 1996), they did not load on either the spatial orienting component or a sensory-specific orienting component. This is not surprising as they are rule-based attention switching tasks, and the modality of the cue is irrelevant – only the rule matters to task performance. This is discussed in more detail below.

3.4.4 Conflict resolution and the role of semantics

TAiL's non-spatial conflict resolution measure loaded on the same auditory-specific factor as the non-spatial distraction measure, also from the attend-frequency task. It is perhaps surprising that the aANT conflict resolution measure did not load onto the auditory-specific component, since this task's Stroop conflict was between the semantic content of the word and its pitch – not overtly a spatial conflict. Our findings echo the correlation between the aANT and vANT conflict resolution found in the Roberts et al. (2006) study. It is possible these two loaded onto a spatial conflict resolution component because the word meanings in the aANT were spatial ("high", "low"). Therefore TAiL's spatial conflict resolution (attend-location), the aANT conflict resolution and the vANT conflict resolution, also spatial (left and right arrow flankers), loaded onto the same factor. Thus, like spatial orienting, spatial conflict resolution appears to be supramodal.

3.4.5 The TEA and working memory

Although the TEA is purportedly based on the attentional network framework (Robertson et al., 1994), none of its measures loaded onto components with any other tests of selective attention used here. While the subtests of the TEA were designed to be ecologically valid, they are rule-based – the cues (both auditory and visual) used to direct attention have no meaning in themselves, but rather direct attention to a rule that needs to be remembered and used correctly. Other factor analysis studies have shown that the TEA's visual elevator task and auditory elevator tasks, both with reversal and distraction, both load onto the same factor as working memory tasks such as the backwards digit span and Paced Auditory Serial Addition Test (Gronwall and Wrightson, 1974: where the listener adds an auditory number to the previously heard number) (Bate et al., 2001; Robertson et al., 1996). These results suggest that the general attention component may be a separable component as its underlying construct may be based in working memory.

3.5 Conclusions

(1) TAiL successfully captures both auditory-specific and supramodal attention using its attend-frequency and attend-location tasks, respectively.

(2) The modality of a task is not just about the attentional networks used; it is also rooted in the stimulus feature being attended to – whether it is spatial or non-spatial.

CHAPTER 4

Neural correlates of TAiL

The previous chapter illustrated that while performance in TAiL's attend-location task relates to visual selective attention test outcomes, performance in TAiL's attend-frequency task does not. This suggests that the TAiL attend-frequency task taps into auditory-specific processes. The aim of this chapter is to continue to deepen understanding of TAiL by investigating its neural underpinnings. This chapter assesses whether the distraction and conflict resolution outcomes from each of the two TAiL tasks are represented by different selective attention-related electroencephalography components.

4.1 Introduction

It is well accepted that attention is not a unitary phenomenon, but rather involves processes that may vary as a function of the task at hand. In auditory attention, internal goal-directed actions enable listeners to prioritise and selectively process task-relevant sounds at a deeper level. This requires listeners to suppress irrelevant information to stay on task and to help prevent information overload (Bidet-Caulet et al., 2010; Degerman et al., 2008; Michie et al., 1993; Münte et al., 2010). Auditory attention also often requires the processing of incongruency in relation to the task demand (i.e. conflict resolution). For instance, prior behavioural studies have shown that listeners take longer to respond to the word "high" when presented at a low pitch (Roberts et al., 2006). In most everyday listening situations, these two processes are required to occur concurrently for successful goal-directed action. This study uses the high temporal resolution of electroencephalography (EEG) to investigate whether TAiL can effectively measure the suppression of distracting irrelevant information and conflict resolution concurrently.

Understanding TAiL's neural correlates may help break down where in auditory processing task instruction modulates performance. Behavioural results from the previous chapter suggest that by simply changing TAiL's task instructions the modality of attention processes change, despite the stimuli remaining constant. Specifically, the results suggest the dual-pathway theory of processing spatial features in a supramodal fashion and non-spatial features in a modality-specific fashion (Driver and Spence, 1998; Rauschecker and Tian, 2000; Turatto et al., 2002). This chapter seeks to determine whether the event-related potentials (ERPs) occur on a timescale similar to the auditory or visual tasks described above, building on the previous chapter's finding that the TAiL's attend-frequency conflict resolution measure is auditory specific, and the attend-location conflict resolution measure is supramodal.

Oddball paradigms have typically been used to examine distraction in auditory selective attention whereby an infrequent target is presented (e.g. a tone of 1500 Hz with a probability of 20%) in amongst irrelevant auditory information (e.g. tones of 1000 Hz with a probability of 80%). Within this methodology the mismatch-negativity (MMN) and later P3 is reported in response to the unexpected stimulus change (for review see Näätänen et al., 2007). These components occur with a variety of stimuli, including auditory (e.g. Näätänen et al., 1978), visual (for a review see Pazo-Alvarez et al., 2003) and audio-visual (e.g. Sams et al., 1991). Furthermore, these components have been shown to occur when the task-relevant and -irrelevant stimuli are embedded within the properties of the same perceptual object (Schröger and Wolff, 1998), and to have different latencies and scalp distribution for different oddball stimulus properties (e.g. duration, frequency and intensity – Escera et al., 2002).

However, the MMN is an automatic response that occurs when the listener is exposed to an unexpected oddball stimulus that contrasts to a sensory memory trace created by the repetitive presentation of identical stimuli (Näätänen et al., 2007). TAiL's methodology differs from this classic oddball stimulus in that there is no continuous string of stimuli, instead each trial involves two sequential tones for which a comparison is required regarding a single feature of the sounds – frequency or location.

An alternative route to assessing attention distraction using scalp-recording of visual ERPs has revealed a distractor positivity (Pd) modulation. This modulation (i.e. component) has been found using mainly visual search paradigms where the target differs from the distractors in one feature (e.g. shape – Hickey et al., 2008; orientation – Hilimire et al., 2011; colour – Sawaki and Luck, 2010). It is thought to reflect the suppression, and possibly the rejection, of irrelevant but potentially distracting lateralised stimuli (Hickey et al., 2008; Hilimire et al., 2011; Sawaki and Luck, 2010). The Pd has an onset ranging from 250-300 ms post-stimulus with a positive parietal placement, contralateral to the presentation of the distractor (Hickey et al., 2008). Furthermore, the Pd has been found when the distractor's saliency is based on bottom-up (e.g. color) or top-down information (e.g. spatial cues) (Kiss et al., 2012). It has been proposed that a similar component, the PTc, reflects the suppression of distractor stimuli with an onset of 290-370 ms and a similar topography – positive and contralateral to the lateralised distractor (Hilimire et al., 2009).

However, there has been discussion of the possibility that the Pd and the PTc are the same component with different onsets due to the salience of the distractor stimuli (Hilimire et al., 2011; Sawaki et al., 2012). Further to these components, the rejection positivity (RP) has been used to describe a component in auditory-based studies akin to the Pd and Ptc – with a frontocentral distribution occurring at 200-250 ms post-stimulus (Alho et al., 1987; Degerman et al., 2008; Michie et al., 1993).

While the methodology of examining auditory distraction in TAiL differs from typical studies, the assessment of conflict resolution matches that of the classic Stroop paradigm – where the difference between incongruent and congruent target and distractor stimulus features provides a measure of conflict resolution (Stroop, 1935). The Stroop task has been widely explored using EEG in the visual domain with studies manipulating a word's meaning and its colour presentation to reveal a frontocentral negative difference wave component, the N450 (e.g. Liotti et al., 2000; Markela-Lerenc et al., 2004; West and Alain, 1999; West, 2003. This component typically has an onset of 350 to 400 ms continuing to 500 ms with an origin in the medial dorsal area, specifically the anterior cingulate cortex (Liotti et al., 2000). Comparatively few EEG studies have explored auditory Stroop tasks; to date there are only two such studies, Donohue et al. (2012) and Buzzell et al. (2013). Both of these studies used verbal stimuli (e.g., "High" and "Low" or "Left" and

"Right") and found difference wave components similar in topography to visual Stroop tasks (frontocentral negativity). However, the ERPs presented earlier with an onset of 200 to 250 ms lasting until 500 ms and peaking at about 300 ms.

A later posterior sustained positivity (SP) was also identified at 500-800 ms for visual and auditory Stroop tasks (e.g. Donohue et al., 2012; Liotti et al., 2000; Markela-Lerenc et al., 2004; West and Alain, 1999; West, 2003). It has been proposed that this component, SP, reflects additional supramodal processing, such as word meaning (Liotti et al., 2000), or the control required to accurately respond to the trial (Larson et al., 2009).

4.2 Method

4.2.1 Participants

Sixteen participants aged 18-25 (M = 22.25 years, SD = 2.26 years; 7 females and 9 males) were recruited through the Rotman Research Institute participant database. Inclusion criteria were normal hearing (thresholds below 20 dB HL bilaterally at frequencies between 250 and 8000 Hz, inclusive), and a normal score (0-3) on the Quick Speech-in-Noise test (Killion et al., 2004). Exclusion criteria were any self-reported history of brain damage, brain surgery, history of language-related or attention-related conditions, Autism Spectrum Disorder (ASD) or any auditory system disorder. Consent, approved by Toronto Academic Health Services Network, was signed by each participant prior to the experiment and each was paid an inconvenience allowance.

4.2.2 Task

TAIL stimuli were presented using a SoundMAX integrated digital HD Audio sound card and Etymotic ER-3A insert earphones. All RT responses were made using two buttons on the keyboard (the letters 'Q' and 'E'), with the hand of the participant's choice to limit motor movement. In order to maintain standard timings across all trials, the two tones within each trial were set at 100 ms and the ISI set to 300 ms in duration.

In addition to the distraction and conflict resolution measures, a baseline measure was calculated for both the attend-frequency and attend-location

TAiL tasks from trials where both sound features (frequency and location) remain constant (i.e. SfSL trials).

4.2.3 Procedure

Both TAiL tasks (attend-frequency and attend-location) were repeated nine times. Each block included 40 trials, providing a total of 360 trials per task condition per participant. The order of the task types was alternated across the blocks, and counterbalanced across participants. The total testing/recording time was $\approx$ 45 minutes with listeners tested individually in a sound-attenuated booth. RTs from correct trials, and accuracy (% correct) were used in the analysis.

4.2.4 EEG recording & analysis

The electrical brain activity was digitised continuously (DC-100 Hz; 512 Hz sampling rate) from an array of 64 electrodes using BioSemi. Eye and facial movements were recorded with electrodes placed on the inferior orbit and from the outer canthi leading to the back of the ear. During the recording, all electrodes were referenced to a Common Mode Sense (CMS) active electrode and Driven Right Leg (DRL) passive electrode serving as ground; for data analysis they were re-referenced to an average reference.

Traces were segmented (-200-1500 ms), baselined to the pre-stimulus interval, and subsequently averaged in the time domain (from trials with correct responses) to obtain ERPs for each TAiL trial type (i.e. SFSL, SFDL, DFSL, DFDL). The group mean number of trials included in the ERP average for each TAiL condition was 74.07% (SD = 18.74%) in the attend-frequency task and 77.20% (SD = 14.75%) in the attend-location task. For each individual average, ocular artifacts were corrected for (e.g. blinks, saccades and lateral movements) by means of ocular source components using the Brain Electrical Source Analysis (BESA) Research 5.3 (released 2012) software (Berg and Scherg, 1994; Picton et al., 2000). ERPs were digitally filtered to attenuate frequencies below 0.5 Hz and above 40 Hz. One participant was excluded due to a high number of artifacts during recording.

4.2.5 Electrophysiological analysis

BESA Statistics 1.0 (released 2014) was used as a data-driven method to compare two conditions over all scalp regions up to 1500 ms post-onset of the first tone. This program uses bootstrapping to determine the probability values of differences between two conditions across time clusters, previously determined via a series of t-tests comparing the amplitude of each of the two conditions. The resulting probability value is based on the proportion of significant permutations at each time cluster and is corrected for multiple comparisons. The number of permutations was set at 1,000 with a cluster alpha of $.05$ for cluster building. The channel diameter was set at 4cm which led to around 4.03 neighbours per channel.

4.3 Results

4.3.1 Behavioural

A 2×2 repeated measures ANOVA (frequency: same, different; location: same, different) showed significant effects for the TAiL measures of distraction and conflict resolution.

Distraction

In the attend-frequency task (Figure 4.1A) RTs were significantly slower for trials where the location of the two tones changed than when they remained constant ($F(1, 15) = 28.44, p < .001, \eta_p^2 = .66$). Similarly, in the attend-location task (Figure 4.1B), participants were slower ($F(1, 15) = 35.30, p < .001, \eta_p^2 = .70$) for trials where the frequency of the two tones changed.

Conflict resolution

In both tasks (Figure 4.1A, Figure 4.1B), participants were faster when both stimulus features stayed the same or changed than when only one of the stimulus features changed (attend-frequency: $F(1, 15) = 17.62, p < .001, \eta_p^2 = .54$; attend-location: $F(1, 15) = 28.16, p < .001, \eta_p^2 = .65$).

First and last blocks

As the original TAIL paradigm had been increased from 6 to 18 blocks, a repeated measures ANOVA was conducted to check for sustained attention effects and assess for training effects between the first and last blocks of each task type. For both task types, there was no significant effect

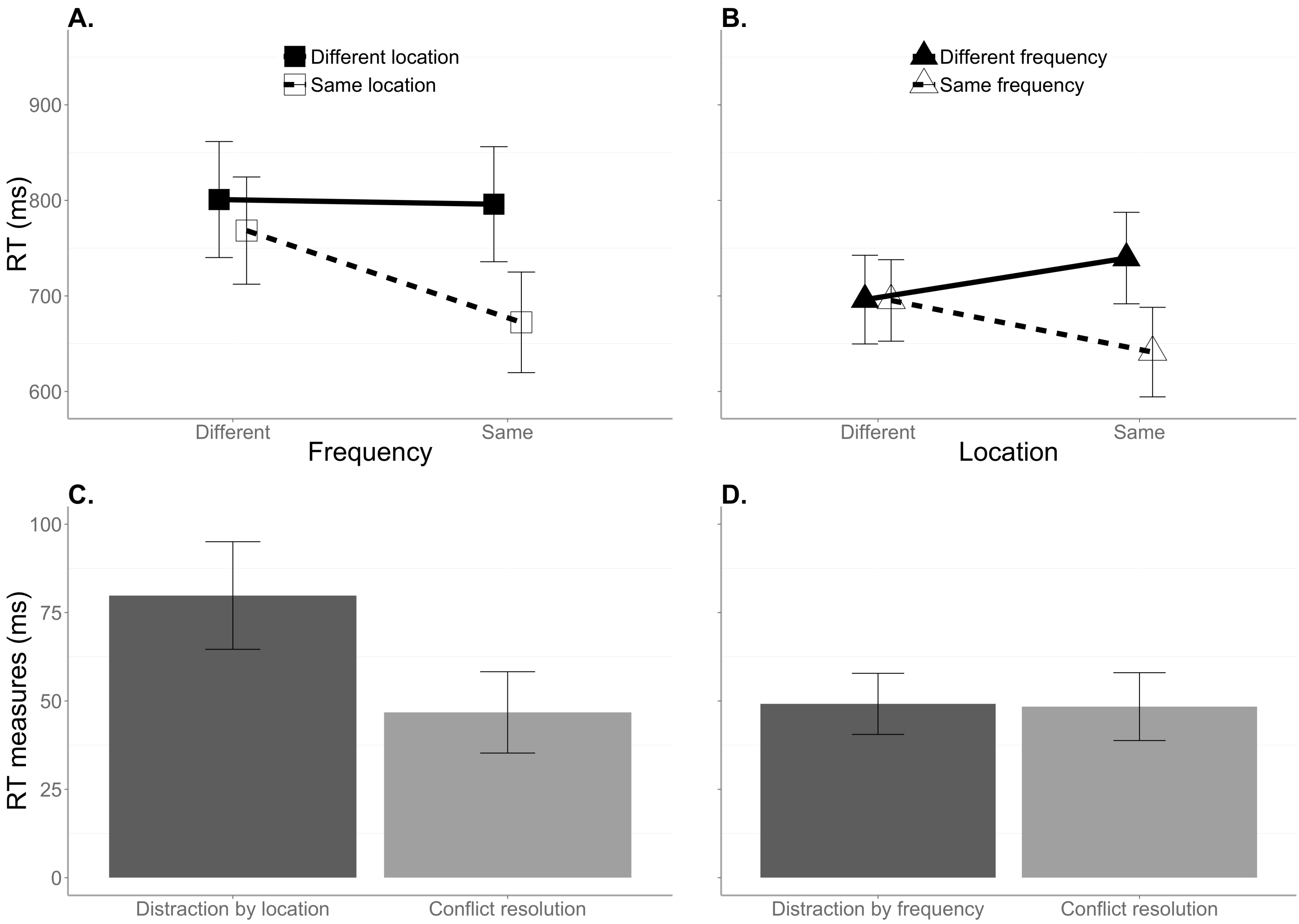

Figure 4.1: Group mean response times for the (A) attend-frequency and (B) attend-location TAiL tasks. Group mean measures of distraction and conflict resolution for the (C) attend-frequency and (D) attend-location TAiL tasks. The error bars represent the standard error of the mean (SEM).

from longer testing time on either the distraction or the conflict resolution measures for RT ($p > .12$) and for accuracy ($p > .36$).

In summary, behavioural evidence of distraction and conflict resolution were found in both the attend-frequency and attend-location tasks (Figure 4.1C, Figure 4.1D).

4.3.2 Electrophysiological data

Figure 4.2 shows butterfly plots for the baseline measure from the attend-frequency and attend-location tasks. In both tasks, the tone pair generated N1 and P2 waves that were time locked on sound onset. The iso-contour maps show that the N1 wave has a frontocentral scalp

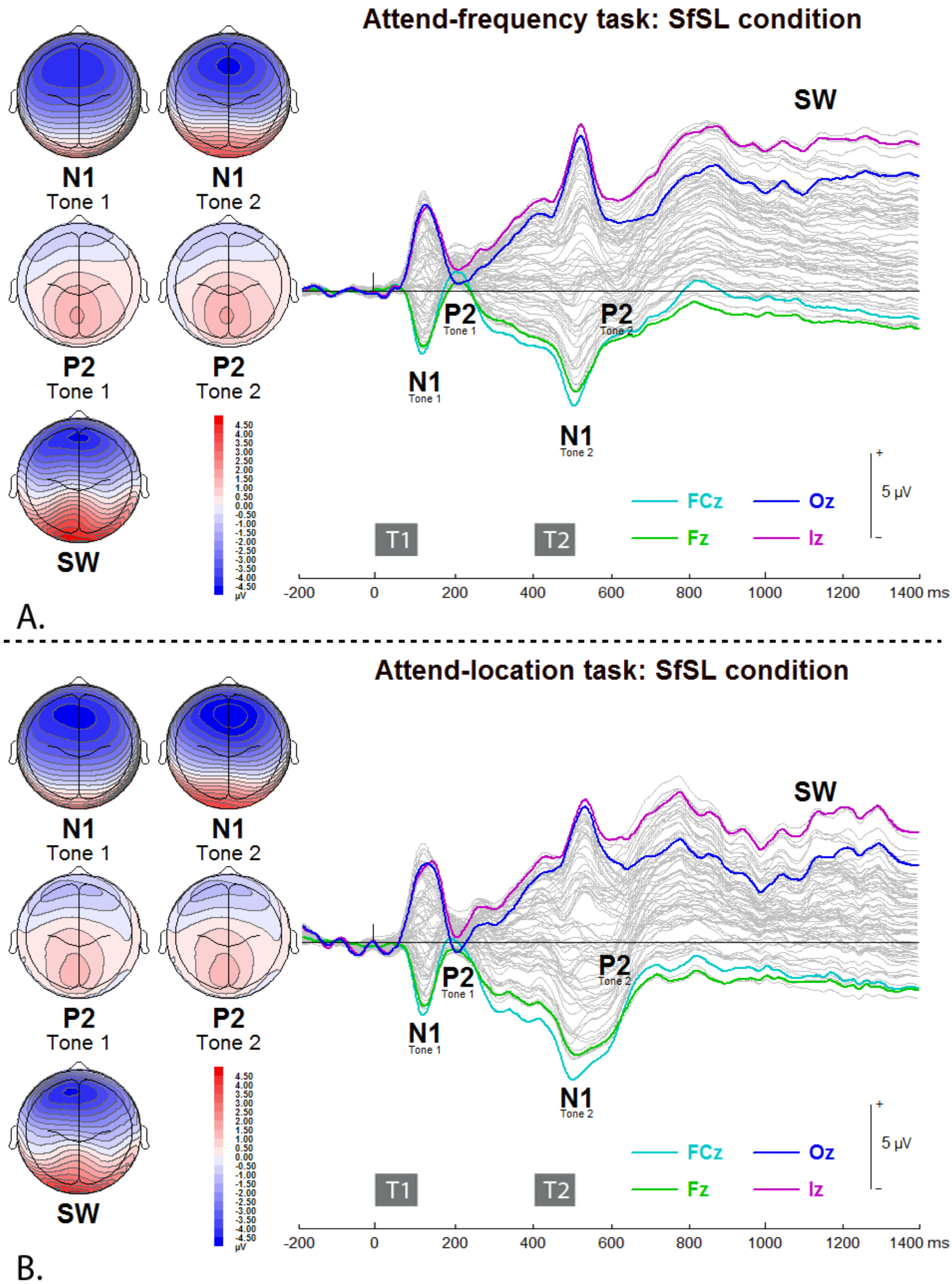

Figure 4.2: Group mean event-related brain potentials (for 65 channels) averaged over all same frequency, same location (SfSL) trials from (A) attend-frequency and (B) attend-location TAiL tasks. The FCz electrode is shown in turquoise, Fz in green, Oz in purple and Iz in pink, all other channels are shown in gray. T1 = first tone; T2 = second tone. Isopotential contour maps are shown for the N1 (115 ms and 100 ms, respectively), P2 (200 ms and 200 ms, respectively) for each tone and slow wave (SW).

distribution and is inverted in polarity at mastoid sites, consistent with generators in the superior temporal gyrus along the Sylvian fissure. The P2 wave has a more centro-parietal distribution whereas the slow wave showed a more frontal distribution, with a peak anterior to that of the N1 wave. The auditory evoked responses elicited by the first tone of the pair were little affected by task instruction. The effect of the TAiL tasks began after the second tone was presented. All future ERP timings are referenced to the onset of tone two at 400 ms.

Distraction

Figure 4.3 shows the ERPs elicited when the task-irrelevant feature changed versus when it remained constant. In both tasks, a significant increase in positivity was found at frontocentral sites ($p < .001$). The polarity of this effect inverted at posterior sites (not shown). In both tasks, the difference wave shows an ERP ranging from around 220-300 ms after the onset of the second tone (T2), peaking at about 255 ms, with a somewhat longer latency in the attend-location task (Figure 4.3B) compared to the attend-frequency task (Figure 4.3A). Evidence from prior research suggests that processing sound identity and sound location engage to a greater extent the ventral and dorsal pathways, respectively (Arnott et al., 2004). Here, the source activity from the frequency and location tasks was compared using dipole source modeling. The analysis was conducted on the distraction difference waves. First two symmetrical dipoles were placed in the temporal lobe near Heschl's gyrus. The source location was then optimised for a 60 ms interval centered on the peak of the difference wave for each task. At a group level the source location for distraction by location (in the attend-frequency task) (M: (22.9, -25.3, 13.5); SEM (1.9, 5.4, 3.0)) was more medial, inferior and posterior than the source location for distraction by frequency (in the attend-location task) (M: (34.7, 1.3, 20.1); SEM (1.9, 3.9, 1.9)). Paired t-tests on the x-, y- and z-axes were significantly different between the frequency and location tasks (x: $t(14) = -2.29, p = .038$; y: $t(14) = -5.72, p < .001$; z: $t(14) = -4.15, p = .001$).

Conflict resolution

Figure 4.4 shows the conflict resolution, which is highlighted by contrasting ERPs for congruent trials (where both tone features remain constant or change) with those elicited by incongruent trials (where just one of the tone features changes). In the attend-frequency task, there was a significant difference, with incongruent trials generating more negative ERPs between

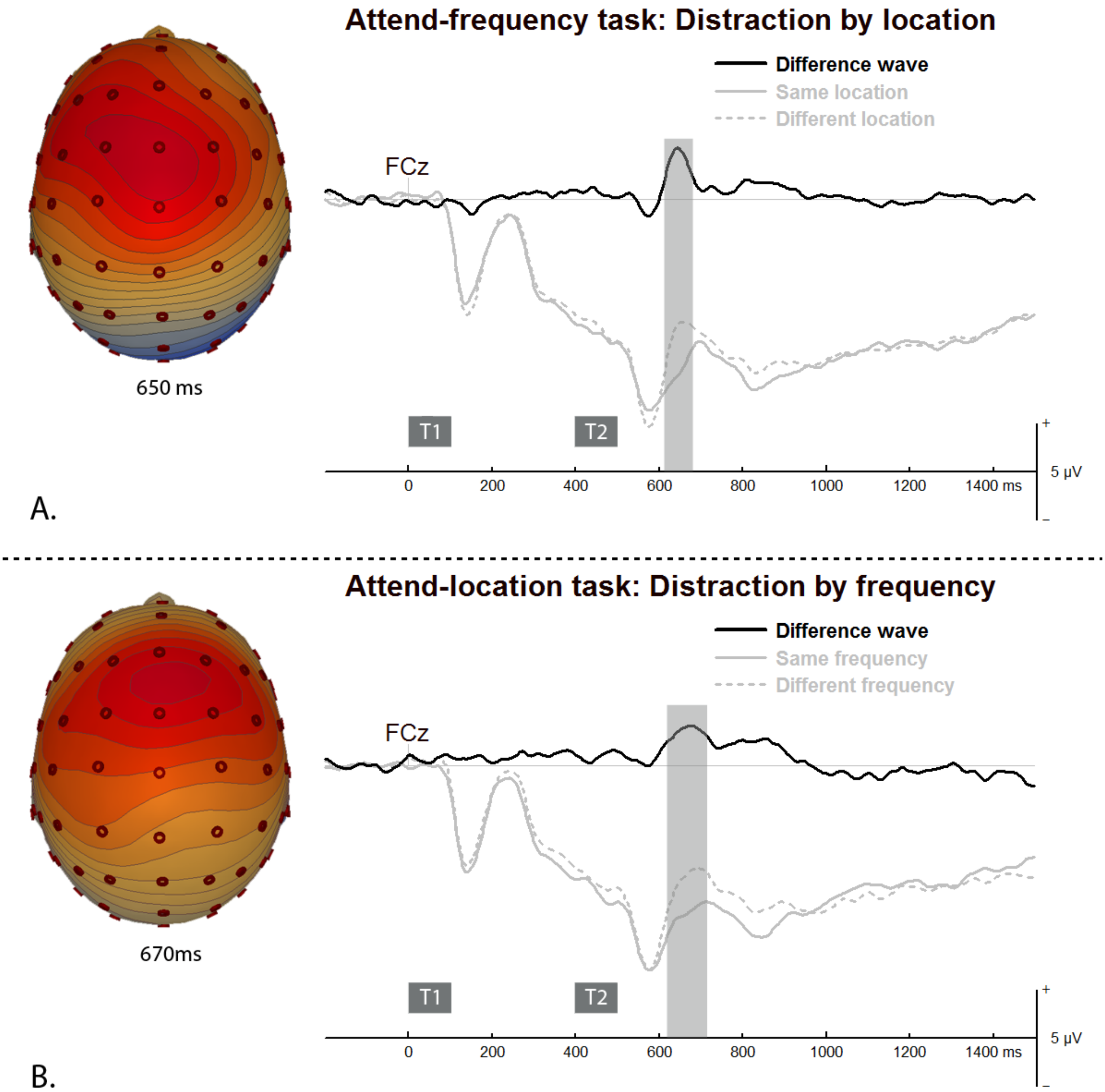

Figure 4.3: Distraction TAiL effect group mean event-related brain potentials recorded over the central frontal (FCz) scalp region for the (A) attend-frequency task and (B) attend-location task. T1 = first tone; T2 = second tone. Shaded areas indicate significant difference $p < .05$. Contour maps illustrate the brain activity at the peak of the difference waves.

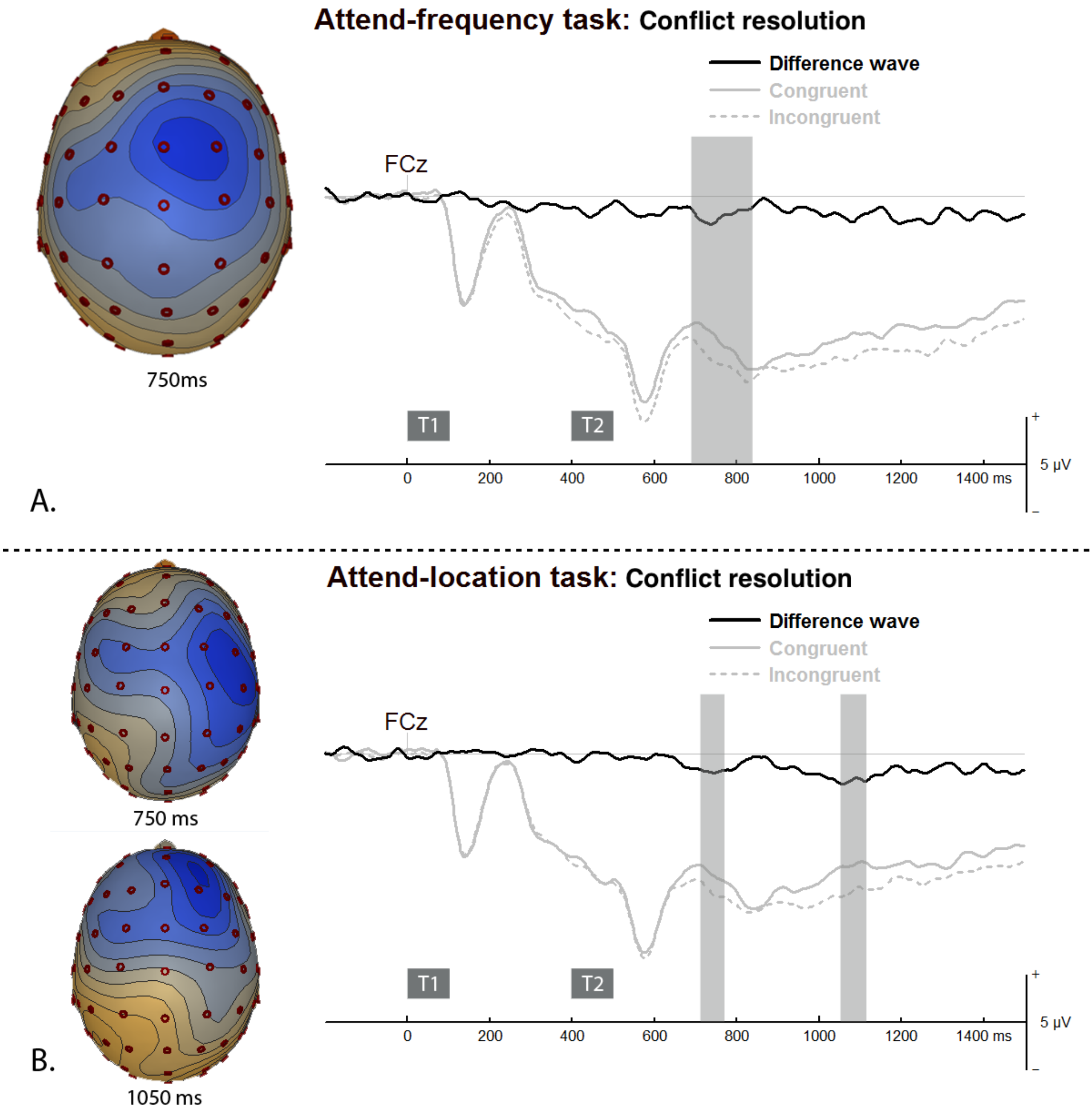

Figure 4.4: Conflict resolution TAiL effect group mean event-related brain potentials recorded over the central frontal (FCz) scalp region for the (A) attend-frequency task and (B) attend-location task. T1 = first tone; T2 = second tone. Shaded areas indicate significant difference $p < .05$. Contour maps illustrate the brain activity at the peak of the difference waves.

300 and 400 ms after the tone 2 (T2) at frontocentral sites (Figure 4.4A). In the attend-location task, the incongruent trials generated significant increases in negativity between 315 and 370 ms and again between 650 and 710 ms over the right frontocentral sites (Figure 4.4B).

4.4 Discussion

In both the attend-frequency and attend-location tasks, interference effects from the irrelevant tone feature were found on RT. These effects illustrate that the irrelevant tone feature changing significantly distracted the listeners. A positive ERP component was found on the difference wave of this effect at frontocentral sites. This component was found at a similar time period for both TAiL tasks, with a peak at 255 ms post-onset of the second tone.

The Pd and Ptc are typically reported in visual selective attention tasks as a parietal positive component with an onset between 250 and 300 ms (Hickey et al., 2008; Hilimire et al., 2011; Sawaki and Luck, 2010; Hilimire et al., 2009). The frontocentral positive distraction component found in this study occurs earlier than this with the peak occurring at 255 ms. Therefore this component corresponds with the earlier RP, as reported in auditory selective attention tasks with an earlier onset of 200-250 ms (Alho et al., 1987; Degerman et al., 2008; Michie et al., 1993). All of these components are thought to index the suppression, or even the rejection, of irrelevant stimuli when they are found not to match the attentional trace of the relevant stimuli (between objects: Hickey et al., 2008; Hilimire et al., 2011; Sawaki and Luck, 2010; and within objects: Degerman et al., 2008).

In both visual and auditory tasks these distraction components have been shown to present in the brain regions that would be enhanced if the distractor were the target (Sawaki et al., 2012). For example, Degerman and colleagues (2008) found that during a continuous stream of auditory tones, when the listener was told to attend to sounds with a specific relevant feature (e.g. in the left or right ear or with high or low pitch), the RP component was based in the brain region associated with the irrelevant sound feature. This result was mirrored in this study, with significantly different dipole sources of the distraction component reflecting the irrelevant stimulus feature. These results suggest that the 'what' and 'where' networks (Arnott et al., 2004; Goodale and Milner, 1992; Mishkin et al., 1983; Rauschecker and Tian, 2000) are at work during the task, with the irrelevant location stimulus feature activating a more posterior network in the attend-frequency task than the irrelevant frequency feature in the attend-location task. Unfortunately the spatial resolution of EEG does not allow for more accurate analysis of the brain regions or network of brain regions suppressing the distractor stimulus feature. However such an investigation can easily be conducted, as the simple structure of TAiL will allow a straightforward translation of the paradigm to one appropriate for use in rapid event functional magnetic resonance imaging (fMRI).

The RP distraction component, in this and other auditory selective attention studies, occurs within an earlier time frame than comparable visual selective attention studies (Degerman et al., 2008; Donohue et al., 2012). This earlier effect with auditory stimuli has also been shown in the Stroop task. Visual Stroop tasks typically report an onset of 350-400 ms with a peak at 450 ms post onset of the stimuli (Liotti et al., 2000; Markela-Lerenc et al., 2004; West and Alain, 1999; West, 2003), whereas auditory Stroop tasks show an earlier onset of 200-250 ms with a peak at around 300 ms (Buzzell et al., 2013; Donohue et al., 2012).

In this study the conflict resolution component was found to occur between 300 and 400 ms in both TAiL tasks. It may be that the auditory stimuli used in TAiL causes earlier component onset than comparable studies in the visual modality as the time from stimulus onset to processing in the primary sensory cortex is markedly shorter in the auditory system when compared to the visual (Hillyard, 1993).

However, a further negative frontocentral component was found to occur 650-710 ms after the second tone onset in the attend-location task's conflict resolution measure. While the distribution of the conflict resolution component in the attend-frequency task is similar to that of previous auditory Stroop studies (Buzzell et al., 2013; Donohue et al., 2012), the timing of this component in the attend-location task straddles the time frames reported in both the auditory and the visual modalities. Therefore these results provide further support to the behavioural results found in the previous chapter whereby TAiL's attend-frequency conflict resolution measure focuses on auditory-specific non-spatial attention, while the attend-location conflict resolution measure assesses supramodal spatial based attention.

The design of TAiL is advantageous firstly because the stimuli used in the two TAiL tasks (attend-frequency and attend-location) are the same, with only the instructions changing, thus reflecting purely cognitive processing differences rather than differences in bottom-up stimulus processing. Secondly, the underlying brain activation of the distraction and conflict resolution measures are calculated from the same blocks of trials allowing them to be directly compared. The results discussed in this chapter suggest that through TAiL's simple paradigm, it is possible to assess a listener's ability to deal with auditory-specific and supramodal conflict resolution between relevant and irrelevant within-object features. Furthermore, results indicate that the distraction measure does indeed result from the task-irrelevant feature, rather than the feature on which the listener is basing their decision.

The present chapter aimed to assess whether TAiL can evaluate listeners' ability to suppress irrelevant sound information and to resolve conflict concurrently, as is often required in everyday listening environments. The results indicate that TAiL's paradigm succeeds in assessing both of these skills simultaneously by displaying distinct neural processes. In addition, by simply changing the task goal through a change in instructions, the timings and distributions of the distraction and conflict resolution measures shift. This provides further support to the findings of the previous chapter that the attend-location TAiL task measures supramodal selective attention, while the attend-frequency TAiL task taps into auditory-specific selective attention. Therefore TAiL's paradigm fits the requisite of an auditory selective attention paradigm required by this thesis to separate cognitive listening ability from sensory ability.

4.5 Conclusions

(1) TAiL's distraction measures produce ERPs representing the suppression of irrelevant information, suggesting these outcomes quantify the listener's distraction by the task-irrelevant information.

(2) ERPs from TAiL's conflict resolution measures are similar to those found in Stroop tasks, indicating that these outcomes assess the listener's ability to deal with conflicting task-relevant and -irrelevant information.

(3) These findings show that TAiL is able to concurrently assess a listener's auditory distraction and conflict resolution skills.

CHAPTER 5

Selective attention to auditory stimuli in typical development

So far in this thesis TAiL has been shown to concurrently assess selective attention measures of distraction and conflict resolution in young adults. Furthermore it has been shown that by simply changing the task instructions, the modality of the attention goals can be shifted from auditory-specific (when attending to the non-spatial stimulus features) to supramodal (when attending to the spatial stimulus features). Therefore, the TAiL fits the requirements of this thesis as a simple non-verbal test to assess auditory selective attention. However, it has not yet been used in a developmental setting. To lay the foundations for the TAiL's use to test auditory selective attention ability in children with LDN, this chapter tracks the developmental trajectory of distraction and conflict resolution using a game-like version of TAiL in children aged 4-11.

5.1 Introduction

While visual attention is dominated by spatial organisation, audition is dominated by spectral organisation (Lund, 1988; Merzenich et al., 1982). As described by the dual-pathway model the adult brain shows clear organisation for processing supramodal spatial information and modality-specific non-spatial information separately in the dorsal and ventral streams, respectively (Rauschecker and Tian, 2000; Arnott et al., 2004; Mishkin et al., 1983; Goodale and Milner, 1992). It may be that different rates of maturation are found in spatial compared to non-spatial auditory tasks. For example, visual evidence suggests that from age 5 spatial perceptual abilities develop more slowly than non-spatial form coherence, before both abilities converge at adult levels by age 10 (Braddick and Atkinson, 2011). Further evidence can be found in studies on children with developmental disorders such as autism (Koldewyn et al., 2010), Williams Syndrome (Atkinson et al., 2003, 1997), and dyslexia (Hansen et al., 2001), which show that visual spatial abilities are more susceptible to disruption than non-spatial global form identifying abilities. While the developmental trajectories for visual spatial and non-spatial attention have been extensively investigated, the development of processing non-verbal auditory spatial and non-spatial features has not been clearly assessed. Further to this there have been no studies assessing a child's ability to deal with conflicting non-verbal auditory information. This study aims to address this gap, first investigating how a developing child orients away from distracting auditory features, and second examining how a developing child deals with auditory conflict resolution.

When provided with exogenous cues children have been shown to display adult-like orientation abilities in the presence of distracting information. A child-adapted version of the vANT found no differences from age 6 to adulthood in the ability to orient to the relevant spatial information when provided with valid spatial cues (Rueda et al., 2004). Findings in audition have been similar – while children aged 10 still perform more poorly than adults when orienting to a target of a specific pitch, the simple provision of a temporal cue can allow children as young as 7 to perform as well as adults (Leibold and Neff, 2007).

However, in everyday environments, such cues are not always present, especially in a typical listening environment where talkers' location and speech properties can change rapidly. Without cues, the speed and accuracy of children's orienting does not reach adult level until a later stage in their development. This is evidenced by the performance of 8 to 11 year olds in behavioural dichotic listening tasks, in which by age 11 the children were as fast as adults at making a correct response (Pearson, 1986 thesis). Children's immaturity of orienting speed and accuracy has also been shown in oddball ERP studies with frequency, duration and intensity deviant targets, in which children aged 9 to 12 showed delayed peak latency compared to young adults for selective auditory attention components[1] (Gomes et al., 2007). Similarly, Berman and Friedman (1995)

[1]Specifically the Negative Difference (Nd) component thought to reflect the processing of task-relevant information.

found age-related effects when comparing 7-10 year olds with young adults on deviant frequency or syllable targets, but only after 200 ms, suggesting a delay in processing.

It may be that younger children are able to differentiate between the streams/features and can preferentially select the more relevant information, but are simply unable to do so at the same level of processing speed and efficiency as older children (Ridderinkhof and Van der Stelt, 2000). For example, instead of the younger children exhausting their limited resources on processing irrelevant auditory information, they may have difficulty separating the relevant from the irrelevant information to be able to quickly and accurately report the answer, or they may be unable to inhibit reporting the irrelevant information (Lane and Pearson, 1982; Karns et al., 2015). This suggests that the younger children possess more information about both the relevant and the irrelevant stimuli as more time is required to make such a distinction. Having more information available in turn means more effort may be required to inhibit the excess of irrelevant information. Therefore while developing the ability to rapidly reorient attention, the children must also learn to accurately deal with conflicting information for efficient selective attending (Gomes et al., 2000; Karns et al., 2015).

In order to coordinate behaviour towards a sensory goal, whether it be perceiving an object or distinguishing one talker from another, executive control is required (Posner and Rothbart, 2007). The executive ability to resolve conflict allows an individual to select a subdominant object or feature in the presence of competing sensory objects/features. In general children's ability to deal with conflicting information increases with age (for review see Ridderinkhof and Van der Stelt, 2000). For example while younger children are more affected by irrelevant information in general, their performance improves when the irrelevant information is congruent with the relevant (Day and Stone, 1980; Shepp and Barrett, 1991). This ability has typically been measured through visual Stroop and flanker paradigms. In a traditional Stroop task (Stroop, 1935) coloured words are presented on the screen and the participant is asked to respond based on the colour, and to inhibit responding based on the word. Trials where the word meaning is incongruent with its colour create a significantly longer reaction time than trials where the word meaning and colour are congruent. This robust difference, referred to as a conflict resolution effect, is found in children from the start of school before peaking at ages 7 through to 9 and then decreasing as the children continue in their reading skill development (Macleod, 1991). This Stroop effect strongly depends on a child's ability to read and so non-verbal variations are also used.

The popular non-verbal vANT has been used in a developmental setting and has shown significant conflict resolution effects in children from the age of 4. The children continue to show improvement in their ability to resolve conflict and reach adult levels by the age of 10 (e.g. Ridderinkhof et al., 1997; Rueda et al., 2004; Mullane et al., 2014). However, adult level performance has been reported as early as age 7 when the child vANT, a more visually-engaging task with cartoon fish pointing in different directions, is used (Rueda et al., 2004; Simonds et al., 2007). The child vANT, like the original vANT, is spatial in nature and has been manipulated by McDermott et al. (2007) to assess conflict resolution to non-spatial stimuli in children. McDermott and colleagues compared the use of shapes and coloured circles; for example, the child was asked to decide the colour of the middle circle while disregarding the conflicting colours of the flanker circles. This trio of child vANT tests showed that all stimulus types resulted in standard conflict resolution effects in children aged 4-6, with the 4 year olds significantly more conflicted than the older children. Furthermore, across the age groups the children were consistently found to be more conflicted by the spatial stimuli compared to the non-spatial stimuli. Unfortunately, comparing developmental trajectories of the three different stimuli was not a goal of the study, which did not include age group comparisons or test an adult comparison group. Yet these results suggest that visual conflict resolution effects can be found from the age of 4 with non-verbal non-spatial and spatial stimuli, when using a visually-engaging task.

While there are a range of studies assessing the development of visual conflict resolution, there have only been a small handful in the auditory field. A sex-stereotype auditory Stroop has shown that both children and adults show typical conflict resolution effects: they are slower and less accurate when responding to incongruent trials (e.g. a male voice saying "Mommy") compared to congruent trials (e.g. a male voice saying "Daddy") (Jerger et al., 1988; Most et al., 2007). The extent of this conflict resolution effect decreases significantly from age 3 to 4 and continues to decline up to the age of 6 (Jerger et al., 1988), although there has been no age group comparison with adults to assess whether 6 year olds have reached maturation in dealing with conflicting auditory verbal information. Therefore comparisons of the development of auditory and visual conflict resolution cannot be made. However, Guy and colleagues (2012) have compared equivalent auditory and visual non-verbal Stroop-like tasks in which children (aged 3 to 6) were presented with cat and dog noises and pictures. In congruent blocks they were asked to respond with the animal that matched the noise, and in incongruent blocks they were asked to respond with the opposite animal. The children were shown to become faster and more accurate in the tasks with age, with a similar progression for both the visual and the auditory tasks. However, the children took longer overall in the auditory trials.

This current study aims to assess the orienting and conflict resolution aspects of auditory selective attention using TAiL's paradigm with its spatial and non-spatial based tasks. It was predicted that children will become faster and more accurate overall in TAiL's tasks as age increases. It follows that as younger children will take longer to conduct the task, they will take longer to orient attention away from the irrelevant information and to the relevant information (i.e. TAiL's distraction effect). Therefore it is expected that TAiL's distraction measure will decrease with age for both the attend-frequency and attend-location TAiL tasks. In line with visual research it is expected that selective attention to spatial and non-spatial stimulus features will mature at different rates, with both tasks reaching adult levels by age 10-11. As shown in Chapter 4, the TAiL distraction measure assesses the listener's ability to orient away from the irrelevant sound feature. Therefore in the attend-frequency task it measures the extent to which the listener is distracted by spatial information, and in the attend-location task the extent to which they are distracted by non-spatial information. It is expected that the distraction in the TAiL attend-location task (i.e. orienting away from irrelevant frequency information) will mature earlier than in the attend-frequency task.

Furthermore, this study will be the first to conduct a feature-based non-verbal auditory Stroop task with spatial and non-spatial stimuli in children. It is predicted that the children will gain more control of their ability to deal with mismatching information with age, and so their speed and accuracy will be less affected by incongruent trials as they mature, illustrated by decreased conflict resolution effects. If auditory conflict resolution does indeed mirror the developmental phasing of visual conflict resolution, as suggested by Guy et al. (2012), the children should reach adult levels by age 10. While a younger age of maturity at age of 7 years has been shown in the visual literature, these results were in studies where the visual stimuli used to make up the trial's decision were engaging for participants (e.g. the pointing fish in the child ANT, Rueda et al., 2004). The current study will use a game-like interface for TAiL (more details in the methodology below). Unlike in the child ANT, the visual display in TAiL is used only to make the task more engaging for the participant, and is not integral to the decisions made by the participant during the task. Therefore it is not expected that the children will demonstrate mature abilities at an earlier stage.

5.2 Method

5.2.1 Participants

Eighty-five children aged 4 to 11 (M = 8.34 years, SD = 2.03 years; 42 females and 44 males) were recruited through the University of Nottingham's Summer Scientist event, which was advertised through local schools, newspapers and radio stations. During this event children from the local area (deprivation index: Q.25 = 5.24[2], Q.75 = 19.56) came to the university and took part in scientific studies in a fun and interactive manner (for information, see www.summerscientist.org). Written consent was obtained from the children's responsible caregiver and each child gave verbal assent to the study, with data collection conducted in accordance with Nottingham School of Psychology Research Ethics Committee approval. The children were subdivided into age categories of 4-5 (M = 5.57, SD = .25; 8 females, 9 males), 6-7 (M = 7.18, SD = .45; 9 females, 13 males), 8-9 (M = 8.87, SD = .51; 14 females, 9 males), and 10-11 (M = 10.98, SD = .52; 10 females, 13 males).

Forty-two adults from the study presented in Chapter 3 were used as a young adult comparison group, aged 19 to 30 (M = 22.69 years, SD = 3.16; 25 females and 16 males). All adult listeners had normal hearing as defined by the British Society of Audiology (2011b) – pure tone thresholds below or equal to 20 dB HL bilaterally at octave frequencies between 250 and 8000 Hz. Each adult participant signed informed consent and was paid an

[2]Assessed with the Government Index of Multiple Deprivation (McLennan et al., 2011) where a low score (≤ 8.49) indicates least deprived and a high score (≥ 34.18) indicates most deprived.

inconvenience allowance. Adult data collection was conducted with approval from NHS Research Ethics Committee East Midlands – Nottingham.

5.2.2 Screening questionnaires

As part of taking part in the Summer Scientist event, each child's caregiver completed a number of screening questionnaires. Caregiver reports showed no children with hearing difficulties, although the Social Aptitude Scale (SAS: Liddle et al., 2009 used to assess for ASD behaviours identified two at-risk children who were subsequently excluded from analysis. Through self-report none of the adult participants reported a history of language-related or attention-related conditions, ASD or any auditory system disorder.

5.2.3 Apparatus

The TAiL was presented to the children on a 15 inch laptop screen using a Fast Track Pro USB audio interface (M-Audio, inMusic Brands) and AKG K702 headphones. It was presented to adults on a 15 inch flat-screen monitor, with Sennheiser HD 25-II headphones via an ASIO driver controlled custom sound card.

5.2.4 Task

Both the child and adult participants completed the TAiL with the same trial foundations and auditory stimuli, with a game-like interface used for the children. Clear feedback and a story have been shown to allow experimental games to engage the interest of children as young as 4 (Berger et al., 2000), and so custom built software was used to present TAiL as a space game for the children. The experimenter introduced each child to the world of TAiL through a backstory in which they were the captain of a lost spaceship who had to navigate their way past aliens to their friend's spaceship. The children were told to 'blow up the aliens' for a different decision and to 'show fireworks to their friends' for a same decision. The children played the game, using their drawing/writing hand, and received immediate auditory and visual feedback regarding their performance. The adult participants completed the standard TAiL (as used in Chapter 3), receiving experimental instructions and visual feedback without the game-like interface.

5.2.5 Procedure

At the Summer Scientist event each participant's session had a 20 minute limit, and so two blocks of each of TAiL's tasks (attend-frequency and attend-location) were completed, providing a total of 80 trials per task for the children. To ensure that the children did not confuse the instructions between the two TAiL tasks they completed one TAiL task before moving to the other, with the presentation order of the two tasks counterbalanced across participants.

The adult listeners completed TAiL as part of a larger battery of counterbalanced tests. To ensure that the foundations were identical for both the children and adult versions of the TAiL, only the blocks of a fixed ISI were used in the analysis from the adults, providing a total of 40 trials per task for the adults.

All participants were tested individually, with the children in a quiet room with minimal visual distractions and adults in a sound-attenuated booth. The experimenter sat alongside the children throughout in order to prompt focus on the task, if required.

5.2.6 Statistical analysis

At the start of each new TAiL task the listeners had to pass practice blocks with at least 60% accuracy. Two children (aged 4 and 5 years) failed to do so in both TAiL tasks and one child (aged 5 years) in the attend-location task . One more child (aged 4 years) was excluded from analysis as they showed a button preference by being twice as likely to choose the different button. This left a total of 80 children for further analysis of the attend-frequency TAiL task, and 79 for the attend-location TAiL task. Unfortunately, this removed all of the 4 year olds from the sample. Finally, trials with a RT shorter than 200 ms or longer than 2500 ms were excluded (5.65% in children and 0.69% in adults) in case of pre-emptive responses, lapses of attention or task interruption.

Contrast measures were calculated through a difference index of the RT and accuracy effects (e.g. for conflict resolution: $\frac{incongruent-congruent}{incongruent+congruent}$) in order to allow a comparison of the distribution of the effects across age groups. In the following analyses homogeneity of variance is assumed in the appropriate groups, as tested by Kruskal-Wallis. Where homogeneity of variance is not assumed, the appropriate non-parametric tests were conducted.

5.3 Results

The TAiL tasks' baseline (trials where both the frequency and the location of the sounds remain constant) were used to assess whether there was a change in RT and accuracy with age. In both TAiL tasks (attend-frequency and attend-location), Mann-Whitney comparisons showed that the children were significantly slower ($U = 488, p < .001; U = 246, p < .001$) and less accurate ($U = 665, p < .001; U = 649, p < .001$) than the adults. Linear regressions (Figure 5.1) showed that the children became faster ($F(1, 78) = 25.03, p < .001, R^2 = .24; F(1, 77) = 15.74, p < .001, R^2 = .17$) and more accurate with age ($F(1, 78) = 31.10, p < .001, R^2 = .29; F(1, 77) = 27.81, p < .001, R^2 = .27$).

To assess whether TAiL's measures quantify different selective attention abilities of distraction and conflict resolution in children, as shown with the young adults, Holm-Bonferonni corrected Pearson correlations were conducted. Results showed that for all of the child age groups the RT contrast measures of distraction and conflict resolution were not correlated with one another, or across the attend-frequency and attend-location tasks (see Table 5.1).

To assess for differences across the age groups (4-5, 6-7, 8-9, 10-11, young adults) and the two TAiL tasks (attend-frequency, attend-location), 5×2 mixed-design ANOVAs were used for the distraction and conflict resolution RT contrast measures. All post-hoc tests were Holm-Bonferonni corrected.

5.3.1 Distraction

For the distraction RT contrast measure a significant main effect of age was found ($F(4, 116) = 2.88, p = .026, \eta_p^2 = .090$), showing the youngest two groups to be significantly less distracted than the young adult group ($p = .003$, $p = .032$, respectively). There was no significant main effect of TAiL task ($F(1, 116) = .064, p = .80, \eta_p^2 = .001$), although there was a significant interaction between age and task-type ($F(4, 116) = 3.82, p = .006, \eta_p^2 = .12$). These effects can be seen in (Figure 5.2A). Post-hoc t-tests showed that (see Table 5.2) in the attend-frequency task the youngest two groups were significantly less distracted than the oldest two groups, and the 8-9 year olds

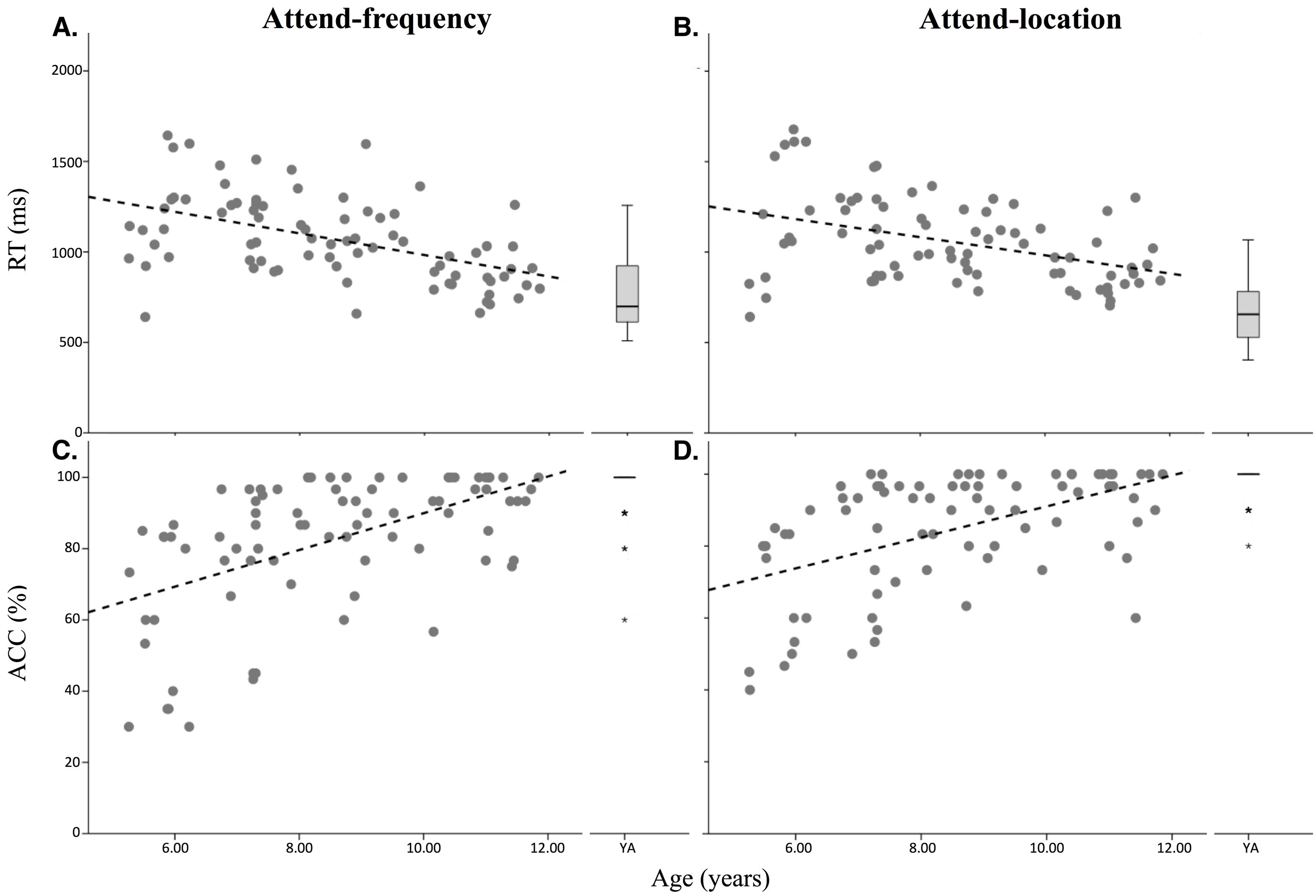

Figure 5.1: Baseline (SfSL trials) RT for (A) attend-frequency and (B) attend-location tasks, and accuracy for (C) attend-frequency and (D) attend-location tasks. Each data point represents a single child and box-plots show the spread for the young adults (YA). Dotted lines represent the linear regression of children's performance with age (x-axis) (A: $y = -0.06{*}x + 1.58$; B: $y = -0.05{*}x + 1.49$; C: $y = 5.15{*}x + 38.36$; D: $y = 4.36{*}x + 47.59$).

were significantly less distracted than the adults. In the attend-location task the 8-9 year olds were significantly more distracted than the youngest and oldest groups. It was also found that the 10-11 year olds and young adults showed significantly less distraction in the attend-location task compared to the attend-frequency task.

Follow-up one-way t-tests (Holm-Bonferonni corrected) compared the distraction RT contrast measures to zero. The distraction effect in the attend-frequency task was significantly different from zero for the 10-11 year olds ($t(22) = 4.61, p < .001$) and young adults ($t(41) = 5.68, p < .001$) only, while in the attend-location task only the 8-9 year olds and adults

		Age	Attend-frequency		Attend-location	
			Distraction	Conflict resolution	Distraction	Conflict resolution
Attend-frequency	Distraction	4-5				
		6-7				
		8-9	–	–	–	–
		10-11				
		YA				
	Conflict resolution	4-5	.05			
		6-7	-.12			
		8-9	-.49 *	–	–	–
		10-11	.21			
		YA	.17			
Attend-location	Distraction	4-5	-.13	.07		
		6-7	-.17	-.12		
		8-9	.06	-.15	–	–
		10-11	.35	-.01		
		YA	.21	-.03		
	Conflict resolution	4-5	.45	-.14	-.14	
		6-7	.08	-.09	-.01	
		8-9	-.07	.31	-.35	–
		10-11	-.02	.34	-.37	
		YA	.12	-.14	-.15	

Table 5.1: Pearson correlations of distraction and conflict resolution measures across the attend-frequency and attend-location tasks at each age group.
$^{*}p = .020$, uncorrected

were significantly different from zero ($t(21) = 5.17, p < .001; t(41) = 3.85, p < .001$).

5.3.2 Conflict resolution

For the conflict resolution RT contrast measures, a significant main effect of age was also found ($F(4, 116) = 6.92, p < .001, \eta_p^2 = .19$). The youngest group showed significantly less conflict resolution than the three oldest groups, the 6-7 year olds showed less than the 8-9 and 10-11 year olds, and the 10-11 year olds showed significantly more conflict resolution than the

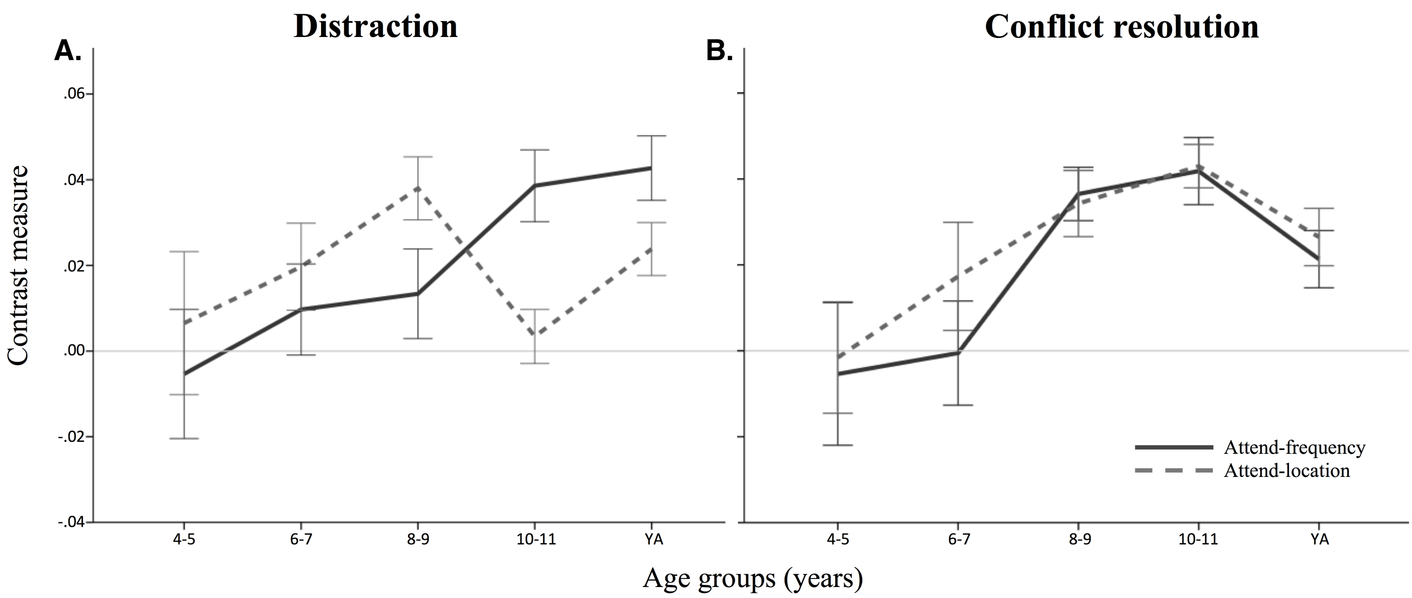

Figure 5.2: RT contrast measures for (A) distraction and (B) conflict resolution across the age groups (x-axis). Solid lines represent the attend-frequency task, and dashed lines the attend-location task. Error bars represent SEM.

young adults (see Table 5.3). There was no significant main effect of TAiL task ($F(1, 116) = .69, p = .41, \eta_p^2 = .006$) and no interaction ($F(4, 116) = .32, p = .86, \eta_p^2 = .011$), suggesting that the development of conflict resolution is similar in both tasks. These effects can be clearly seen in (Figure 5.2B).

The conflict resolution RT contrast measures were compared to zero using one-way t-tests (Holm-Bonferonni corrected). The conflict resolution effect was significantly different from zero in the 8-9 year old ($t(21) = 5.87, p < .001; t(21) = 4.45, p < .001$), 10-11 year old ($t(22) = 5.35, p < .001; t(22) = 8.49, p < .001$), and young adult ($t(41) = 5.68, p < .001; t(41) = 3.97, p < .001$) groups only, for both the attend-frequency and attend-location tasks.

5.3.3 Speed-accuracy trade-off

To assess speed-accuracy trade-offs Wilcoxon signed-rank tests were run to compare the accuracy to irrelevant same and irrelevant different trials for the distraction measure (Figure 5.3A, C). In the attend-frequency task the 8-9 year olds and young adults performed significantly more accurately for trials where the irrelevant feature stayed constant ($Z = -2.07, p = .038$; $Z = -2.15, p = .031$). The same pattern was found for the 6-7 year olds in the attend-location task ($Z = -2.32, p = .020$).

	Task comparison				Age group comparison		
Age group	Task	M	SEM	p	Age group	attF p	attL p
4-5	attF	-.005	.014	.50	6-7	.38	.37
					8-9	.28	.035
	attL	.007	.012		10-11	.011	.83
					YA	.003	.20
6-7	attF	.01	.01	.44	6-7	–	–
					8-9	.80	.14
	attL	.02	.009		10-11	.045	.19
					YA	.01	.70
8-9	attF	.013	.01	.06	6-7	–	–
					8-9	–	–
	attL	.038	.009		10-11	.08	.006
					YA	.022	.19
10-11	attF	.039	.01	.007	6-7	–	–
					8-9	–	–
	attL	.003	.009		10-11	–	–
					YA	.74	.058
YA	attF	.043	.007	.047	6-7	–	–
					8-9	–	–
	attL	.024	.006		10-11	–	–
					YA	–	–

Table 5.2: Distraction RT contrast measure: interaction of task and age group in the attend-frequency and attend-location.

Accuracy comparisons were made between the congruent and incongruent trials for the conflict resolution (Figure 5.3B, D) measure showing 6-7, 8-9 and 10-11 year olds to be more accurate for congruent trials in the attend-frequency task ($Z = -3.57, p < .001; Z = -3.46, p = .001; Z = -3.45, p = .001$) and attend-location task ($Z = -3.81, p < .001; Z = -3.64, p < .001; Z = -3.30, p = .001$).

Age group	**M**	**SEM**	**Age group**	p
4-5	-.003	.009	6-7	.27
			8-9	<.001
			10-11	<.001
			YA	.006
6-7	.008	.006	6-7	–
			8-9	.004
			10-11	<.001
			YA	.053
8-9	.035	.006	6-7	–
			8-9	–
			10-11	.44
			YA	.15
10-11	.042	.006	6-7	–
			8-9	–
			10-11	–
			YA	.019
YA	.024	.005	6-7	–
			8-9	–
			10-11	–
			YA	–

Table 5.3: Conflict resolution RT contrast measure: main effect of age group across the two TAiL tasks.

5.4 Discussion

The aim of this chapter was to assess children's development in the ability to orient away from irrelevant auditory features (i.e. their distraction by those irrelevant features) and the ability to deal with conflicting auditory information. TAiL was used as it has been shown in Chapters 3 and 4 to effectively quantify these abilities in adults. Furthermore, it has been shown that by using the same stimuli but changing the task instructions, the attention goals of TAiL's tasks change from non-spatial to spatial, which the dual-pathway model describes as being auditory-specific and supramodal, respectively.

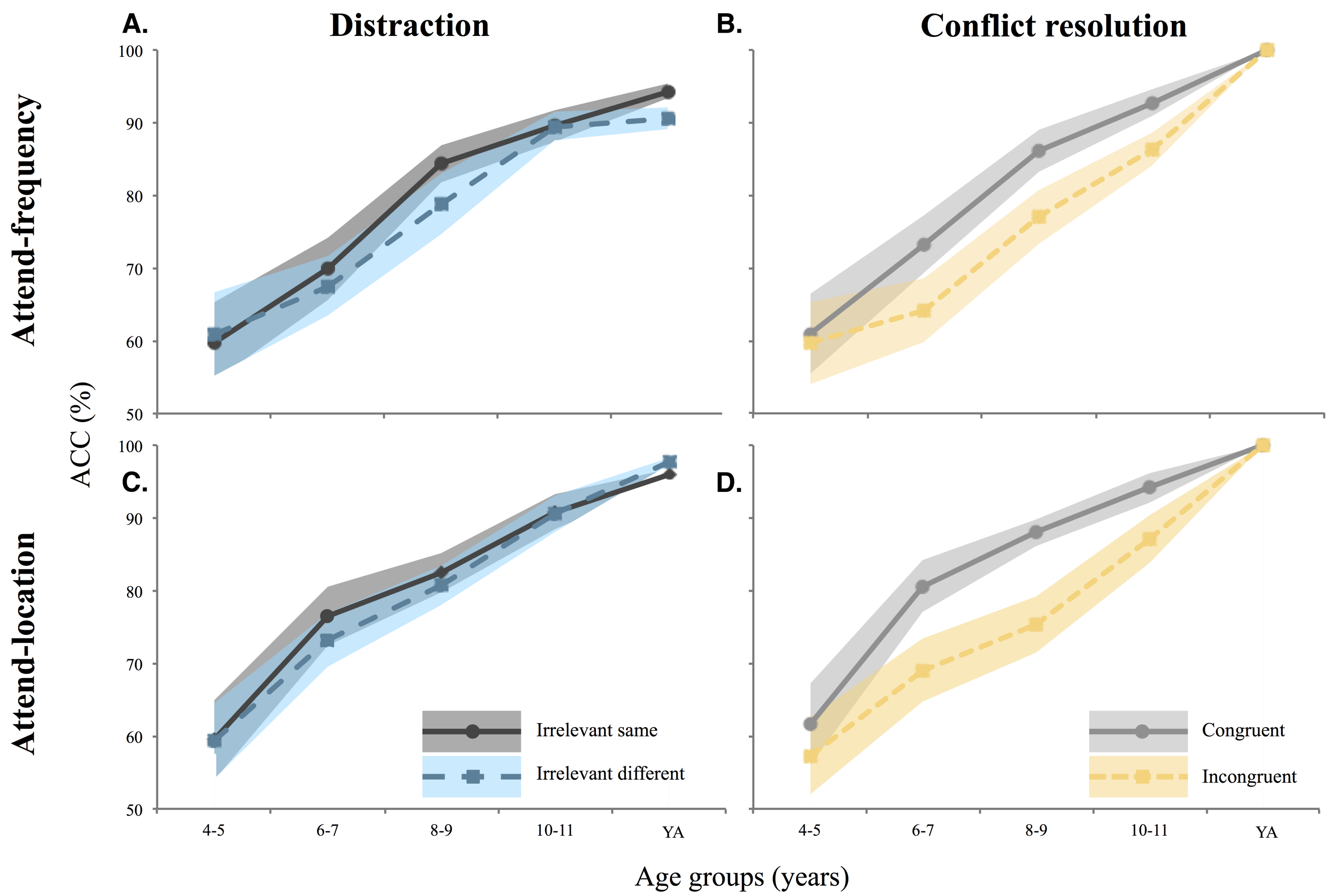

Figure 5.3: Accuracy comparisons of task-irrelevant same and task-irrelevant different feature changes in the distraction measure for (A) attend-frequency and (C) attend-location across the age groups (x-axis). Accuracy comparisons of congruent and incongruent trials in the conflict resolution measure for (B) attend-frequency and (D) attend-location across the age groups (x-axis). Shaded areas indicate age group SEM.

Although the aim was to test equal numbers of children in each age group it was only possible to test a small number of 4 year olds. These 4 year olds were then removed from further analysis, either due to being unable to complete TAiL at a high enough level of accuracy in the practice blocks, or due to showing a button preference. This was unfortunate, as while it has been shown that 4 year olds are able to switch between rules for within-stimulus features in the visual modality (Zelazo et al., 1996), this has yet to be shown in the auditory modality.

Overall it was found that the children were significantly slower and less accurate in both TAiL tasks compared to the adults. However, as predicted, they became faster and more accurate with age. As in the original TAiL design, the TAiL's measures were not correlated to one another in any of the age groups. These measures thus conform to the separable orientating and executive function networks from Posner and Petersen's attentional networks framework (1990, Petersen and Posner, 2012) on which the TAiL's distraction and conflict resolution measures were based, respectively (Zhang et al., 2012).

5.4.1 Distraction and development

Existing evidence from both the visual and auditory domains shows that, as children age, they gain increased ability to disengage from irrelevant sensory information and instead orient to the relevant sensory information of a task (e.g. Rueda et al., 2004; Coch et al., 2005). It was therefore expected that in TAiL the children would show less distraction as age increased, becoming better able to orient their attention away from the irrelevant feature of the task. Instead the opposite effect was found, with distraction increasing through the age groups. This pattern of distraction development is quite clear in the attend-frequency task where listeners are required to orient away from the irrelevant spatial feature of the sounds. Younger children, in the 4-5 and 6-7 age groups, were significantly less distracted than 10-11 year olds and adults, and the 8-9 year olds significantly less distracted than the adults. Children displayed adult-like behaviour by age 10-11 years in the ability to orient away from irrelevant spatial information. In contrast, the pattern of distraction development is unclear in the attend-location task, where listeners are required to orient away from the irrelevant non-spatial frequency feature. In the attend-location task, distraction peaked in the 8-9 year olds before dropping in the 10-11 year olds, and rising again in the young adults.

However, a follow-up analysis showed that the children's distraction effects were significantly different from zero only in the 10-11 age group in the attend-frequency task, and the 8-9 age group in the attend-location task. These results indicate that the younger groups take the same amount of time to respond to a trial regardless of the irrelevant features relationship between the trial's two sounds, while the older groups and adults are significantly faster when the irrelevant feature remains constant within a trial. This does not appear to be a universal speed-accuracy trade-off as the younger groups take the same amount of time regardless of whether the irrelevant feature changed or not, and do not show a drop in accuracy in trials where the irrelevant feature changed compared to trials where it remained constant.

As evidenced in the trials where both features remain constant (the task baseline), there is an age effect on speed. Therefore it may be that the younger groups, showing a lack of a distraction effect, are taking longer to process the information before making a decision. Instead of aiming to orient away from the irrelevant sound feature and back to the relevant sound feature, it is possible that these groups are purposefully processing both of the sound features regardless of relevance. For example, Smith et al. (1975) found that children aged 5-6 were distracted from a visual task by irrelevant colour stimuli, peripheral border changes and auditory stimuli. Therefore regardless of how removed the distractor was from the task, the children in that age group still attended to the distractor. In comparison they found that children aged 7-10 were more able to disregard the distractor the more abstract from the task it was (i.e. auditory distractors in a visual task). In TAiL the distracting information is within the same sound object as the relevant information. Therefore even at middle childhood the children may be struggling to ignore the irrelevant sound features.

An alternative explanation for this pattern of results may be that the groups with a distraction effect not significantly different from zero experienced a dense auditory task created by a substantial processing load (Karns et al., 2015). According to Lavie's (1995) load theory of selective attention, when a task has a low perceptual load an individual's capacity to process the task-relevant information is not used to capacity, leaving capacity available for processing task-irrelevant information and thereby causing distraction due to late selection. Differences in perception of perceptual load have been shown in vision with children reaching a higher load faster than adults, resulting in early selection. For example, Huang-Pollock et al. (2002) showed that children were less affected by task flankers than young adults at a smaller task-relevant set size. Therefore it is possible that where an adult finds a task's auditory perceptual load to be low enough to allow for distraction by late selection, children may find the auditory perceptual load of the same task to be high, leading to early selection of relevant features.

In TAiL the listener is asked to discriminate between the frequency or spatial location of two tones. As the location of the tones can only be in the left or right ear this suggests a low perceptual load. However, the frequency separation between the two tones can range from around 4 semitones to 45 semitones. While children from the age of 4 are able to perceive a 4 semitone separation at adult levels, this is still a harder distinction to make than a 45 semitone separation (Bregman, 1978). This suggests that the range of frequency separations in TAiL may cause the younger children to experience the task at a high perceptual load, causing them to make early selections of the features to be processed. Therefore the younger children's inability to process the irrelevant sound features may be due to all of their available capacity being 'used up'.

5.4.2 Conflict resolution and development

It was predicted that the children would gain more control of their ability to deal with conflicting information with age, reflected by decreasing conflict resolution effects. It was expected that the children would reach adult-like performance by age 10, with a similar developmental path for both the spatial and non-spatial TAiL tasks. However, in both TAiL tasks the children's conflict resolution effect significantly increased with each age group, until a significant decrease in RT from the 10-11 year olds to the young adults. However, similar to the distraction effect, the follow-up analysis showed that the effect of conflict resolution was not significantly different from zero for the two youngest groups (4-5 and 6-7 year olds). Instead of taking longer to deal with the incongruent trials, children up to the age of 7 responded at the same speed as in congruent trials. While this does not appear to be due to a speed-accuracy trade-off in the youngest group, it is possible in the 6-7 year olds as they show a significantly lower level of accuracy for the incongruent trials compared to congruent trials. However, this pattern of speed-over-accuracy trade-off is found in all of the older child age groups, for both the attend-frequency and attend-location tasks.

As discussed above with regard to the distraction measure, it is possible that given the longer response times required to make a distinction in the younger age groups, the listeners in these groups may possess more information about the relevant and irrelevant features. These listeners would thus require more time to process the information before responding correctly, regardless of congruency. Alternatively, it is possible that the younger children (aged 4-7) experience an overwhelming level of perpetual load and are therefore unable to process the irrelevant sound features, and so do not show a RT difference in congruent versus incongruent trials. In comparison, the older children (aged 8 and upwards) and young adults may experience a lower perceptual load from the task and therefore show the expected conflict resolution effect from incongruent features. Furthermore, as illustrated by their speed-over-accuracy trade-off, the older children may continue to develop their ability to deal with auditory conflicting information.

Overall this study has shown that TAiL can be used in children from the age of 5, with increasing levels of accuracy and faster RT through to adulthood. The pattern of distraction and conflict resolution effects maturing with age was not as expected. Instead of the effects decreasing to adult-like levels as age increased, the results suggested different patterns of development. However, further analysis showed that the youngest groups displayed effects that were not significantly different from zero. While these small effects could not be explained by a speed-accuracy trade-off, given that the younger children take longer to respond to the task it is possible that they are processing both the relevant and irrelevant sound features as they need more time to make the within-object distinction. Therefore the younger children may take the same amount of time to respond to a trial regardless of whether the irrelevant sound feature changed or not, showing little distraction, and regardless of the trials congruency, showing little conflict resolution. Alternatively, the younger children may actually possess less information regarding the irrelevant sound feature compared to the older children and young adults. This may be due to the younger children experiencing a high level of perceptual load during the task causing early selection of relevant features and leaving no perceptual capacity to process the irrelevant sound feature. Thus, the young listeners are not distracted and so do not obtain enough irrelevant information to require conflict resolution. These contrasting explanations are further explored in Chapter 6, where the perceptual load of TAiL's task is manipulated in the hope of uncovering whether perceived auditory perceptual load is reduced with increasing age, as found in vision.

5.5 Conclusions

(1) Children as young as 5 are able to complete both the attend-frequency and attend-location TAiL tasks when the tasks are presented in a game-like environment.

(2) The children's RT decreased and levels of accuracy increased with age, progressing towards young adult performance, on both of TAiL's tasks.

(3) The younger groups of children do not show effects of distraction and conflict resolution significantly different from zero, with two possible explanations:

  (a) The younger children take longer to discriminate the features within a sound object and so accrue more information on the sounds, leading to similar RT regardless of the trial type.

  (b) The younger children experience a high level of perceptual load, causing early selection of relevant sound features. With an increase in age comes a decrease in perceptual load experienced, leading to later selection of relevant sound features, which in turn causes more distraction by the irrelevant sound feature and more need for conflict resolution.

CHAPTER 6

The effect of perceptual load on auditory attentional processes

The perceptual simplicity of TAiL does not consume all available processing capacity, thus allowing young adult listeners to process task-irrelevant information, in accordance with the load theory of selective attention. The previous chapter's results showed that the younger children did not show significant distraction or conflict resolution effects. This may be due to the children finding TAiL to be more perceptually demanding than the adults do, leaving insufficient resources for processing irrelevant information. This chapter assesses how children selectively attend to auditory features in a task of varying perceptual loads, while maintaining the cognitive load. With Chapters 3 and 4 suggesting that TAiL's attend-frequency task employs auditory-specific selective attention while the attend-location task utilises supramodal selective attention, this chapter focuses on the attend-frequency task only.

6.1 Introduction

The pattern of results found in the previous chapter could be explained by Lavie's load theory of selective attention (1995). The older age groups may have experienced TAiL as a perceptually undemanding task, and were therefore able to complete it under low perceptual load conditions. This may allow the adults to have capacity left over to process the irrelevant stimuli (represented by significant distraction effects), causing conflict and requiring inhibition to stay on task (represented by significant conflict resolution effects). The younger age groups, on the other hand, may have found TAiL to be a more perceptually demanding task, therefore completing it under high perceptual load conditions. Consequently, they may not have had spare capacity to process the irrelevant stimuli (represented by non-significant distraction effects), processing less of the conflicting information and not requiring inhibition to complete the task (represented by non-significant conflict resolution effects). Using a visual paradigm it has been shown that children reach a high perceptual load earlier than adults[1] (Huang-Pollock et al., 2002). To investigate whether this holds true in audition, this chapter varies the perceptual load of TAiL's attend-frequency task to investigate the developmental change of the effect of perceptual load in an auditory selective attention task.

Before continuing, it is worth clarifying what is meant by perceptual load. The load theory defines perceptual load as the amount of attention required to identify a stimulus, or the number of different features within the stimulus that need to be perceived (Lavie, 1995). This has been described as distinct from cognitive load, which affects the active control processes required to inhibit the identified irrelevant information in tasks of low perceptual load. Therefore, if the task is high in cognitive load (induced by a secondary task, such as digit string recall during the search task) there would be little cognitive capacity left over for the identified irrelevant information to be inhibited, causing the lag in response to increase compared to when a task's cognitive load is low.

Lavie suggests that a task can be moved from a low to high perceptual load by increasing the task's perceptual demands or the amount of different-identity items to be perceived, therefore reducing distractibility. Additionally, cognitive load can be increased by adding a second, concurrent task or increasing the working memory requirements of the task, therefore increasing distractibility due to less cognition capacity being available to actively control the irrelevant information (Lavie, 2005). For a clear interpretation of the results, it is vital to this chapter that the cognitive load remains constant and only the perceptual load is manipulated.

While the impact of perceptual load on vision has been widely explored, there have been few attempts in audition (Gomes et al., 2008). A selection of methods has been used to vary the perceptual load of the auditory tasks, each of which has been subject to critiques. For example, Alain and Izenberg

[1]Perceptual load was parametrically manipulated by adjusting the distinctiveness of the central target by adding in more central search items. Children were found to reach a high perceptual load with a visual search area of four items; whist adults did not reach a high perceptual load until a visual search area of six items.

(2003) manipulated the complexity of task instructions to investigate the effect on auditory stream segregation (ASS). In the low perceptual load task the listeners had to respond to rare (20% of trials) shorter duration sounds, while in the high perceptual load task they also had to determine whether the tone was tuned or not. Their results showed that load had little effect on ASS. However, when listeners were asked to identify two simultaneously presented vowels (Alain et al., 2005), ASS was affected by increased separation between the talkers' fundamental frequencies.

Francis (2010) compared these two results and noted that while both tasks require accurate ASS (object-formation), the Alain et al. (2005) task also required identification and categorisation of the vowels (object-selection). He suggested that perceptual load does not affect auditory selective attention until after successful object-formation is completed. This same critique can be applied to other attempts at investigating auditory perceptual load effects. For example, Muller-Gass and Schröger (2007) and Gomes et al. (2008) used a shorter ISI to increase perceptual load as this would require the stimuli to be processed more quickly, therefore making the task more demanding. Neither found an effect of the perceptual load on distraction processing. However, shorter ISIs have been shown to make stream separation easier (Bregman, 1990). Therefore, instead of increasing the perceptual load of the object-selection, the ISI manipulation may actually have affected the ease of successful object-formation.

Francis (2010) followed up his review by asking listeners to separate an auditory target from auditory flankers (object-formation) and respond only when the target contained a specific physical property (object-selection). Results showed that when perceptual difficulty was increased (asking the listeners to respond to a combination of specific physical properties of the target - the object-selection stage) the processing of auditory flankers decreased, in line with the findings of visual perceptual load studies.

In TAiL the listener hears two sequential tones, allowing for easy object-formation by temporal separation. The object-selection part of the task is separating out the relevant sound feature from the irrelevant, in order to make a same/different decision. To make this decision the listener must identify and categorise the information they have selected. Therefore, in consideration of Francis' critique, a manipulation of perceptual load within TAiL should target the perceptual demands of determining the same/different decision.

While listeners are able to spatially focus their auditory attention, it has been shown that it is easier to identify an auditory object by its frequency than by its location (Woods and Alain, 2001). In fact, frequency has been shown to take priority over ear presentation when determining auditory perceptual organisation (Deutsch, 1975). Kubovy (1981) has suggested that the use of frequency in audition is parallel to that of location in vision. This extends to a neuroanatomical level, as the organisation of frequency in audition can be compared to that of location in vision – whereas visual cortical areas are organised spatiotopically (Lund, 1988), auditory cortical areas are organised tonotopically (Merzenich et al., 1982). Chapters 3 and 4 of this thesis showed that TAiL's attend-frequency task can be used to assess auditory-specific selective attention, and so this TAiL task is the focus of this chapter.

As previously described, the frequencies of the two tones in TAiL are roved between 476-6188 Hz with a separation of at least $\approx$ 4 semitones (Zhang et al., 2012). A possible method of varying the perceptual load of the TAiL task would be to adjust the frequency separation between the two presented tones, therefore manipulating their distinctiveness from each other. The closer the tones are to each other, the harder it will be to discriminate them as different (Bregman, 1978). Näätänen et al. (1980) showed that when asked to respond to a 1000 Hz target stimulus and to ignore the irrelevant stimulus of a different frequency, listeners performed faster as the frequency separations between the relevant and irrelevant stimuli increased. However, Näätänen's paradigm used an ISI of five seconds, which may have led to sustained attention effects. Woods and Alain (2001) repeated this study with much shorter ISIs ranging from 91-483 ms (mean = 240 ms). Their results confirmed that the reaction time to respond to the relevant stimulus could be predicted by the frequency separation between the relevant and irrelevant stimuli, for both 500 Hz and 1000 Hz target tones, even with much shorter ISIs.

A similar result has also been found in children. For example, Duell and Anderson (1967) asked primary school children (range: 6-9 years old) to decide if two tones were same or different while manipulating the frequency interval between $\frac{1}{3}$ of a semitone and 9 semitones. Their results showed that as the size of the frequency interval increased, so did the percentage of correct discriminations. Therefore, this project will vary the perceptual load of the task by manipulating how distinct the two tones are from each other, by adjusting the frequency separation between them. To ensure that the two tones are distinguishable even at the hardest condition, the smallest frequency separation used in this methodology will be four semitones – a frequency separation children aged 4 can accurately discriminate at adult levels (Jensen and Neff, 1993).

The aim of this chapter is to investigate the development of listeners' distraction and conflict resolution at different levels of auditory perceptual load. It is predicted that RT will decrease and accuracy levels will increase as the frequency separation increases in the TAiL task. It is predicted that the children will experience a higher perceptual load than the adults at a larger frequency separation. An increase in perceptual load is expected to be illustrated by smaller distraction and conflict resolution effects due to the listener not having the capacity to process the irrelevant feature and not requiring inhibition to deal with conflicting information.

6.2 Method

6.2.1 Participants

Eighty-two children aged 4 to 11 (M = 7.64 years, SD = 2.02 years; 39 females and 43 males) were recruited through another Summer Scientist Week run by the University of Nottingham Psychology department. During this event children from the local area (Socio Economic Scale: Q.25 = .58, Q.75 = .93) were invited to attend the university to participate in a number of scientific studies in the form of 'games' (for information, see www.summerscientist.org). Written consent was obtained by the children's responsible caregiver and each child gave verbal assent to the study. The children were subdivided into age categories of 4-5 (M = 5.23, SD = .58; 9 females, 12 males), 6-7 (M = 6.88, SD = .61; 14 females, 12 males), 8-9 (M = 9.03, SD = .51; 11 females, 12 males), and 10-11 years (M = 10.84, SD = .57; 5 females, 7 males).

Twenty-nine young adults aged 17 to 29 (M = 21.65 years, SD = 3.67 years; 18 females and 11 males) were recruited through poster advertisements placed in the University of Nottingham. Written consent was given by each adult participant prior to the experiment, and they were paid an inconvenience allowance for their time. Adults hearing ability was assessed with pure tone thresholds between 250 and 8000 Hz (in accordance with the British Society of Audiology, 2011b). Two adults were excluded from the study as they failed to obtain pure tone threshold below 20 dB HL bilaterally.

All procedures were approved by the University of Nottingham's School of Psychology Research Ethics Committee (children) or the NHS Research Ethics Committee East Midlands – Nottingham (adults).

6.2.2 Screening questionnaires

The children's caregivers completed a medical history report and a range of questionnaires including the SAS (Liddle et al., 2009) to assess for ASD behaviours. One child did not complete the study due to single-sided deafness, and another was removed from the analysis due to suspected ASD.

In the adult group each participant completed the Autism Spectrum Quotient-10 (Allison et al., 2012) to assess for ASD behaviours, and the Adult Self-Report Scale V1.1 screener (Kessler et al., 2005) to assess for attention-deficit hyperactivity disorder (ADHD) behaviours. These questionnaires led to a further six adults not being included in this study due to suspected ADHD.

6.2.3 Apparatus & stimuli

As in the previous chapter, as part of the Summer Scientist Week event, the total testing time was restricted to 20 minutes per listener. To ensure TAiL was suitable for young children a game interface was used. This study used only the attend-frequency TAiL task, whereby the listener had to decide if the frequencies of the two sequential tones remained the same or changed, while ignoring the location of the two sounds.

To create different levels of perceptual load within TAiL, the frequency separation between the two tones was manipulated to be either 4, 12 or 20 semitones apart (near, medium and far respectively). Each of these frequency separations were presented in separate blocks. To keep within TAiL's range of 476.20-6187.50 Hz, even when the frequency separation was 20 semitones, there were three possible tones in each block type based around TAiL's middle tone of 1716.50 Hz. The remaining stimuli make-up remained as before – tones were made up of sinusoids of 100 ms duration, gated on/off by 10 ms cos ramps, had an ISI of 300 ms and were played at 70 dB SPL.

TAiL was presented using a Fast Track Pro USB audio interface (M-Audio, inMusic Brands) and Sennheiser HD 25-II headphones. The game-like interface was presented on a 15 inch laptop screen and all RT responses were made using a three-choice button box placed in front of the participant with buttons arranged from left to right.

6.2.4 Procedure

Each listener was tested individually in a sound-attenuated chamber, with the experimenter being present throughout to prompt the participant to focus on the task if required. The listener sat in front of the laptop screen and was asked to place their writing/drawing hand on a hand outline in front of the response button box. They were asked to return their hand to this starting point after each button press.

Each block type (frequency separations of 4, 12 or 20 semitones) was presented twice with each block being composed of 32 trials, providing a total of 64 trials per task condition per participant. A random number generator was used to assign an initial order to the six testing blocks of TAiL, and this order was then counterbalanced across participants using a Latin-square design.

6.2.5 Statistical analysis

A series of checks were conducted to ensure that the listeners had completed the task set to them. First, the listeners had to pass TAiL's practice blocks to illustrate task understanding; one child failed to reach the required level of 60% accuracy and so did not continue with the main task. Second, listeners who were at least twice as likely to press one button over the other in the furthest frequency separation blocks (20 semitones) were removed from further analysis due to suspected button preference (n = 3 children). Finally, trials with RTs shorter than 200 ms and longer than 2500 ms were excluded (6.44% in children and 0.88% in adults) in case of pre-emptive responses, lapses of attention or an interruption in performance. These checks left a total of 21 adults and 76 children for further analysis.

Contrast measures of distraction and conflict resolution were calculated through a difference index of the RT and accuracy effects (e.g. for conflict resolution: $\frac{incongruent-congruent}{incongruent+congruent}$) in order to allow a comparison of the distribution of the effects across age groups. In the following analyses homogeneity of variance is assumed in the appropriate groups, as tested by Kruskal-Wallis; where homogeneity of variance is not assumed the appropriate non-parametric tests were conducted.

6.3 Results

At TAiL's baseline (trials where both the frequency and the location of the sounds stayed constant) at blocks of 4, 12 and 20 semitone separations the children were found to be significantly slower (4 semitones: $t(95) = 6.24, p < .001$; 12 semitones: $t(95) = 5.79, p < .001$; 20 semitones: $t(95) = 5.94, p < .001$) and less accurate (4 semitones: $t(95) = -5.83, p < .001$; 12 semitones: $t(95) = -5.39, p < .001$; 20 semitones: $t(95) = -5.52, p < .001$) than adults (Figure 6.1). Furthermore the children were found to become more accurate with age for each of the three perceptual loads (4 semitones: $r_p(76) = .53, p < .001$; 12 semitones: $r_p(76) = .45, p < .001$; 20 semitones: $r_p(76) = .50, p < .001$) .

6.3.1 Effect of perceptual load

To assess whether each age group found an increase in perceptual demand as the frequency separation decreased, an average RT and accuracy for each frequency separation was calculated from trials where at least one sound feature changed (i.e. SfDL, DfSL and DFDL trials) (Figure 6.2). Repeated measures ANOVAS showed that the young adults' RT became significantly faster ($F(2, 40) = 3.38, p = .044, \eta_p^2 = .15$) as the frequency separation increased from 4 to 12 semitones ($p = .015$) and from 4 to 20 semitones ($p = .043$). All age groups, except for the 4-5 year olds, showed a significant increase in accuracy with larger frequency separations (6-7: $F(2, 46) = 6.25, p = .004, \eta_p^2 = .21$; 8-9: $F(2, 40) = 6.05, p = .005, \eta_p^2 = .23$; 10-11: $F(2, 22) = 10.53, p = .001, \eta_p^2 = .49$; young adults: $F(2, 40) = 8.05, p = .001, \eta_p^2 = .29$). Post-hoc t-tests showed a significant increase in accuracy was found between the near (4 semitones) and far (20 semitones) frequency separations for each age group ($p < .015$), and again between near and medium (12 semitones) frequency separations ($p < .05$). No

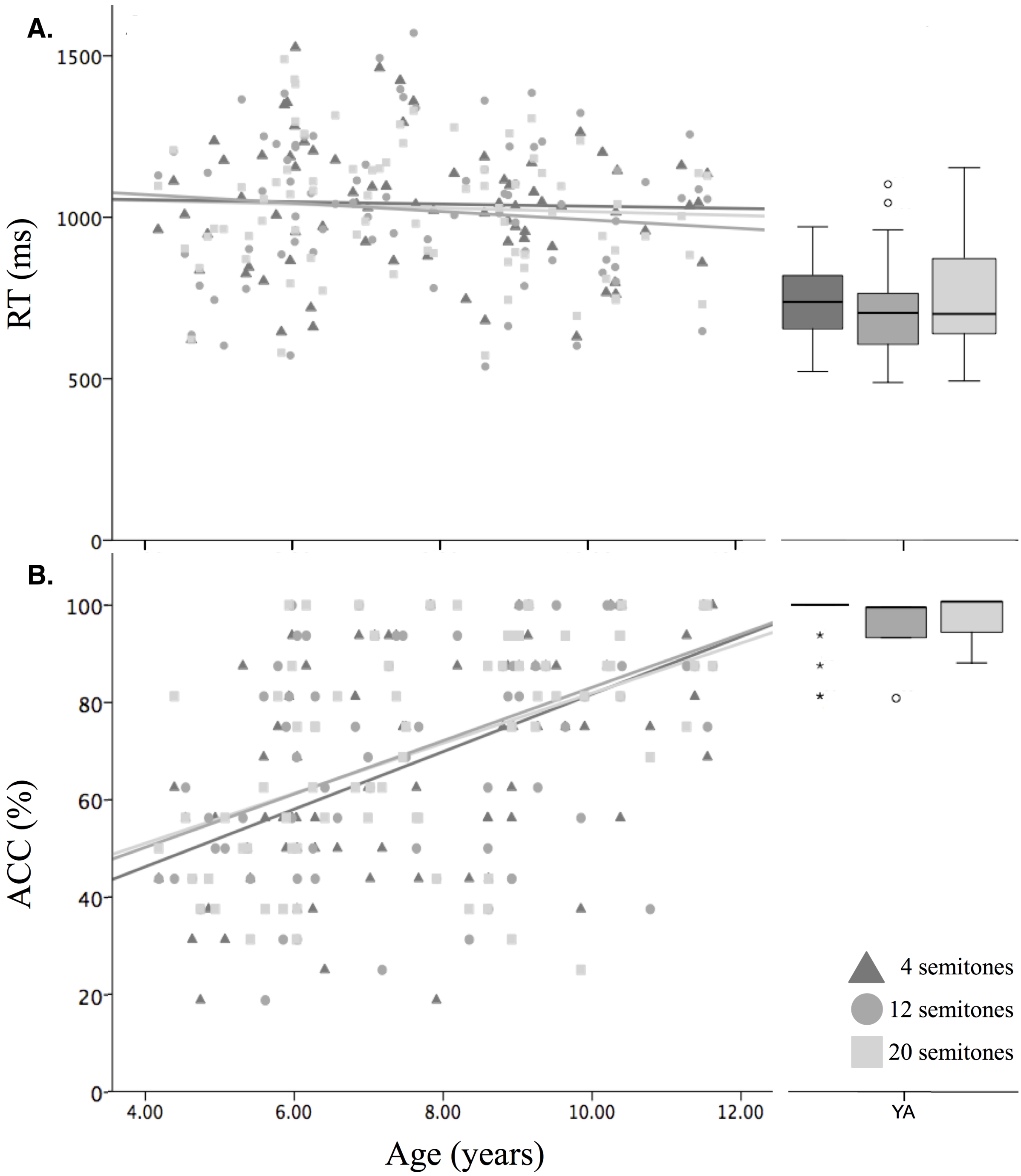

Figure 6.1: Baseline (SfSL trials) (A) RT and (B) accuracy for the attend-frequency TAiL task. Each data point represents a single child with age along the x-axis, and the box-plots show the spread for the young adults. The dark grey (triangles) indicate baseline for the 4 semitones separation task, medium grey (circles) for the 12, and light grey (squares) for the 20. Lines represent the Pearson correlation of performance with age.

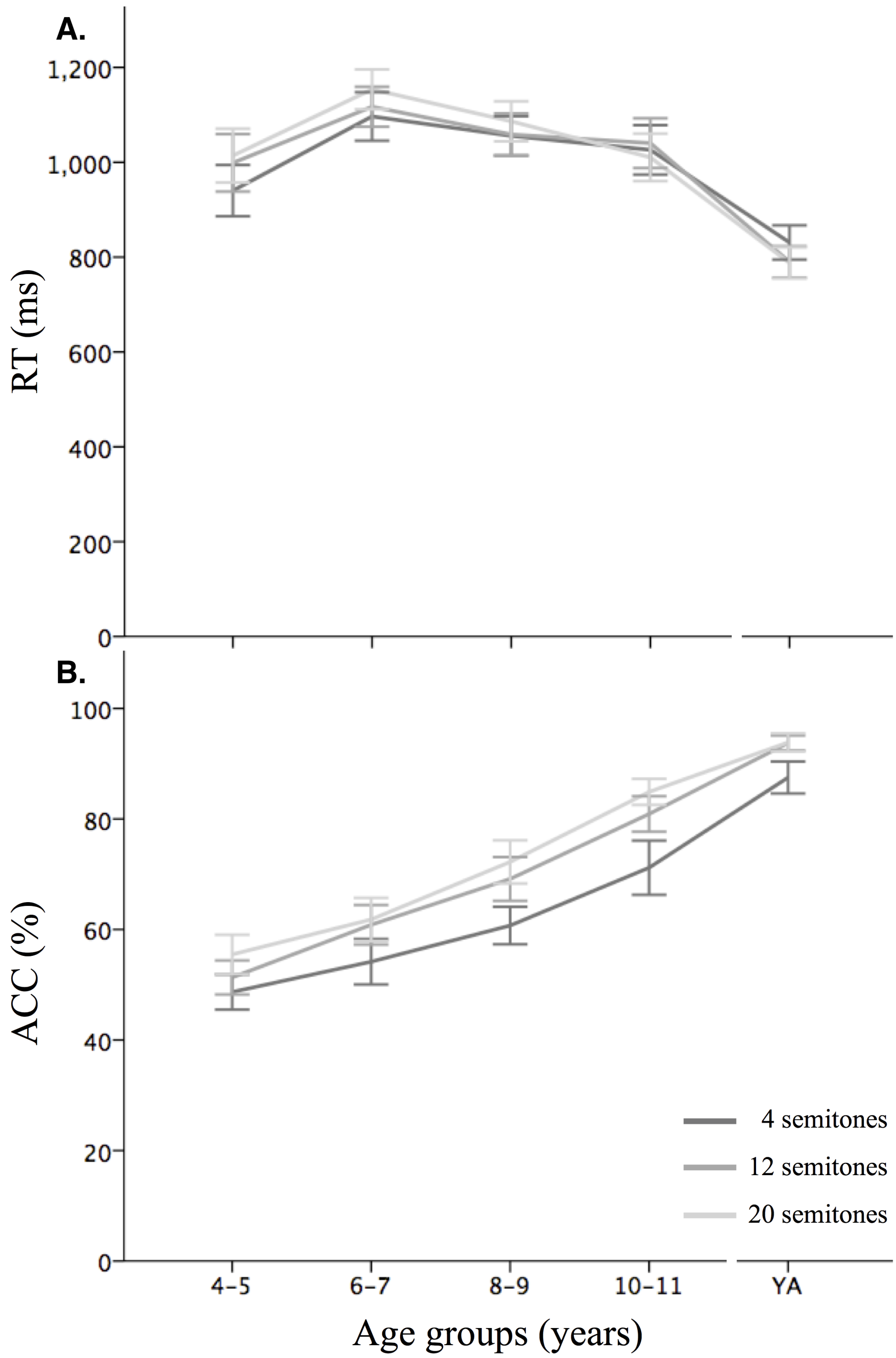

Figure 6.2: (A) RT and (B) accuracy of the three frequency separations (dark grey = 4 semitones, medium grey = 12 semitones, light grey = 20 semitones) across the age groups (x-axis) for trials where at least one sound feature changed within a trial (i.e. SfDL, DfSL and DfDL trials). Error bars represent SEM.

significant differences in accuracy were found between the medium and far frequency separations at any age. This suggests a successful manipulation of perceptual load from the age of 6, with significant increases in accuracy as perceptual demand decreases from 4 to 12, and from 4 to 20 semitones separation.

6.3.2 Distraction

With a successful manipulation of perceptual load, 3×5 mixed-design ANOVAs assessed the effect of increasing frequency separation (4, 12, 20 semitones) across the age groups (4-5, 6-7, 8-9, 10-11, young adults) on distraction and conflict resolution RT and accuracy contrast measures. All post-hoc tests are Holm-Bonferonni corrected.

For the distraction RT contrast measure (Figure 6.3A) there was a significant main effect of age group ($F(4, 92) = 2.55, p = .045, \eta_p^2 = .10$). There was no main effect of frequency separations ($F(2, 184) = .61, p = .54, \eta_p^2 = .007$) and no significant interaction between the age groups and the frequency separations ($F(8, 184) = .42, p = .91, \eta_p^2 = .018$), implying that the listeners distraction was similarly affected across the three frequency separations. Post-hoc t-tests showed that whilst the children age groups between 4-9 years of age were significantly less distracted than the young adutls, all of the children groups were not significantly different from one another (see Table 6.1). This indicates that the children's level of distraction did not change with age. For the distraction accuracy contrast measure (Figure 6.3B) no differences between age groups ($F(4, 92) = 2.10, p = .087, \eta_p^2 = .084$) or frequency separations were found ($F(2, 184) = .93, p = .40, \eta_p^2 = .078$), nor an interaction between these two variables ($F(8, 184) = 1.83, p = .074, \eta_p^2 = .074$). This suggests that the change in distraction RT between the children and young adults was not due to a speed-accuracy trade-off.

6.3.3 Conflict resolution

Results for the conflict resolution RT contrast measure were similar to the distraction results, with a significant main effect of age group indicating that listeners became more conflicted with age ($F(4, 92) = 5.95, p < .001, \eta_p^2 = .21$). As in the distraction results, there was no main effect of frequency separations ($F(2, 184) = .43, p = .65, \eta_p^2 = .005$) and no interaction between

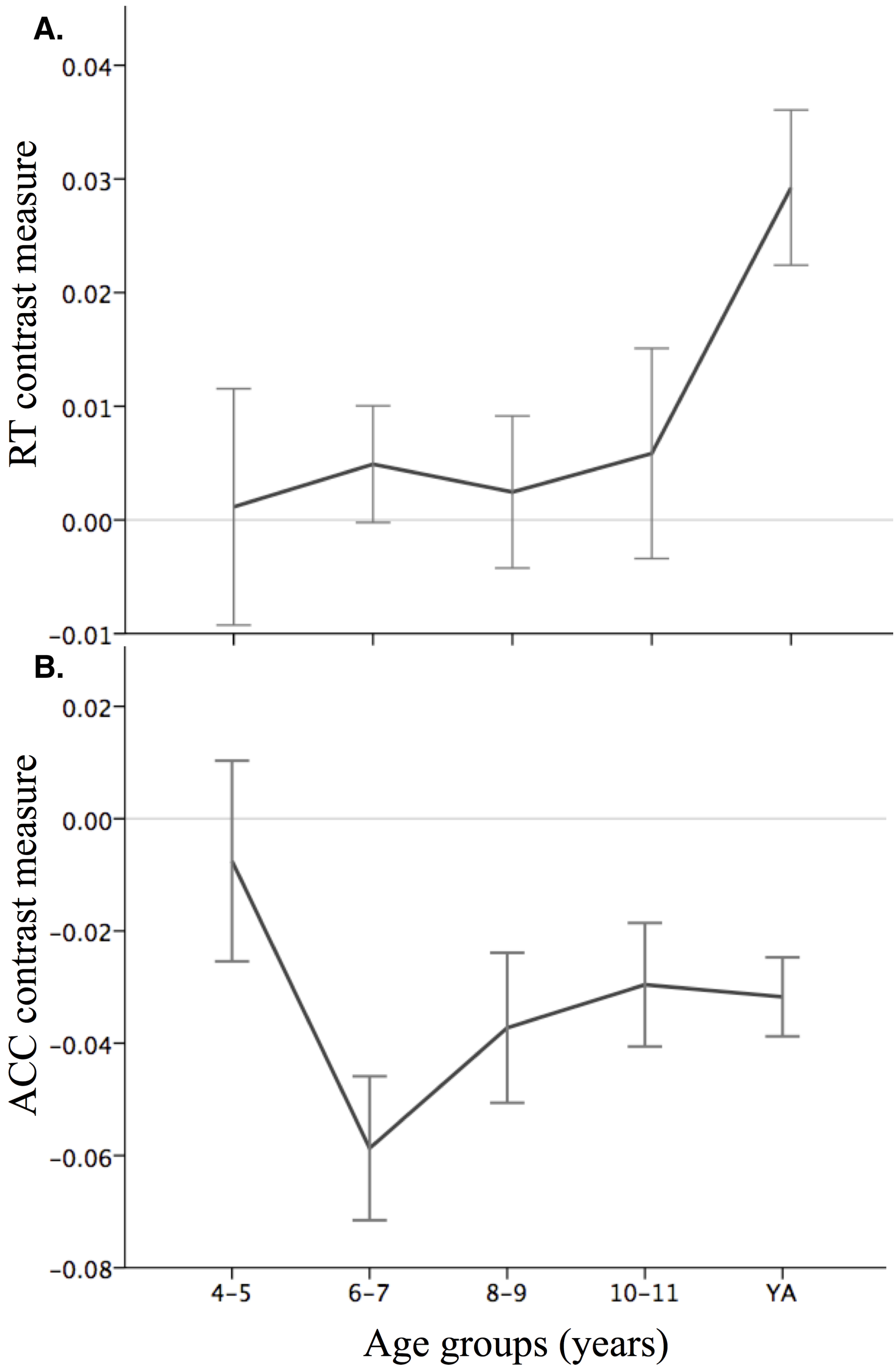

Figure 6.3: Distraction (A) RT and (B) accuracy contrast measures across the age groups (x-axis). Error bars represent SEM.

Age group	**M**	**SEM**	**Age group**	p
4-5	.001	.008	6-7	.71
			8-9	.90
			10-11	.70
			YA	.009
6-7	.005	.007	6-7	–
			8-9	.81
			10-11	.94
			YA	.016
8-9	.002	.007	6-7	–
			8-9	–
			10-11	.78
			YA	.01
10-11	.006	.01	6-7	–
			8-9	–
			10-11	–
			YA	.054
YA	.029	.007	6-7	–
			8-9	–
			10-11	–
			YA	–

Table 6.1: Distraction RT contrast measure main effect of age group across the 2 TAiL tasks.

the age groups and frequency separations ($F(8, 184) = 1.70, p = .10, \eta_p^2 = .069$). Post-hoc t-tests suggest that young adult levels of conflict resolution were reached by the age of 8-9, with the 4-5 year olds significantly less conflicted than all of the other age groups and the 6-7 year olds less than the young adults (see Table 6.2). Correlational analysis showed that while children's conflict resolution RT increased with age ($r_s(76) = .33, p = .004$) (Figure 6.4A), their accuracy effect did not change ($r_s(76) = -.13, p = .28$) (Figure 6.4C).

The children were split into a younger (aged 4-7, n = 43) and an older (aged 8-11, n = 33) group. Wilcoxon signed-rank tests showed that while

Age group	M	SEM	Age group	p
4-5	-.009	.008	6-7	.027
			8-9	<.001
			10-11	.02
			YA	<.001
6-7	.014	.007	6-7	–
			8-9	.072
			10-11	.56
			YA	.019
8-9	.032	.007	6-7	–
			8-9	–
			10-11	.35
			YA	.58
10-11	.021	.01	6-7	–
			8-9	–
			10-11	–
			YA	.16
YA	.038	.007	6-7	–
			8-9	–
			10-11	–
			YA	–

Table 6.2: Conflict resolution RT contrast measure main effect of age group across the 2 TAiL tasks.

older children and adults performed as typically found in conflict resolution measures (significantly faster in congruent compared to incongruent trials (older children: $Z = -4.10, p < .001$; young adults: $Z = -3.98, p < .001$)), the younger children were no faster on congruent than incongruent trials ($Z = -1.01, p = .31$) (Figure 6.4B). However the accuracy pattern of performance was the same for all groups: significantly more accurate on congruent compared to incongruent trials (younger children: $Z = -3.10, p = .002$; older children: $Z = -4.70, p < .001$; young adults: $Z = -3.77, p < .001$) (Figure 6.4D).

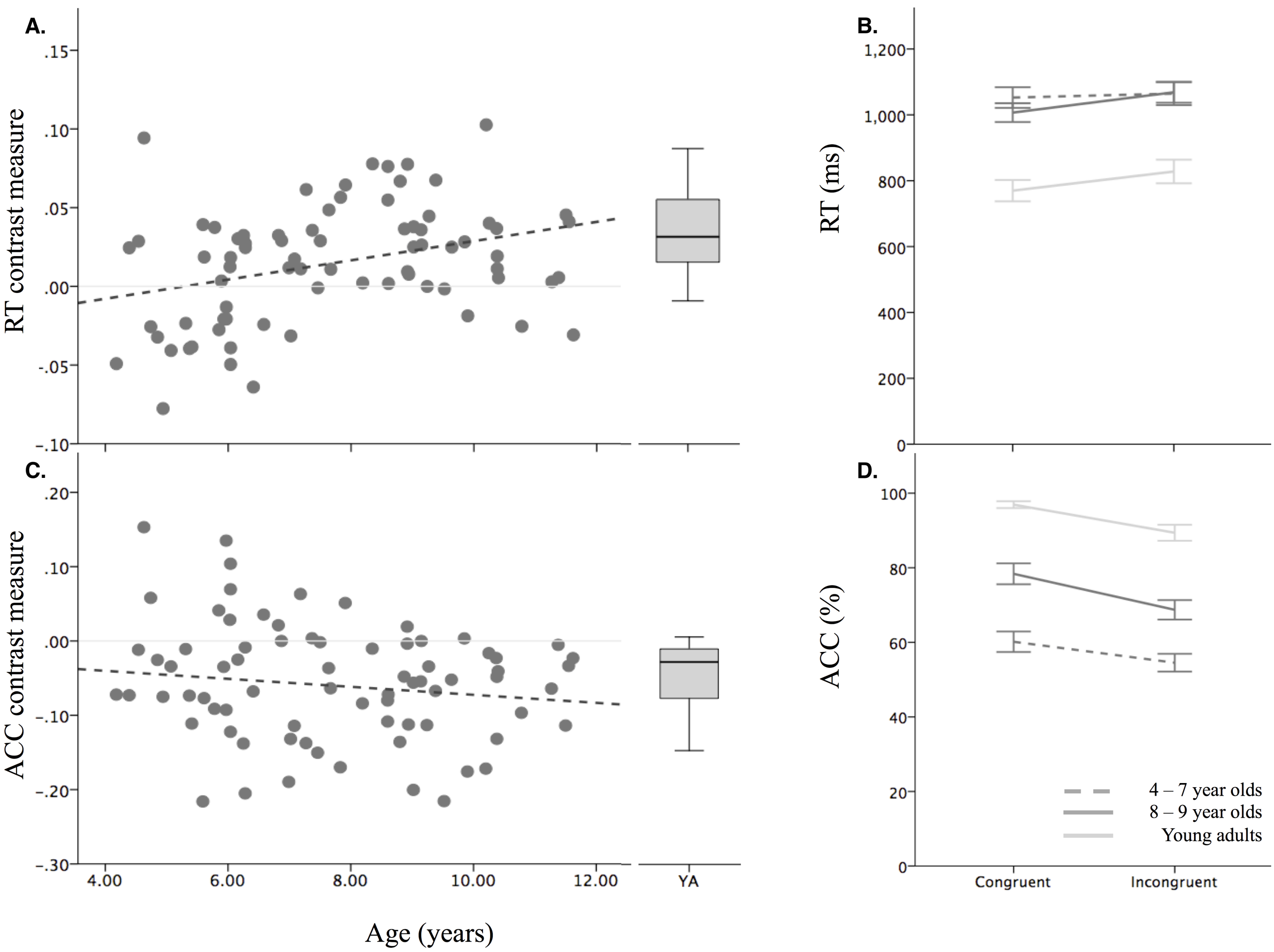

Figure 6.4: Conflict resolution (A) RT and (C) accuracy contrast measures across age (x-axis). Each data point represents a single child and the box plots show the spread of the young adults. (B) RT and (D) accuracy to congruent and incongruent trials with the children split into younger (aged 4-7: dotted dark grey line) and older (aged 8-11: solid dark grey line) compared to the young adults (solid light grey line). Error bars represent SEM.

6.4 Discussion

The previous chapter found that younger children did not show distraction and conflict resolution effects significantly different from zero. It was thought that the lack of these effects may have been due to changes in the perception of perceptual load changing with age. The aim of this chapter was to assess listeners' selective attention abilities to auditory stimuli at different levels of perceptual load by manipulating how distinct the two tones frequencies were from each another. In the original TAiL methodology the two tones could be anything from 4 to 45 semitones separation, whereas in this chapter listeners' completed blocks of trials where the tones were separated by 4, 12, or 20 semitones.

When both sound features stayed constant (TAiL's baseline) the children were significantly slower and less accurate than the adults at each frequency separation. Children were found to become more accurate with age at each frequency separation. However, unlike the previous chapter their RT to baseline trials did not change with age. In trials where a sound feature changed it was predicted that the listener would become slower and less accurate as the separation between the two tones decreased, indicating an increase in perceptual demand. While the youngest children (aged 4-5) are able to perform the task, their RT and accuracy did not change across the different frequency separations. It is therefore possible that despite this age group having adult-like frequency discrimination abilities (Jensen and Neff, 1993), they perceived all of the frequency separations as equally demanding.

Results showed that adults became slower with decreasing frequency separation, as previously shown by Näätänen et al. (1980) and Woods and Alain (2001). Similar to the baseline trials, the children's RT to change trials did not differ across the different frequency separation, however from age 6 they became significantly less accurate as the frequency separation decreased, as found by Duell and Anderson (1967). These results suggest that from age 6 the listeners perceive decreasing perceptual demand between 4 and 12 semitone separation, and between 4 and 20 semitone separation, indicating a successful manipulation of perceptual load.

6.4.1 Distraction

It was expected that when the listener perceived a high perceptual load during the TAiL task, they would not have spare capacity to process irrelevant sound feature changes and so would have small distraction effects due to an early selection of attention. It was predicted that, as found in vision, children would experience the task at a high perceptual load at a frequency separation the adults perceived as a low perceptual load (i.e. the children would show small distraction effects, while adults show large distraction effects). Accordingly, results from this study show that children had significantly smaller distraction effects, regardless of the change in the perceptual load of the task. Therefore, despite perceiving change in the task's perceptual demands, even by the age of 10-11 the children appear to be using all available perceptual capacity and so are not distracted by the irrelevant sound features. This result could suggest that the children have smaller perceptual capacities, than young adults, as they are fully occupied by processing both a task with low perceptual demand (i.e. 20 semitones separation) and a task with high perceptual demand (i.e. 4 semitones separation). Comparatively, the adults seem to perceive the task at a low level of perceptual load throughout the frequency separations as they display significant distraction effects, suggesting a late selection of attention, as despite attending to the relevant sound feature they have enough capacity left to also process the irrelevant sound feature.

Evidence from visual research suggests that children aged 7-8 have perceptual capacities large enough to process distracting visual information (Huang-Pollock et al., 2002). It is possible that the bottom-up stimulus processing in the visual tasks is less demanding than the auditory tasks conducted in this chapter. Alternatively, the children may possess different perceptual capacities for different modalities. Findings from Chapters 3 and 4 suggest that TAiL's attend-location task is a supramodal measure of selective attention, whereas the attend-frequency TAiL task is auditory-specific. It is therefore possible to assess whether different modality perceptual capacities exist while keeping consistent the demands of bottom-up stimulus processing. Currently the spatial discrimination in TAiL's attend-location task is based on whether the two tones were in the same or different ears (i.e. 180° from one another). With infants aged 18 months showing a minimal audible angle (MAA) in the azimuthal plane of 5.7° and 5 year olds a MAA of 1.55°, compared to an adult's .78° for a single-source stimuli (Litovsky, 1997), it can be predicted that by reducing the spatial separation between the two sounds the perceptual demands of TAiL's attend-location task can be manipulated.

6.4.2 Conflict resolution

It was predicted that if the children reached a high perceptual load and showed small distraction effects it would follow that they would have a lesser need for conflict resolution due to possessing less information regarding the irrelevant sound feature. Analysis showed that the children's conflict resolution effect increased with age and reached adult levels by the age of 8-9 years. However, no change in distraction was found across the frequency separations until the age of 10-11, suggesting that the children have smaller perceptual capacities than the young adults. The different age trajectories for the two selective attention skills suggest different underlying mechanisms. Hence, differences in conflict resolution with age may not be due to differences in perceptual load.

Traditional Stroop task effects are thought to represent two processes: the failure to maintain the task goal of ignoring the irrelevant dimension (in this task the sounds' locations) represented by lower accuracy for incongruent trials compared to congruent; and the time-consuming resolution of conflict between the relevant and irrelevant dimensions (in this task the sounds' frequency and location, respectively) represented by slower responses to incongruent trials (Kane and Engle, 2003). Analysis shows that despite the children taking longer to deal with conflicting auditory information as they aged their accuracy was not affected. This suggests that the children's ability to maintain the task goal does not change from the age of 4 onwards. Instead, it is their method of dealing with the conflicting information that changes with age. A finer analysis of the conflict resolution RT data showed that the older children (aged 8-11) had a similar pattern of performance to the young adults, albeit slower, taking significantly longer to respond to incongruent trials than congruent trials. However, the younger children (aged 4-7) took no longer to respond to incongruent trials than to congruent trials. This suggests a qualitative difference in how attention is allocated in listeners of different ages. The results of the previous chapter suggested that the children reached adult levels of conflict resolution by age 10-11. The current study suggests that adult-like conflict resolution ability is reached by age 8-9, albeit not at adult speeds.

In attention research older children are considered to be more efficient than younger children in dealing with conflicting information (for review see Ridderinkhof and Van der Stelt, 2000). However, other studies have also found evidence of younger children being less affected by conflicting information. For example, Smith et al. (1975) used a multi-sensory task with a visual target and conflicting visual or auditory information and found that young children (aged 5-6) performed best in conditions that caused conflict for older children (aged 10-11), specifically when the conflict came from within the same object. The older children were found to be more accurate when the conflict came from separate objects. This suggests that while the younger children process the information as if all of a source's dimensions are required, the older children attempt to focus on the relevant dimension only.

Smith and colleagues' (1975) finding of the younger children being less conflicted than adults and older children is further discussed by Nardini et al. (2010), who examined differences in how groups of children aged 6, 8, 10 and 12 fused stimulus features compared to young adults. They suggested that adults and older children fuse the stimulus features into one complete object, while the younger children keep the stimulus features separate in order to deal with the dynamic world around them more effectively as they grow. Thus, as the younger children keep the feature information separate they do not need more time to make a decision regarding one stimulus feature (i.e. frequency) than they do with two stimulus features (i.e. frequency and location). Conversely, older children and young adults automatically fuse the stimulus features. Consequently, the time they need to disentangle the information and decide if a change in the relevant stimulus feature occurred is longer in trials where a single stimulus feature changed than in trials where both of the stimulus features changed. Therefore, younger children are less conflicted than older children and young adults, regardless of the perceived task difficulty or perceptual load.

This qualitative difference in selectively attending features within auditory objects in children could be further investigated by manipulating TAiL's methodology. In TAiL listeners could simply be asked if the two tones of a trial are the same or different, without the tester defining what constitutes a different decision (i.e. changing frequency or location). It would be expected that if the younger children are indeed keeping the stimulus features separate they would perform similarly to trials where either one or both features changed. If the older children and young adults are fusing the stimulus features into an auditory object before separating them they should be fastest when both features changed, as they do not have to break down the auditory object to work out which feature changed.

6.5 Conclusions

(1) Adjusting the frequency difference between the two pure tones in TAiL's attend-frequency task was a successful manipulation of perceptual demand for both children and young adults.

(2) Distraction:

   (a) The children's level of distraction did not change between the ages of 4 and 11.

   (b) The children showed small distraction RT effects compared to the young adults, regardless of the perceptual demands of the task. This suggests that the children have smaller processing capacities when dealing with non-spatial auditory information. Therefore the children select auditory information for further processing at an early stage.

   (c) The young adults were distracted by changes in the irrelevant stimulus features across the range of frequency separations. They experienced TAiL's attend-frequency task at a low perceptual load regardless of the frequency separation and had capacities large enough to process the irrelevant information as well, suggesting late selection.

(3) Conflict resolution:

   (a) Children showed increasing conflict resolution effects as age increased, using adult-like conflict resolution strategies, but not speed, by age 8-9.

   (b) The younger children (aged 4-7) were found not to take any longer in responding to incongruent compared to congruent trials.

   (c) Younger children do not automatically fuse stimulus features to form an auditory object and so do not have to disentangle feature information before making a decision, resulting in no conflict resolution effects. The older children and young adults, on the other hand, automatically form single objects by fusing stimulus features and therefore show typical conflict resolution effects due to having to disentangle the features from within auditory objects before making a decision.

CHAPTER 7

Selective attention and Auditory Processing Disorder

This study draws on the dual-pathways theory of processing to examine the selective attention ability of children with LDN as compared to typically developing children. It builds on Chapters 3 and 4, which demonstrate the applicability of the dual-pathways theory to auditory selective attention to spatial and non-spatial features. Chapters 3 and 4 support the theory's assertion that non-spatial features are processed in a modality-specific fashion, whereas spatial features are processed in a supramodal system. This chapter has two aims: 1) to investigate whether children with LDN show selective attention difficulties; and 2) to determine whether any difficulties found relate to non-spatial modality-specific or spatial supramodal features.

7.1 Introduction

Importance has been assigned in recent years to the contribution of cognitive skills, in particular attention, to listening ability (Moore et al., 2010). Work has begun in assessing and quantifying such difficulties in children with developmental APD. Due to varying methods of diagnosis across countries and research institutions, some studies explicitly refer to APD – a disorder – while others refer to LDN – a set of symptoms. Children with LDN have been shown to take longer to identify an auditory target and have more false alarms in a verbal auditory switching attention paradigm (Dhamani et al., 2013; Sharma et al., 2014). In addition, using a sustained attention story-telling task it has been shown that children with LDN miss more word targets and that their sensitivity to contextual cues declines with time (Roebuck and Barry, submitted). Together these results suggest that children with LDN take longer to switch between auditory stimuli, have reduced control of their inhibition and are unable to maintain auditory task requirements over a period of time. Clearly the ability to allocate attention to relevant auditory information is vital for effective listening skills, especially in a noisy environment where there is an increased level of irrelevant auditory information. In such an environment the sound to be attended to is detected through an identifiable auditory feature (pitch/source location etc.) while ignoring competing, and often overlapping, irrelevant auditory information (British Society of Audiology, 2011a). Despite the most frequent complaint by children with APD being the inability to listen to a target source in a noisy environment, their selective attention ability has not previously been assessed.

This chapter's main aim is to explore selective attention abilities of children with LDN using TAiL, which Chapters 3 and 4 have shown to assess auditory-specific and supramodal selective attention using auditory stimuli. Posner and Petersen's attentional networks framework (1990; updated in Petersen and Posner, 2012) describes three separable skills: alerting (maintaining an aroused state), orienting (selecting relevant while ignoring irrelevant features/objects) and conflict resolution (executive function ability). With regard to APD, this chapter will not assess whether the children are responsive to startle sounds (alerting), but whether they are able to ignore task-irrelevant features while orienting to task-relevant features (orienting) and are able to deal with mismatching feature information (conflict resolution).

Regarding orienting, TAiL quantifies a listener's distraction to the irrelevant sound feature using a calculation that draws on Lavie's load theory of selective attention. Lavie's theory holds that after processing the relevant task information, any remaining processing capacity is spent on the irrelevant task information (Lavie, 1995). Chapter 5 of this thesis has shown that in an auditory task typically developing children reach adult-like levels of distraction (orienting to irrelevant task information), but not speed of recovery, by age 10-11. Results from Chapter 6 suggest that this transition may be due to the typically developing children having a smaller auditory processing capacity, causing early selection of non-spatial features for further processing, regardless of the perceptual demands of the task. Given the finding that children with LDN take longer to switch between auditory objects (Dhamani et al., 2013; Sharma et al., 2014), it is possible that the children with LDN have poorer orienting abilities and so experience a higher perceptual load during an auditory task than their normal-hearing peers. It was therefore predicted that the LDN children tested in this chapter would show smaller distraction effects in TAiL than their peers due to experiencing a higher perceptual load when performing the task, thus leaving no resources for processing irrelevant information.

Children with LDN were also expected to differ from typically developing children in relation to the executive function skill of conflict resolution. In an attention switching paradigm, children with LDN have been shown to have significantly more false alarms than typically developing children, indicating that control of inhibition, an executive function skill, is reduced (Dhamani et al., 2013; Sharma et al., 2014). Results presented previously in this thesis (Chapters 5 and 6) have shown that typically developing children use adult-like conflict resolution strategies, another executive function skill, by age 8-9. It was expected that the children with LDN tested in this study, who were aged 8-13, would use the same strategy as their typically developing peers, but have less control of it. It was therefore expected that the children with LDN would show a greater cost for incongruent trials and, consequently, a larger conflict resolution effect than the children without LDN.

This chapter has a second aim: to assess the children's selective attention abilities in auditory and visual tasks. This aim builds on Chapters 3 and 4 of this thesis, which sub-divided selective attention skills into attending to non-spatial modality-specific stimulus features and attending to spatial supramodal stimulus features. LDN has typically been considered an auditory-specific developmental disorder, whereas other developmental disorders (e.g. ADHD) have typically been considered to be supramodal (Katz, 1992; Chermak et al., 1999; Dawes and Bishop, 2009). A comparison of APD and ADHD symptoms, ranked by frequency of occurrence, illustrates that individuals with APD symptoms also often present with an assortment of ADHD symptoms ranging from mild inattention to more serious symptoms of impulsivity. The difference is that ADHD symptoms typically impact attention across sensory modalities, whereas APD symptoms are modality-specific, affecting audition only (Chermak et al., 2002).

However, it has also been suggested that a spatial processing deficit – a supramodal difficulty – may be a major cause of APD. Children with LDN have been found to be unable to use binaural processing skills to selectively attend to a specific auditory source while suppressing background auditory information (Jerger, 1998). Support for this has been found using the Listening in Spatialized Noise-Sentences test (LiSN-S), an adaptive speech-in-noise test where the listener must identify a target voice source from two distracting voice sources that are different in pitch (talker), location ($\pm 90^{\circ}$ on the azimuth), or both pitch and location. Results show that children with suspected APD require a significantly greater signal-to-noise ratio to achieve the same speech reception thresholds as normal-hearing children, but only when the physical location of the distractors differs from the target talker (Cameron and Dillon, 2008). This suggests that these suspected APD children cannot take advantage of the binaural cues to filter the target voice from the surrounding irrelevant voices, and they are therefore described as having spatial processing difficulties.

These seemingly contradictory findings leave the modality of selective attention abilities in LDN open to examination. LDN has typically been considered to be modality-specific (Chermak et al., 2002). The dual-pathway theory argues specifically that non-spatial feature processing is modality-specific (Mishkin et al., 1983; Goodale and Milner, 1992; Rauschecker and Tian, 2000; Arnott et al., 2004). However, studies using the LiSN-S paradigm have shown that children with suspected APD have difficulties with spatial processing, which the dual-pathway theory argues is supramodal. Therefore while it is predicted that the children with LDN will show selective attention difficulties, it is unclear whether a further division of ability will occur in the non-spatial auditory task only, or whether they will also show difficulties across the spatial auditory and visual tasks.

To assess this finer distinction of selective attention abilities in the auditory domain, the attend-frequency and attend-location tasks of TAiL were used to investigate both non-spatial and spatial processing. To create a visual non-spatial and spatial comparison, two versions of the vANT were used with its original (as used in Chapter 3) and modified stimuli. The original (spatial) vANT is based on a flanker task where irrelevant arrows have to be ignored to decide which direction the target arrow is pointing. To create a non-spatial version of the vANT the stimuli were changed from arrows to shapes; with the decision to be made whether the target shape is a circle or a star while ignoring flanking shapes. This method has successfully been used in children from the age of 4 (McDermott et al., 2007).

7.2 Method

7.2.1 Participants

Fourteen children aged 8 to 13 (M = 10.58 years, SD = 1.54 years; 4 females and 10 males) with caregiver-reported listening difficulties in noise (LDN+) were recruited from NHS clinics in Nottingham and Essex. Eleven children aged 9 to 12 (M = 10.39 years, SD = 1.03 years; 5 females and 6 males) with no caregiver-reported listening difficulties in noise (LDN-) were recruited through letters to schools in Nottinghamshire.

The Nottingham Research Ethics Committee 1 approved all procedures, with caregivers providing written informed consent and each child providing verbal assent to take part in the study. Each participant received an inconvenience allowance for his or her time.

<table>
<tr><th></th><th></th><th></th><th>Test (assesses)</th><th>Completed by</th></tr>
<tr><td rowspan="5">Hearing</td><td rowspan="5" colspan="2"></td><td>Bilateral otoscope</td><td rowspan="4">Child</td></tr>
<tr><td>Bilateral tympanogram</td></tr>
<tr><td>Bilateral pure tone threshold</td></tr>
<tr><td>FD</td></tr>
<tr><td>ECLiPS (LDN)</td><td>Caregiver</td></tr>
<tr><td rowspan="4">Cognitive skills</td><td rowspan="4" colspan="2"></td><td>Conners' (ADHD)</td><td rowspan="2">Caregiver</td></tr>
<tr><td>SAS (ASD)</td></tr>
<tr><td>NEPSY-I finger tapping (dyspraxia)</td><td rowspan="2">Child</td></tr>
<tr><td>WASI non-verbal IQ</td></tr>
<tr><td rowspan="4">Attention</td><td rowspan="2">Auditory</td><td>Non-spatial</td><td>TAiL attend-frequency</td><td rowspan="4">Child</td></tr>
<tr><td>Spatial</td><td>TAiL attend-location</td></tr>
<tr><td rowspan="2">Visual</td><td>Non-spatial</td><td>vANT shapes</td></tr>
<tr><td>Spatial</td><td>vANT arrows</td></tr>
</table>

Table 7.1: Testing battery for children and their caregiver. FD = frequency discrimination; ECLiPS = Evaluation of Children's Listening and Processing Skills; SAS = Social Aptitude Scale; NEPSY-I = A Developmental NEuroPSYchological Assessment; WASI = Wechsler Abbreviated Scale of Intelligence; TAiL = Test of Attention in Listening; vANT = visual Attention Network Test.

7.2.2 Screening

A full list of screening and testing measures can be seen in Table 7.1. Participants had to have a clear bilateral otoscopic examination, bilateral type A tympanogram and obtain a pure tone threshold below 20 dB HL bilaterally at octave frequencies between 250 and 8000 Hz (in accordance with the British Society of Audiology, 2011b). One LDN- child failed to reach these levels and so did not complete the testing paradigm. To assess the participants' listening abilities the Evaluation of Children's Listening and Processing Skills (ECLiPS; Barry and Moore, 2014) was used, whereby children with scores below the 10th percentile are identified as experiencing clinically significant difficulties in listening in noisy environments. Each LDN+ child scored below the 10th percentile for factors capturing listening and language abilities, while all of the LDN- children scored above this marker (Table 7.2). In addition, the children's FD ability was tested, as TAiL's attend-frequency task is based on the ability to determine pitch differences between two pure tones.

	LDN-				LDN+				Mann-Whitney	
	Min	**Max**	**M**	**SD**	**Min**	**Max**	**M**	**SD**	*Z*	*p*
Age	9.08	12.20	10.39	1.04	8.08	13.37	10.58	1.54	-.18	.89
ECLiPS										
Listening	10	91	39.6	28.82	<1	5	2.11	2.00	-4.14	<.001
Language	10	92	42.2	29.26	<1	5	2.36	2.14	-4.15	<.001
Conners'	44	65	53.3	6.7	52	88	68.31	10.05	-3.04	.002
SAS	16	31	23.8	5.45	10	30	16.43	5.11	-2.86	.003
Finger-tapping										
Preferred hand	15	44	29.0	8.87	27	45	31.21	5.91	-.80	.44
Non-preferred hand	19	41	31.0	7.17	26	45	32.14	5.83	-.35	.75
Repetitive	12	24	20.1	4.04	13	27	20.5	4.36	-.18	.89
Sequential	22	62	39.9	12.45	33	61	42.86	8.13	-.94	.37
Non-verbal IQ	89	116	100.3	9.3	81	140	107.71	15.41	-1.49	.14

Table 7.2: Summary of scores for children with and without LDN across the screening questionnaires and tests, with Mann-Whitney group comparisons.

Due to high comorbidity between APD and other developmental disorders (Sharma et al., 2009; Dawes and Bishop, 2009), characteristics of ADHD, ASD and dyspraxia were assessed. Findings of such characteristics were not exclusion criteria, as this would render the sample less representative of children who experience LDN. The Conners' Parent Rating Scales-Revised (Conners, 2001), assessing ADHD behaviours, indicated that 12 of the LDN+ children and two of the LDN- children scored above the threshold of atypical attention abilities (score > 60). The SAS (Liddle et al., 2009) highlighted an indication of ASD (score $\leq$ 12) in three of the LDN+ children, and none of the LDN- children. As the tests used in this battery required fast and accurate button-presses to indicate the participant's decision, the finger-tapping test from the developmental NEuroPSYchological Assessment-I (NEPSY-I) was used as an indicator for difficulties with fine motor movements (i.e. dyspraxia indicators). Normalised age scores indicated that all participants scored either at the 'expected level' or above (score $\geq$ 9). All participants had a non-verbal IQ $\geq$ 80, assessed using the Wechsler Abbreviated Scale of Intelligence Second Edition (WASI-II; Wechsler, 1999). A summary of these scores for each group, along with Mann-Whitney group comparisons, can be found in (Table 7.2). The two groups of children only differed in their caregiver-reported listening and language skills.

7.2.3 Apparatus

The children were tested either in a sound-attenuated booth or in a room at their home with minimal auditory and visual distractors. A GSI 37 Auto Tymp portable screening tympanometer and a travel audiometer were used to assess the children's hearing abilities.

Audio stimuli were presented through AKG K702 headphones and a Fast Track Pro USB audio interface (M-Audio, inMusic Brands). Visual stimuli were presented on a 15 inch laptop screen placed 65 cm in front of the participant. All tests were fully automated and responses were made using the far left and far right buttons of a three-choice button box placed between the laptop and the participant, along with a hand-guide to ensure the children placed their hand back onto the table after each trial. This hand-guide also provided task-specific response reminders with images of the stimuli relevant to that button being pressed.

7.2.4 Stimuli & procedure

The children completed a large test battery (Table 7.1) covering selective attention abilities, FD, finger-tapping and non-verbal IQ. The full test battery took up to two hours with short breaks after each task and where needed. The tests were counterbalanced across the participants.

Selective attention

The attention tests assessed auditory and visual selective attention with spatial and non-spatial stimuli. TAiL's attend-frequency and attend-location tasks (Figure 7.1A) were used for the auditory tasks where the children had to decide if the relevant sound feature was same or different. For both of TAiL's tasks the game interface was used, with alternating blocks of the tones being either 4 or 20 semitones apart as a manipulation of the task perceptual demand, as in the previous chapter. Participants completed four blocks of each of TAiL's tasks made up of 40 trials each, resulting in 80 trials for each TAiL task at each perceptual load.

The vANTs with arrows (Figure 7.1B) (as used in Chapter 3) and with shapes (Figure 7.1C) were used as the visual attention tasks. In the vANT tasks the children had to decide from a horizontal row of stimuli whether the central shape was a star or a triangle (non-spatial vANT with shapes), or whether the central arrow pointed left or right (spatial vANT with arrows), while ignoring the irrelevant flanking items. Each trial began with a central fixation cross, followed by either a visual cue to alert the child to when (temporal cue) or where (spatial cue) the target would occur or no visual cue (no-cue condition). A horizontal line of stimuli was then presented either below or above the fixation cross. The line of stimuli could either contain the target arrow/shape only, or be accompanied by congruent or incongruent flankers. Participants completed one block of 144 trials for each vANT task, where all cue types and flanker conditions were randomised (4 cue conditions $\times$ 2 target locations $\times$ 2 target directions $\times$ 3 flanker conditions $\times$ 3 repetitions). Both vANT tasks used a 60% grey background and white shapes. Stimulus timings from both vANT tasks and the arrow vANT stimuli sizing were taken from Fan et al. (2002) and the shape vANT stimuli sizing from McDermott et al. (2007).

At the start of each of the four attention tasks the task instructions were provided verbally. The participants then had to pass a practice block (5 trials for the auditory tasks, and 8 trials for the visual tasks) at 60% accuracy

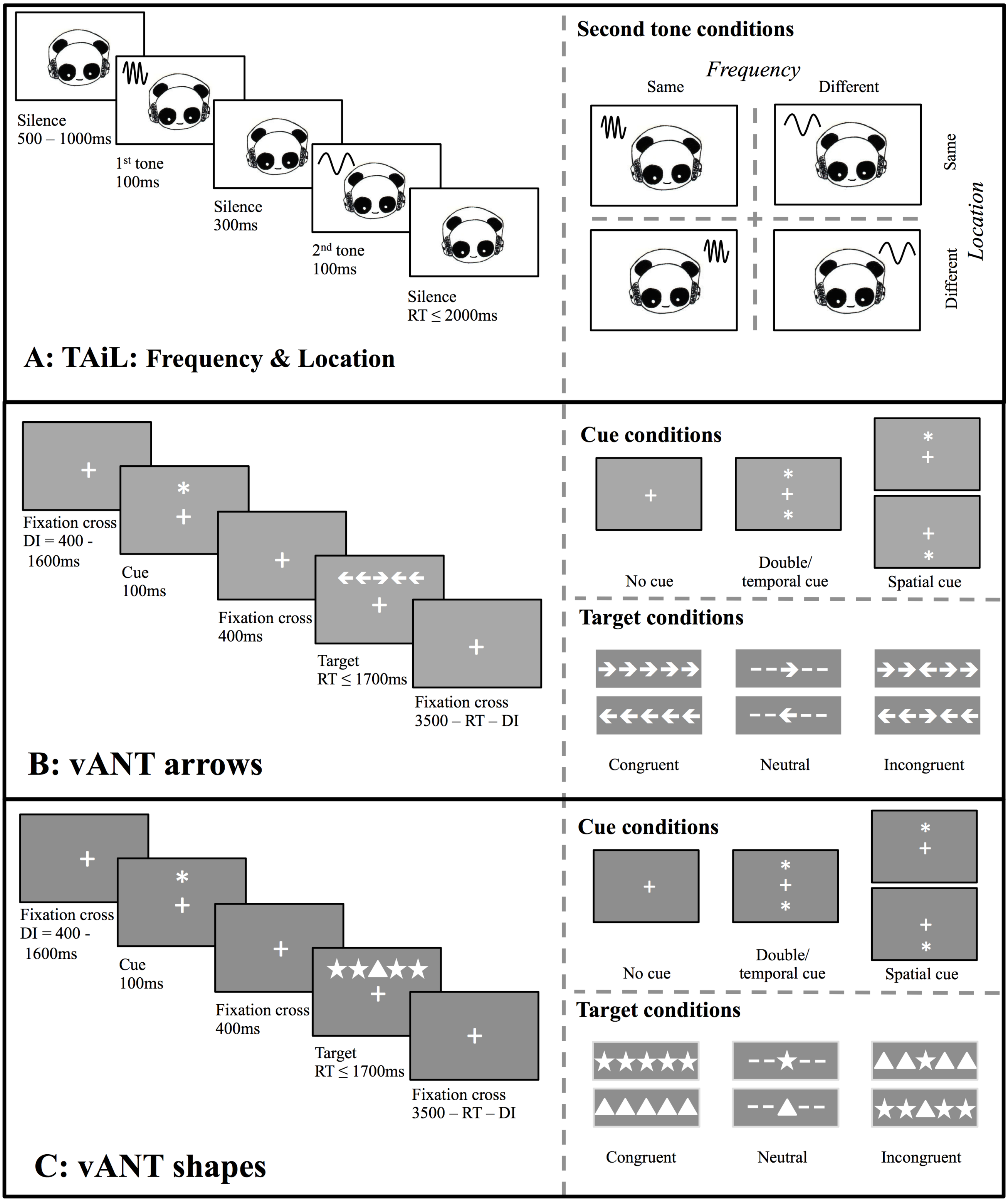

Figure 7.1: Trial paradigm illustrations, including cue and target conditions, for the (A) TAiL attend-frequency and attend-location tasks, (B) vANT tests with arrows and (C) with shapes.

or more to be able to move on to the main task. If required each child was given up to three attempts at the practice session.

Frequency discrimination

Trials involved two identical standard tones of 800 Hz and a third, randomly ordered, target tone of a higher frequency. Each of the tones was 100 ms long (10 ms rise-fall times) with an ISI of 500 ms. The initial ΔF was 50% higher than the standard tones with a 1-down/1-up rule during which the ΔF was halved after each correct response, until the first error. A 3-down/1-up adaptive staircase was then used, whereby the ΔF was multiplied or divided by a factor of $\sqrt{2}$. However, if the child had two successive increases in target frequency an easier trial was presented by doubling the step size to encourage increased attention (Moore et al., 2008).

The task was presented in a game-like environment with three cartoon animals on the screen that jumped to 'make' the tones. The children were asked to report which of the animals was the 'odd one out' using the same horizontal three-choice button box used for the attention tasks, with unlimited response times. After completing a familiarisation track of 5 trials, the children completed two full tracks of 30 trials each.

7.2.5 Statistical analysis

To ensure that the children had completed the attention tasks set to them, three checks were conducted. First, each child reached at least 60% accuracy in the attention tasks practice blocks. Second, no children were found to have a button preference, i.e. if the child was twice as likely to press one button over the other in the least perceptually demanding TAiL tasks (20 semitones separation in the attend-frequency and attend-location tasks) and in the vANTs. Third, trials with RTs shorter than 200 ms and longer than 2500 ms were not used in the analysis below (Table 7.3), in case of pre-emptive responses, lapses of attention or task interruption.

Contrast scores were calculated for RT and accuracy measures of distraction/orienting and conflict resolution from each attention task (Table 7.4). In the following analyses homogeneity of variance is assumed in the appropriate groups as tested by Kruskal-Wallis, and all post-hoc tests are Holm-Bonferonni corrected.

Selective attention task		Trials outwith RT cutoffs (< 200 ms & > 2500 ms	
		LDN+	LDN-
TAiL attend-frequency	4 semitones	13.48%	5.25%
	20 semitones	13.66%	5.13%
TAiL attend-location	4 semitones	12.86%	7.50%
	20 semitones	11.25%	7.88%
vANT shapes		6.55%	1.44%
vANT arrows		8.66%	4.84%

Table 7.3: Summary of trials not included in analysis due to RT being < 200 ms and > 2500 ms across the four attention tasks.

Measure	Task		Calculation
Distraction	TAiL	Non-spatial	$\frac{DifferentLocation-SameLocation}{DifferentLocation+SameLocation}$
		Spatial	$\frac{DifferentFrequency-SameFrequency}{DifferentFrequency+SameFrequency}$
Orienting	vANTs	Non-spatial	$\frac{SpatialCue-DoubleCue}{SpatialCue+DoubleCue}$
		Spatial	
Conflict resolution	TAiL	Non-spatial	$\frac{Incongruent-Congruent}{Incongruent+Congruent}$
		Spatial	
	vANTs	Non-spatial	
		Spatial	

Table 7.4: Calculations used for contrast scores in TAiL and vANT spatial and non-spatial tasks for measures of distraction, orienting and conflict resolution.

7.3 Results

One-way ANOVAs of the tasks' RT baselines[1] showed that the LDN+ group was significantly slower than the LDN- group in the auditory non-spatial task (TAiL attend-frequency) at both frequency separations (4 semitones separation: $F(1, 22) = 15.22, p = .001$; 20 semitones separation: $F(1, 22) = 8.12, p = .009$), but not in the auditory spatial task or either of the visual tasks. One-way ANOVAs further showed that the two groups did not significantly differ in accuracy baselines in any of the four selective attention tasks.

7.3.1 Auditory selective attention: TAiL

A 2×2×2 mixed-design ANOVA compared the groups (LDN+, LDN-) distraction RT contrast scores in the TAiL tasks (non-spatial attend-frequency task, spatial attend-location task) at differing levels of frequency separation (4, 20 semitones separation) (Figure 7.2A). Overall there were main effects of frequency separation ($F(1, 22) = 10.47, p = .004, \eta_p^2 = .32$) and task type ($F(1, 22) = 5.38, p = .030, \eta_p^2 = .20$) whereby the children were more distracted at 20 semitones separation, and in the attend-frequency task when the to-be-attended feature was non-spatial. Importantly, there was a main effect of group ($F(1, 22) = 6.05, p = .022, \eta_p^2 = .22$) such that the LDN+ children were significantly less distracted than the LDN- children. Furthermore, there was a significant interaction between the task type and group ($F(1, 22) = 11.76, p = .002, \eta_p^2 = .35$) whereby the LDN+ children were significantly less distracted than the LDN- children in the non-spatial attend-frequency task ($p < .001$) but not the spatial attend-location task ($p = .68$). Also, while the LDN+ children performed similarly across task types ($p = .40$) the LDN- children were significantly more distracted in the non-spatial attend-frequency task ($p = .001$).

The above 2×2×2 mixed-design ANOVA was applied to the conflict resolution RT contrast scores (Figure 7.2C). No difference in conflict resolution cost was found between the groups (LDN+, LDN-), the TAiL tasks (non-spatial attend-frequency task, spatial attend-location task) or the differing levels of frequency separation (4, 20 semitones).

[1]Comparing the auditory task baselines (TAiL trials where both the frequency and location of the sounds stayed constant)

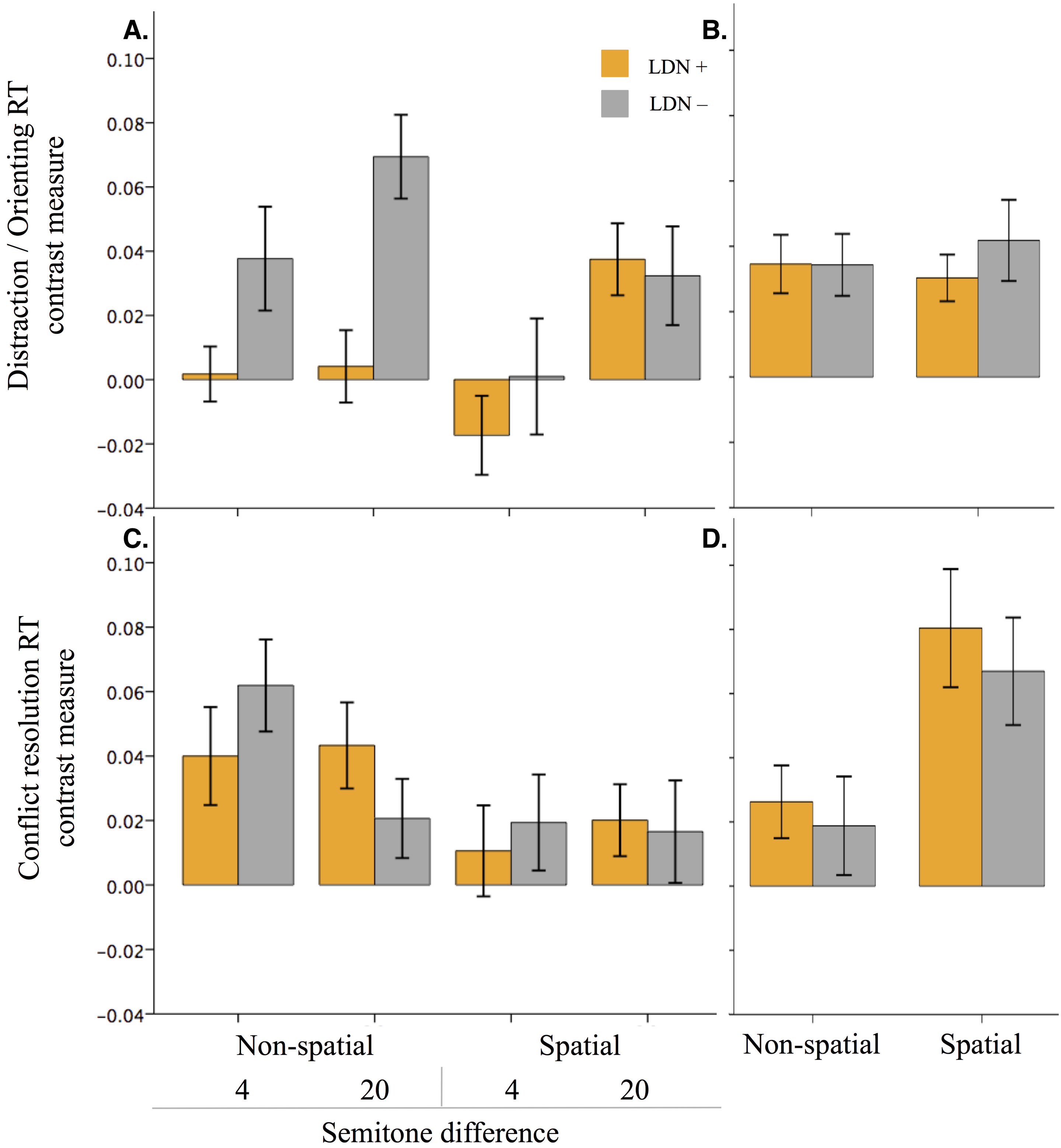

Figure 7.2: Group mean distraction/orienting and conflict resolution RT contrast measures across the (A), (C) auditory (TAiL) and (B), (D) visual (vANT) non-spatial and spatial tasks. Error bars represent the standard error of the mean. Orange represents the LDN+ group and grey the LDN- group.

7.3.2 Visual selective attention: vANT

The analysis applied to the visual tasks was similar to that applied to the auditory tasks. A 2×2 mixed-design ANOVA showed no main effects or interactions between the groups (LDN+, LDN-) and their orienting RT contrast scores in the vANT tasks (non-spatial vANT with shapes, spatial vANT with arrows) (Figure 7.2B).

A 2×2 mixed-design ANOVA showed a significant main effect of task type ($F(1, 21) = 10.55, p = .004, \eta_p^2 = .33$) where the children showed larger conflict resolution effects in the spatial task (vANT arrows) (M = .074, SE = .013) than in the non-spatial task (vANT shapes) (M = .023, SE = .009) (Figure 7.2D). There was no difference in conflict resolution cost between the groups.

7.3.3 Accuracy data

The above RT analysis was repeated with the accuracy contrast scores for each of the four selective attention tasks, and found no main effects or interactions. Therefore the LDN+ and the LDN- children performed with similar accuracy across the tasks.

7.3.4 Frequency discrimination

The average of two tracks was calculated after tracks where the optimised procedure did not adequately fit the data (i.e. with a negative fitted slope or when the fitted value was outside the measured range) were removed. The FD performance of the LDN+ children (M = 8.53; SD = 7.76) and LDN- children (M = 11.20; SE = 9.35) did not significantly differ ($t(19) = -.72, p = .48$) (Figure 7.3).

For three LDN+ children, thresholds could not be calculated in either of the two tracks. The selective attention task analysis above was re-run without these three LDN+ children (leaving 11 LND+ children). The majority of the results remained the same. Only in the analysis of the auditory selective attention task's distraction RT measure did a change occur – the children no longer showed a difference between the non-spatial (attend-frequency) and spatial (attend-location) tasks.

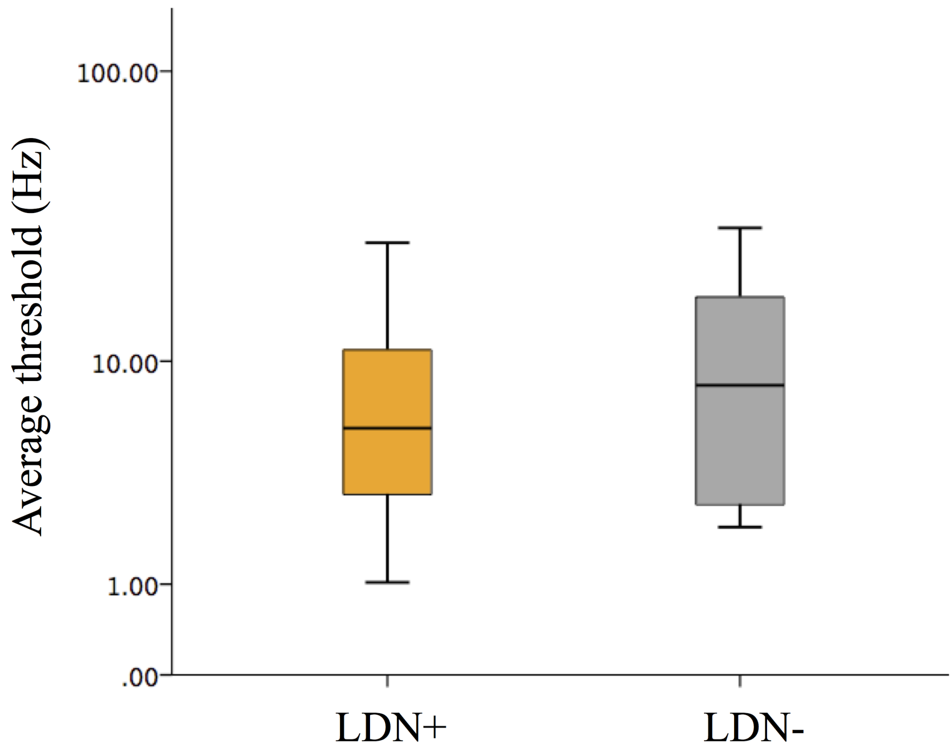

Figure 7.3: Boxplots of group frequency discrimination (FD) thresholds (on a log-10 y-axis) at 800 Hz for the LDN+ (orange) and LDN- (grey) groups. Stimulus duration was 100 ms with an ISI of 500 ms.

Independent variable	t_{18}	p	β
ECLiPS listening	3.74	.001	.001
ECLiPS language	-1.34	.20	-.65
FD	.14	.89	.025
Conners' index	.56	.58	.13
SAS	-.48	.64	-.11
Non-verbal IQ	-.33	.75	-.061

Table 7.5: The effect of variables on a linear regression predicting an individual's distraction RT effect in the auditory (TAiL) non-spatial task.
FD = frequency discrimination threshold; SAS = social aptitude scale

7.3.5 Regression

A stepwise multiple regression was conducted to evaluate whether a child's distraction in the auditory non-spatial task (TAiL attend-frequency, averaged over the 4 and 20 semitone separations) could be predicted by FD threshold, caregiver reports (ECLiPS listening & language scores, Conners' index score, SAS score) and their non-verbal IQ. At step one of the analysis the ECLiPS

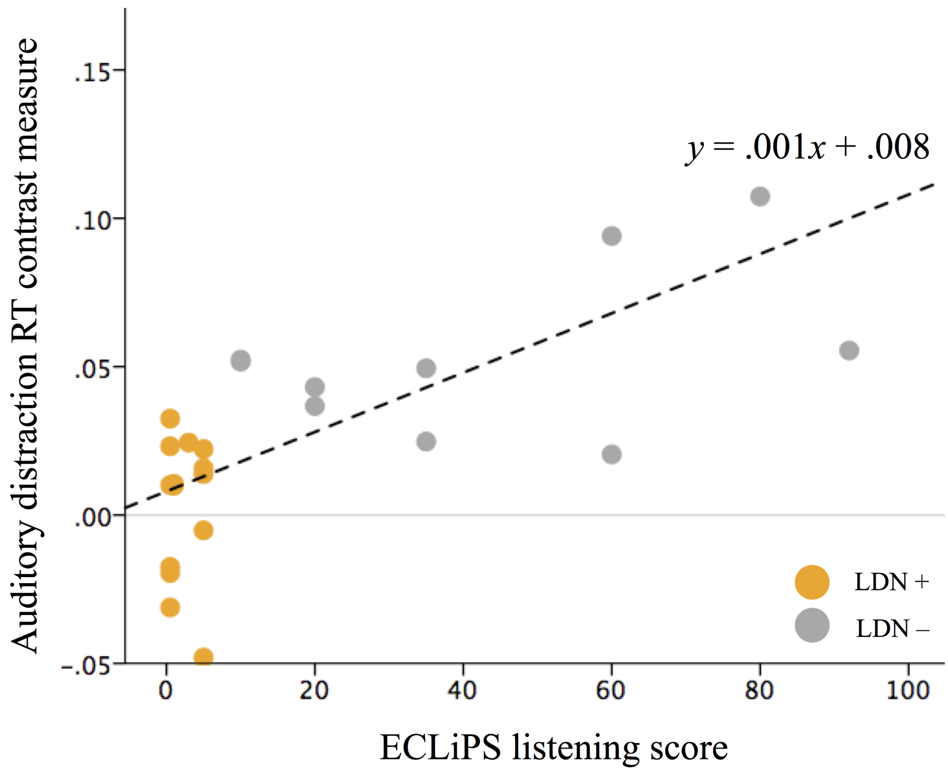

Figure 7.4: The prediction of an individual's ECLiPS listening score (x-axis) on their distraction RT contrast measure in the auditory (TAiL) non-spatial task (y-axis). Orange represents the LDN+ group and grey represents the LDN- group. The dotted line represents the linear regression: $y = .001x + .008$

listening score was entered into the regression and was significantly related to the auditory non-spatial distraction RT effect ($F(1, 18) = 14.02, p = .001$). The multiple regression coefficient was .66, indicating that the ECLiPS listening score could account for 43.8% of the variance in the distraction RT measure in the auditory non-spatial task. The childrens' FD, ECLiPS language score, Conner's index score, SAS score and non-verbal IQ did not enter the equation at step two of the analysis (see Table 7.5). This outcome produced the regression equation (Figure 7.4):

Auditory non-spatial distraction = .001(ECLiPS listening score) + .008

7.4 Discussion

The aim of this study was to compare selective attention ability in auditory (TAiL) and visual (vANT) tasks in children with and without LDN. Comparisons were made between non-spatial and spatial stimuli, which the dual-pathway model describes as being managed by modality-specific and supramodal processes, respectively. Differences between children with and without LDN were shown to be specific to auditory selective attention, and specific to the non-spatial stimulus feature.

The LDN+ children showed significantly less distraction RT effects to the irrelevant sound features than the LDN- children in the auditory non-spatial TAiL task. Following Lavie's load theory (1995), these results suggest that the LDN+ children found the non-spatial auditory task to be perceptually demanding and so did not have the capacity to processes the irrelevant task information. Comparatively the LDN- children showed distraction RT effects suggesting they found the task perceptually easy and had leftover capacity to processes the irrelevant task information. Crucially this group difference was not due to differences in being able to perceive frequency differences because there was no group difference in FD acuity. While FD thresholds could not be calculated for three LDN+ children, when removed from the attention task analysis the group results did not change.

This finding supports the results of previous studies on the contribution of FD acuity to auditory selective attention. Using an oddball-paradigm it has been shown that despite typically developing children aged 9-12 having adult-like FD abilities, the children required larger frequency separations than young adults for passive stream segregation but not for active stream segregation (Sussman & Steinschneider, 2009). These findings suggest that the ability to accurately segregate different auditory objects is not the only factor affecting response to auditory stimuli – automatic attention processes are also vital in detecting sound feature contrasts. This finding by Sussman and Steinschneider agrees with Shinn-Cunningham's (2008) proposition that auditory selective attention consists of two stages: object-formation and object-selection.

On object formation, Sussman and Steinschneider's finding (2009) suggests that even at ages 9-12 the automatic behavioural and neural processes involved in object-formation are still immature. This is further demonstrated in the conflict resolution measure results in Chapter 6. While younger children (aged 4-7) do not yet automatically fuse auditory features to form auditory objects and so are not subject to resolving conflict between features, older children (aged 8-11) use slow, yet adult-like methods of automatically fusing auditory features into objects and so are subject to conflict resolution. In the current study the children (aged 8-13) did not show any group differences in their ability to deal with conflicting auditory or visual[2] information regardless of whether the stimuli were non-spatial or spatial, suggesting that LDN+ children have age appropriate object-formation ability and control in resolving conflict.

In contrast, this study showed a difference between LDN+ and LDN- children in object-selection, specifically in their ability to selectively attend to an auditory-specific relevant task feature. As the LDN+ children performed similarly to the LDN- children in the spatial auditory task, the group differences found in the non-spatial auditory task are not due to insufficient sensory information (Norman and Bobrow, 1975). Furthermore, the stimuli across TAiL's tasks are the same. It is the listeners' attention goals that change through different task instruction – to attend to the sounds' frequency relationship (attend-frequency), or the sounds' location relationship (attend-location).

The study showed that this difference in object-selection is due to a difference in auditory processing capacity. When comparing the non-spatial TAiL task's baseline measure (i.e. in the absence of distracting or conflicting sound feature information) the LDN+ children were significantly slower than the LDN- children. However, their accuracy was no different. Hence, with additional time, the LDN+ children can selectively orient just as well to relevant auditory features as their peers. This suggests that the LDN+ children have smaller auditory processing capacities than their peers, which limits the information available to make a decision (Norman and Bobrow, 1975). The smaller processing capacity causes a bottleneck in the listeners' ability to selectively orient attention to the auditory-specific task, causing the task to become perceptually overwhelming and so forcing early selection of auditory features.

Further support for this interpretation can be found in the studies by Dhamani et al. (2013) and Sharma et al. (2014). As detailed in Chapter 1, these studies presented a verbal auditory switching paradigm, where children with LDN were shown to take longer to switch between auditory objects (Dhamani et al., 2013; Sharma et al., 2014). Together with this chapter's results, these findings suggest that LDN+ children have

[2] A small note on the visual selective attention tasks – results showed that overall the children, regardless of LDN, were more conflicted in the spatial visual task than in the non-spatial visual task. This same result was found by McDermott whereby a younger age group of 4-6 year old children were more conflicted on spatial stimuli than non-spatial. Therefore even by the ages of 8-13 the children still show a higher conflict resolution effect to spatial stimuli.

smaller auditory processing capacities than their LDN- peers, which causes them to experience a higher perceptual demand, causing slower orienting abilities when completing an auditory task. This deficit appears to be auditory-specific as it was observed in the TAiL task shown to be auditory-specific (Chapters 3 and 4). Furthermore, no other group differences were found in either the auditory spatial task or the visual tasks, supporting the assertion that APD is a modality-specific developmental disorder (Chermak et al., 2002). Moreover, a regression analysis showed that 43.8% of the non-spatial auditory distraction RT measure variance could be predicted by the listeners' ECLiPS listening score, while other auditory processing abilities and cognitive skills (ECLiPS language score, FD threshold, non-verbal IQ, ADHD and ASD behaviour screener scores) proved to be non-significant predictors. Thus, the LDN+ children's difficulties in auditory-specific selective attention are indeed specific to their listening abilities – a relationship previously not found when examining LDN from a bottom-up perspective (e.g. Moore et al., 2010).

The results from this study suggest that the children with LDN do not show a developmental delay of auditory object-formation, but rather have a smaller auditory processing capacity, causing a bottleneck in the ability to selectively orient to non-spatial auditory information. If the LDN+ children require longer to orient to relevant auditory information in a simple non-verbal task presented in the quiet, as found in this study, the effort required to stay focused and on task in a noisy environment would likely be exhausting, causing everyday tasks to become perceptually overwhelming. This in turn may explain why, over time, children with LDN fail to maintain the demands of an auditory task (e.g. clicking every time they hear a mispronounced word) (Gyldenkærne et al., 2014; Roebuck and Barry, submitted) – the exertion required to stay on task is simply too much.

7.5 Conclusions

(1) LDN+ children have smaller auditory processing capacities, causing a bottleneck in the orienting of object-selection during auditory tasks.

(2) LDN+ children showed age-appropriate strategies of object-formation.

(3) LDN+ children showed age-appropriate control of conflict resolution.

CHAPTER 8

General discussion

This thesis set out to explore auditory selective attention in children with and without LDN – a set of symptoms often diagnosed as Auditory Processing Disorder. The primary aim was to assess whether children with LDN have auditory selective attention difficulties such as struggling to orient to the relevant information in an auditory task or poorer control of their auditory conflict resolution. To achieve this research aim two pathways were taken: examining a new non-verbal method of assessing auditory selective attention, and assessing typical development of auditory selective attention. Results suggest that children with LDN have age-appropriate object-formation abilities, but struggle with object-selection due to a smaller perceptual capacity available to process non-spatial auditory tasks, causing an auditory-specific bottleneck in their separation of relevant from irrelevant information. In this chapter the experimental results of Chapters 3-7 are reviewed and their implications discussed along with limitations of the present work, and future research is suggested.

8.1 Assessing auditory selective attention

8.1.1 Task measures

To answer the overall aim of this thesis – assessing auditory selective attention in children with LDN – an auditory-specific test of selective attention was required. TAiL – a new method of testing selective attention using non-verbal auditory stimuli – was examined in Chapter 3 by comparing the outcome measures from different tests of selective attention using both auditory and visual stimuli. Factor analysis showed that instead of the attentional networks (i.e. orienting, conflict resolution) dictating the selective attention modality, components were instead based on the type of stimulus features being processed to complete the task. Non-spatial features were found to be modality-specific and spatial features were found to be processed supramodally. Although contrary to the study's predictions, these findings closely followed the predictions of the dual-pathway model whereby spatial features of an object are processed in a supramodal dorsal 'where' pathway and non-spatial features in a modality-specific ventral 'what' pathway (Mishkin et al., 1983; Goodale and Milner, 1992; Rauschecker and Tian, 2000; Arnott et al., 2004). Unfortunately, a non-spatial visual test of selective attention was not included in this chapter, but based on the results and the dual-pathway theory it can be predicted that its measures would have separated into a visual-specific component.

TAiL contains two tasks: the attend-frequency task, where the listener responds based on the tones' frequencies; and the attend-location task, where the listener responds based on the tones' spatial locations. Chapter 3 illustrated that while both tasks contain the same stimuli, by simply changing the task instructions the listener's cognitive goals changed (Lee et al., 2013), and so both the 'what' and 'where' pathways can be assessed with auditory stimuli. Thus, TAiL is able to assess auditory-specific selective attention – a requirement for realising the main aim of this thesis.

Selective attention is described as not only orienting towards relevant task information, but also suppressing the irrelevant task information (Shinn-Cunningham, 2008). The TAiL distraction measure built on the load theory of selective attention (Lavie, 1995) whereby when the task has a low perceptual load the listener has the capacity to process irrelevant information, indicating a late selection of relevant task-relevant information. However, when the task has a high perceptual load the listener does not have the capacity to process irrelevant information, indicating an early selection of task-relevant information. Chapter 4 examined the neural underpinnings of TAiL's tasks using EEG. Results illustrated that the TAiL distraction measure represented the listeners actively suppressing responding based on the change in the task-irrelevant features at both a neural and behavioural level, indicating that the young adult listeners were able to process both task-relevant and task-irrelevant information before selecting the relevant information for further processing. This suggests that for young adults the TAiL task has a low perceptual load.

The temporal and spatial properties of the ERP components associated with the distraction measure in Chapter 4 correspond to those found in other auditory selective attention tasks (e.g. Alho et al., 1987; Degerman et al., 2008; Michie et al., 1993) indicating that the suppression of task-irrelevant information occurs earlier than in similar visual selective attention tasks (Hickey et al., 2008; Hilimire et al., 2011; Sawaki and Luck, 2010). Selective attention components with shorter latencies to auditory stimuli were also found for the TAiL conflict resolution measure, in keeping with other auditory Stroop paradigms (e.g. Buzzell et al., 2013; Donohue et al., 2012). This suggests that the time from stimulus onset to processing is markedly shorter in the auditory system compared to the visual, in alignment with the findings of Hillyard (1993). Interestingly, the timing of the conflict resolution component in the attend-location task extended to overlap with the timings associated with visual Stroop paradigms (e.g. Liotti et al., 2000). Along with the dipole analysis of the distraction measure ERPs, these findings provide support for conclusions based on the behavioural findings of Chapter 3 – that TAiL is able to assess the 'what' and 'where' pathways with the same auditory stimuli but different task instructions.

8.1.2 Use with children

With the results from Chapters 3 and 4 suggesting that TAiL can simultaneously measure a listener's suppression of irrelevant distracting information and their ability to resolve conflicting information, TAiL looked to be a simple paradigm to assess selective attention ability in children, with both auditory-specific non-spatial and supramodal spatial auditory stimuli. A game-like version of TAiL's paradigm was used for the children. Results from Chapters 5 and 6 showed that children were able to complete the attend-frequency and attend-location TAiL tasks from the ages of 4 and 5, respectively. As expected the children became faster and more accurate in their responses with age. Furthermore, as found with the young adults (Zhang et al., 2012), the children's measures of distraction and conflict resolution were not correlated with each other or across the two tasks, therefore indicating the assessment of separate orienting and executive control attentional networks (Posner and Petersen, 1990; Petersen and Posner, 2012).

While the factor analysis in Chapter 3 showed all measurements from the TEA test loading onto one component, suggesting the TEA tasks to be heavily based in WM, none of the TAiL measures loaded onto this component. Together with short task instructions and each block lasting a maximum of 2.5 minutes, this suggests that TAiL has a low WM requirement. Therefore the listener does not have to retain a set of rules to be able to stay on task. However, when changing between the two TAiL tasks the listener has to switch rules, as what was previously the relevant feature now becomes the irrelevant feature. In vision, children as young as 4 have been shown to be able to switch between rules for within-stimulus features (Zelazo et al., 1996). A replication of this finding with auditory stimuli was hoped for in Chapter 5, but due to recruitment logistics, data from the few 4 year olds recruited did not reach the data analysis stage. The results showed that from the age of 5 the children were able to successfully switch from one within-stimulus rule to the other.

8.2 The development of auditory selective attention

Chapter 5 first assessed selective attention to auditory stimuli using the game-like version of TAiL's paradigm. Chapter 6 extended this assessment by investigating the effect of different perceptual demands on auditory-specific selective attention. Below the two main measures from TAiL – distraction and conflict resolution – are discussed in turn.

8.2.1 Distraction

Results from Chapter 4 showed that the young adults were actively suppressing the processing of the task-irrelevant information, suggesting that they experience TAiL's tasks at a low perceptual load and have the capacity available to process the task-irrelevant information as well as the task-relevant information. It was expected that the children would also experience TAiL's tasks at a low perceptual load and, as found in previous auditory studies (e.g. Coch et al., 2005), would become faster with age at selecting the task-relevant information and disengaging from the task-irrelevant information. Therefore it was predicted that the children would show decreasing distraction effects with age.

However, results from Chapter 5 showed that the majority of the children took the same amount of time to respond regardless of whether the task-irrelevant feature changed, irrespective of age. Yet they also did not show an increase in accuracy when the relevant feature remained constant compared to when it changed, suggesting the lack of a distraction effect is not due to a speed-accuracy trade-off. Two interpretations of this result were considered. First, it is possible that the children take longer to process the information due to processing both of the sound features regardless of their task-relevance. This interpretation suggests that even by middle childhood the children struggled to separate the relevant from the irrelevant within-object auditory feature. Second, it may be that the children experienced the TAiL task at a high perceptual load and did not have capacity available to process the irrelevant feature.

Chapter 6 further investigated the second interpretation using the auditory-specific TAiL attend-frequency task. Care was taken in choosing a method to manipulate the perceptual load of the object-selection stage of selective attention rather than that of the object-formation stage – a distinction which Francis (2010) identifies as critical in the manipulation of auditory perceptual load. In every TAiL trial the two tones are temporally separated, creating distinct auditory objects. The goal of each trial is to select the relevant feature from each tone and compare them for a same/different decision. Therefore, to manipulate the perceptual load of the selection stage, the frequency separation between the two tones was manipulated.

Results from Chapter 6 showed that the young adults took longer to respond as frequency separations decreased. In children aged 6 and above, accuracy decreased as frequency separations decreased. These findings align with previous research (adults: Näätänen et al., 1980; Woods and Alain, 2001; children: Duell and Anderson, 1967). Thus, from 6 years of age the smaller frequency separation was significantly more perceptually demanding. Despite this finding, even by the age of 10-11 the children still did not show a RT effect of distraction, even at a large frequency separation. They also showed no improvement in accuracy, indicating that they were not choosing accuracy over speed. Instead, it appears that the children have a smaller auditory perceptual capacity than young adults, leading them to select the relevant sound feature early in the stream of information-processing as they do not have the capacity to process the irrelevant features.

Processing capacity has also been shown to increase with age in vision (Huang-Pollock et al., 2002). However, it has been shown that children already have the capacity to process both relevant and irrelevant information at low perceptual loads by the age of 7-8 years. An alternative interpretation is that although the children found a large frequency separation to be less perceptually demanding than a small separation, both presented a high perceptual load. However, this interpretation is purely theoretical, as perceptual load is based on operational definitions rather than quantitative measures. To further examine whether or not the children reach a stage at which their lack of capacity to process the task-irrelevant features causes them to suppress those features, EEG could be used, as in Chapter 4. To explore whether the limited capacity affects all auditory stimuli or just non-spatial stimuli, the distinction of the other TAiL feature (spatial location of the tones) could be adjusted. For example, the degree of angular separation of the two tones could be manipulated.

8.2.2 Conflict resolution

Chapter 5 was the first reporting of a feature-based non-verbal auditory Stroop task in children. It was expected that the development of auditory conflict resolution would follow that of visual conflict resolution – gaining more control with age, with the accompanying decrease in the cost of conflict resolution to adult levels by age 10-11. However, the results of Chapter 5 showed that until the age of 8-9 the children showed no cost when processing incongruent compared to congruent trials, in both the TAiL attend-frequency and attend-location tasks. Again, two interpretations of the results were discussed. First, due to longer processing times needed by the younger children to process both features (frequency and location) regardless of task-relevance, the same amount of time was taken to process the information regardless of the trial's congruency. Second, due to experiencing an overwhelming level of perceptual demand the younger children did not process the irrelevant sound feature and so did not experience conflict between the relevant and irrelevant information.

The results from Chapter 6 showed that, even with a manipulation of perceptual demand, children took longer to deal with conflicting information. Further analysis showed that based on the age split found in Chapter 5 (4-7 years compared to 8-9 years), the younger children did not show conflict resolution costs, whereas the older children did, although they were slower to respond than the young adults. This same effect has been displayed in vision and has been interpreted as the younger children not automatically fusing stimulus features into objects and therefore not requiring additional time to disentangle them to respond correctly (Nardini et al., 2010). The older children use a similar strategy to young adults, whereby they automatically fuse stimulus features into objects. In order to make a same/different decision based on one feature, they need time to separate the features again.

The fusing of stimulus features is a vital part of the object-formation element of selective attention. The results from Chapters 5 and 6 suggest that children do not use the same object-formation method as young adults until the age of 8-9. However, by the age of 10-11 they are still not at young adult speeds. This effect of object-formation on conflict resolution ability could be further investigated. For example, children could be asked to complete the TAiL without being told which are the relevant and irrelevant task features. For this interpretation of object-formation to hold true, the younger children should show no difference in responding when one or both features change, while the older children and young adults should be faster in responding when both features change.

8.3 Selective attention and APD

The results of assessing typical development in Chapters 5 and 6 propose different trajectories of object-formation and object-selection – the two stages of auditory selective attention. The TAiL conflict resolution measure suggests that children do not automatically fuse auditory stimuli into auditory objects until the age of 8-9 years, whereupon they are not yet at young adult speeds. Furthermore, the TAiL distraction measure indicates that children have a reduced auditory processing capacity and therefore find tasks of low perceptual demand to nonetheless be perceptually overwhelming. This section discusses the results from Chapter 7, in which the selective attention abilities of children with and without LDN were assessed. Based on the findings from Chapter 3, both auditory and visual selective attention tasks using non-spatial and spatial stimuli to tap into modality-specific and supramodal selective attention abilities were used. Despite smaller sample sizes than the previous developmental chapters, the results clearly show that the children with LDN perform similarly to their peers, except in the auditory-specific non-spatial TAiL task (attend-frequency).

The attend-frequency TAiL task asks listeners to base a same/different decision on the frequencies of two tones. Results from Chapter 7 showed that the children with LDN were significantly slower at this task, but showed similar levels of accuracy to children without LDN, suggesting that the result is not based on the child's ability to distinguish frequencies. This is further supported by the lack of difference in FD ability between the groups. Moreover, the result does not indicate a developmental delay in the object-formation process, as the children with LDN were able to deal with conflicting auditory information at a level similar to their peers.

Rather than of object-formation, the deficit appears to be rooted in the child's object-selection ability. The TAiL's distraction measure showed that no matter the perceptual demands of the task, the children with LDN were significantly less distracted than the children without LDN. Although slower to respond, children with LDN displayed similar accuracy to those without LDN, indicating that the children with LDN were able to accurately select the relevant auditory information. However, the children with LDN experience a bottleneck in their object-selection procedure, possibly due to a smaller auditory perceptual capacity, which means they need longer to make an accurate decision. Therefore, even when completing a simple non-verbal auditory task in the quiet, children with LDN take longer to orient to the task-relevant information. Previous bottom-up studies (e.g. Moore et al., 2010) have not shown a consistent relationship between caregiver reports of listening ability and poor auditory processing skills. This study, which used a top-down approach, found that the children's distraction measure was related to their caregiver's report of listening ability – the most frequently reported symptom of APD.

This interpretation corresponds to one of the main symptoms of those diagnosed with APD, in that more time is required to process and respond to auditory information (Campbell, 2011). Further support can be found in evidence of children with LDN taking longer to switch attention between verbal auditory objects (Dhamani et al., 2013; Sharma et al., 2014). With a constant lag in processing the dynamic listening environment and trying to 'keep on top' of the incoming information, it may be that the children with LDN become overwhelmed. This may explain why children with LDN have been shown to be unable to maintain the demands of an auditory task over time (Gyldenkærne et al., 2014; Roebuck and Barry, submitted).

A further conclusion that can be drawn from the findings of Chapter 7 is that while the children with LDN displayed smaller distraction effects than their typically developing peers in the non-spatial TAiL task, they showed similar distraction effect sizes in the spatial TAiL task. This suggests that auditory-specific and supramodal processing capacities are separate.

8.3.1 Treatment

Current methods of treating APD may allow children to make maximum use of what little they have managed to hear. For example, training tasks used to enhance listeners' discrimination ability can range from auditory closure activities (e.g. missing word/syllable/phoneme exercises) to vocabulary building (to make it easier to anticipate a word based on context) (Bellis, 2003). Additionally, compensatory strategies to improve auditory working memory, practiced via storytelling games (Campbell, 2011), may be successful in training listeners to hold what they heard in their mind for longer in order to allow for the delay in further processing. However, these techniques are not always effective and can be draining over time. Furthermore, they are indirect methods of dealing with an auditory object-selection delay, which Chapter 7 of this thesis suggests is caused by a smaller auditory processing capacity, causing a bottleneck in selecting the relevant auditory information from the irrelevant.

An alternative, more direct approach, based on the findings of this thesis, would be to provide training to expand the child's auditory processing capacity. However, it is currently unclear whether the reduction in processing capacity is due to the recruitment of different brain regions or to the co-ordination between brain regions. Neuroimaging techniques would help model the performance of children with LDN, as successfully done in relation to the working memory capacity of typically developing children (Astle et al., 2015; Barnes et al., 2016). This could facilitate the design of a training technique directly targeting the children's auditory processing capacity with the goal of speeding up their auditory object-selection.

8.4 Final conclusions

(1) The modality of a selective attention task depends on whether non-spatial (modality-specific) or spatial (supramodal) stimulus features are selected to complete the task.

(2) By changing the task instructions while keeping the auditory stimuli the same, the two TAiL tasks (attend-frequency and attend-location) can change listening goals to assess auditory-specific and supramodal selective attention.

(3) Young adults experience low perceptual demand from TAiL, as they have the perceptual capacity left over to actively suppress the processing of the task-irrelevant information.

(4) Object-selection with auditory-specific stimulus features is a faster process than with supramodal stimulus features.

(5) Modality-specific and supramodal perceptual capacities used to process auditory information are separate.

(6) Children use a different object-formation method than young adults until the age of 8-9, and are still slower at object-formation than young adults at the age of 10-11.

(7) Children have a small auditory-specific processing capacity that does not change between the ages of 4 and 11.

(8) Children with LDN have a reduced auditory-specific processing capacity, which causes a processing bottleneck.

(9) Children with LDN require more time to complete auditory-specific tasks and can be perceptually overwhelmed by auditory information, due to the processing bottleneck identified in these children.

(10) LDN in children appears to stem from difficulty with object-selection based on non-spatial auditory features, rather than auditory object-formation.

APPENDIX A

Instructions for TAiL

Below are the verbal instructions given prior to the game-like version of TAiL. If needed demonstrations of the tones were given by singing different pitches of tones whilst pointing to the ears that the tones would play in.

> "You are the captain of a spaceship and you are lost in space surrounded by aliens!
>
> Your friends have come to help you. But you need to make sure you don't shoot them.
>
> Space is dark so you have to listen carefully and use sound to find out if the other spaceships are friends or aliens.
>
> If the two sounds have the same pitch/location, they are your friends. Press the right/blue button to light up fireworks to show your friends where you are.
>
> If the two sounds have different pitch/locations, it's an alien. Press the left/red button to blow up the alien.
>
> Do it as quickly and as accurate as you can! If you miss the alien or blow up your friends by accident there will be an 'oops!' noise.
>
> We'll start with some practice shots. Press the middle/yellow button to start."

Before the practice blocks

"Remember friends have two sounds with the same pitch/location, so use the right/blue button to light up fireworks.

And aliens have two sounds with different pitches/locations, so use the left/red button to blow them up!

Do it as quickly and as accurate as you can. We want very little 'oops' sounds!

Press the middle/yellow button to start."

Before the testing blocks

References

Ahmmed, A. U., Ahmmed, A. A., Bath, J. R., Ferguson, M. A., Plack, C. J., and Moore, D. R. (2014). Assessment of children with suspected auditory processing disorder: A factor analysis study. *Ear and hearing*, **35**, 295–305. 13

Ahveninen, J., Jääskeläinen, I. P., Raij, T., Bonmassar, G., Devore, S., Hämäläinen, M., Levänen, S., Lin, F.-H., Sams, M., Shinn-Cunningham, B. G., Witzel, T., and Belliveau, J. W. (2006). Task-modulated 'what' and 'where' pathways in human auditory cortex. *Proceedings of the National Academy of Sciences of the United States of America*, **103**(39), 14608–13. 37

Alain, C. and Izenberg, A. (2003). Effects of attentional load on auditory scene analysis. *Journal of Cognitive Neuroscience*, **15**(7), 1063–1073. 76

Alain, C., Reinke, K., He, Y., Wang, C., and Lobaugh, N. (2005). Hearing Two Things at Once : Neurophysiological Indices of Speech Segregation and Identification. *Journal of Cognitive Neuroscience*, **17**(5), 811–818. 77

Alho, Töttölä, K., Reinikainen, K., Sams, M., and Näätänen, R. (1987). Brain mechanism of selective listening reflected by event-related potentials. *Electroencephalography and clinical neurophysiology*, **68**, 458–470. 43, 52, 116

Allison, C., Auyeung, B., and Baron-Cohen, S. (2012). Toward brief "red flags" for autism screening: the short autism spectrum quotient and the short quantitative checklist in 1,000 cases and 3,000 controls. *Journal of the American Academy of Child & Adolescent Psychiatry*, **51**(2), 202–212. 80

American Speech-Language-Hearing Association Working Group on Auditory Processing Disorders (2005). (Central) Auditory Processing Disorders: The Role of the Audiologist. 3

Arnott, S. R. and Alain, C. (2011). The auditory dorsal pathway: orienting vision. *Neuroscience and biobehavioral reviews*, **35**(10), 2162–73. 37

Arnott, S. R., Binns, M. A., Grady, C. L., and Alain, C. (2004). Assessing the auditory dual-pathway model in humans. *NeuroImage*, **22**(1), 401–408. 36, 49, 52, 55, 98, 115

Astle, D. E., Barnes, J. J., Baker, K., Colclough, G. L., and Woolrich, M. W. (2015). Cognitive training enhances intrinsic brain connectivity in childhood. *The Journal of Neuroscience*, **35**(16), 6277–6283. 122

Atkinson, J., Braddick, O., Anker, S., Curran, W., Andrew, R., Wattam-Bell, J., and Braddick, F. (2003). Neurobiological models of visuospatial cognition in children with Williams syndrome: Measures of dorsal-stream and frontal function. *Developmental neuropsychology*, **23**(1-2), 139–172. 56

Atkinson, J., King, J., Braddick, O., Nokes, L., Anker, S., and Braddick, F. (1997). A specific deficit of dorsal stream function in Williams' syndrome. *Neuroreport*, **8**(8), 1919–1922. 56

Baizer, J. S., Ungerleider, L. G., and Desimone, R. (1991). Organization of visual inputs to the inferior temporal and posterior parietal cortex in macaques. *The Journal of neuroscience*, **11**(1), 168–190. 36

Barnes, J. J., Woolrich, M. W., Baker, K., Colclough, G. L., and Astle, D. E. (2016). Electrophysiological measures of resting state functional connectivity and their relationship with working memory capacity in childhood. *Developmental science*, **19**(1), 19–31. 122

Barry, J. G. and Moore, D. R. (2014). Evaluation of children's listening and processing skills (ECLiPS). 100

Bartgis, J., Thomas, D. G., Lefler, E. K., and Hartung, C. M. (2008). The development of attention and response inhibition in early childhood. *Infant and Child Development*, **17**(5), 491–502. 11

Bate, A. J., Mathias, J. L., and Crawford, J. R. (2001). Performance on the Test of Everyday Attention and standard tests of attention following severe traumatic brain injury. *The Clinical Neuropsychologist*, **15**(3), 405–422. 29, 39

Beck, D. L. and Flexer, C. (2011). Listening is where hearing meets brain. *Children and Adults. Hearing Review*, **18**(2), 30–34. 4

Bellis, T. J. (2003). *Assessment and Management of Central Auditory Processing Disorders in the Educational Setting from Science to Practice*. Delmar, Cengage Learning, Clifton Park, NY, 2nd edition. 5, 122

Berg, P. and Scherg, M. (1994). A multiple source approach to the correction of eye artifacts. *Electroencephalography and Clinical Neurophysiology*, **90**(3), 229–241. 45

Berger, A., Jones, L., Rothbart, M. K., and Posner, M. I. (2000). Computerized games to study the development of attention in childhood. *Behavior Research Methods, Instruments, & Computers*, **32**(2), 297–303. 61

Berman, S. and Friedman, D. (1995). The Development of Selective Attention as Reflected by Event-Related Brain Potentials. *Journal of Experimental Child Psychology*, **58**, 1–31. 56

BESA (released 2012). BESA Research 5.3. 45

BESA (released 2014). BESA Statistics 1.0. 46

Bidet-Caulet, A., Mikyska, C., and Knight, R. T. (2010). Load effects in auditory selective attention: Evidence for distinct facilitation and inhibition mechanisms. *NeuroImage*, **50**(1), 277–284. 41

Braddick, O. and Atkinson, J. (2011). Development of human visual function. *Vision Research*, **51**(13), 1588–1609. 56

Bregman, A. S. (1978). The formation of auditory streams. In Requin, J., editor, *Attention and Performance VII*. Lawrence Erlbaum, Hillsdale, New Jersey. 72, 78

Bregman, A. S. (1990). *Auditory Scene Analysis: The Perceptual Organization of Sound*. MIT Press, Cambridge, MA, 1994 edition. 7, 77

Bregman, A. S. (1993). *Auditory scene analysis: Hearing in complex environments*. Clarendon Press/Oxford University Press. 6

Bregman, A. S. and Rudnicky, A. I. (1975). Auditory segregation: stream or streams? *Journal of experimental psychology. Human perception and performance*, **1**(3), 263–7. 6, 7

British Society of Audiology (2011a). Practice Guidance: An Overview of Current Management of Auditory Processing Disorder (APD). 96

British Society of Audiology (2011b). Pure-tone air-conduction and bone-conduction threshold audiometry with and without masking. 25, 60, 80, 100

Broadbent, D. E. (1956). Successive responses to simultaneous stimuli. 8, 11

Buzzell, G. A., Roberts, D. M., Baldwin, C. L., and McDonald, C. G. (2013). An electrophysiological correlate of conflict processing in an auditory spatial stroop task: The effect of individual differences in navigational style. *International Journal of Psychophysiology*, **90**(2), 265–271. 43, 53, 116

Cameron, S. and Dillon, H. (2008). The listening in spatialized noise-sentences test (LISN-S): comparison to the prototype LISN and results from children with either a suspected (central) auditory processing disorder or a confirmed language disorder. *Journal of the American Academy of Audiology*, **19**(5), 377–391. 98

Campbell, N. (2011). Supporting children with auditory processing disorder. *British Journal of School Nursing*, **6**(6), 273–277. 1, 2, 121, 122

Carlyon, R. P. (2004). How the brain separates sounds. *Trends in Cognitive Sciences*, **8**(10), 465–471. 6

Cattell, R. B. (1966). The scree test for the number of factors. *Multivariate behavioural research*, **1**(2), 245–276. 32

Chermak, G. D., Hall, J. W., and Musiek, F. E. (1999). Differential Diagnosis and Management of Central Auditory Processing Disorder and Attention Deficit Hyperactivity Disorder. *Journal of American Academy of Audiology*, **10**, 289–303. 97

Chermak, G. D., Tucker, E., and Seikel, J. A. (2002). Behavioral characteristics of auditory processing disorder and attention-deficit hyperactivity disorder: predominantly inattentive type. *Journal of the American Academy of Audiology*, **13**(6), 332–338. 97, 98, 113

Cherry (1992). Screening and Evaluation of Central Auditory Processing Disorders in Young Children. In Katz, J., Stecker, N. A., and Henderson, D., editors, *Central Auditory Processing: A Transdisciplinary View*, chapter 10. Mosby Incorporated. 3

Cherry, R. S. (1981). Development of selective auditory attention skills in children. *Perceptual and Motor Skills*, **52**(2), 379–385. 11

Coch, D., Sanders, L. D., and Neville, H. J. (2005). An event-related potential study of selective auditory attention in children and adults. *Journal of cognitive neuroscience*, **17**(4), 605–622. 11, 12, 70, 117

Conners, C. K. (2001). Conners' Rating Scales Revised. 101

Corteen, R. and Dunn, D. (1974). Shock-associated words in a nonattended message: A test for momentary awareness. *Journal of Experimental Psychology*, **102**(6), 1143–1144. 9

Crawford, J. R., Sommerville, J., and Robertson, I. H. (1997). Assessing the reliability and abnormality of subtest differences on the Test of Everyday Attention. *British Journal of Clinical Psychology*, **36**(4), 609–617. 30

Dawes, P. and Bishop, D. (2009). Auditory processing disorder in relation to developmental disorders of language, communication and attention: a review and critique. *International Journal of Language & Communication Disorders*, **44**, 440–465. 1, 12, 97, 101

Day, M. C. and Stone, C. A. (1980). Children's use of perceptual set. *Journal of Experimental Child Psychology*, **29**(3), 428–445. 57

de Fockert, J. W., Rees, G., Frith, C. D., and Lavie, N. (2001). The role of working memory in visual selective attention. *Science (New York, N.Y.)*, **291**(5509), 1803–1806. 10

Degerman, A., Rinne, T., Särkkä, A.-K., Salmi, J., and Alho, K. (2008). Selective attention to sound location or pitch studied with event-related brain potentials and magnetic fields. *The European journal of neuroscience*, **27**(12), 3329–3341. 41, 43, 52, 53, 116

Desimone, R., Schein, S. J., Moran, J., and Ungerleider, L. G. (1985). Contour, color and shape analysis beyond the striate cortex. *Vision research*, **25**(3), 441–452. 36

Deutsch, D. (1975). Two-channel listening to musical scales. *The Journal of the Acoustical Society of America*, **57**, 1156–1160. 78

Deutsch, J. A. and Deutsch, D. (1963). Attention: some theoretical considerations. *Psychological review*, **70**(1), 80–90. 8

Dhamani, I., Leung, J., Carlile, S., and Sharma, M. (2013). Switch Attention to Listen. *Scientific reports*, **3**, 10.1038/srep01297–10.1038/srep01297. 5, 13, 95, 96, 97, 112, 121

Donohue, S. E., Liotti, M., Perez, R., Woldorff, M. G., Iii, R. P., and Woldorff, M. G. (2012). Is conflict monitoring supramodal? Spatiotemporal dynamics of cognitive control processes in an auditory Stroop task. *Cognitive, affective & behavioral neuroscience*, **12**(1), 1–15. 24, 43, 44, 53, 116

Doyle, A.-B. (1973). Listening to Distraction : A Developmental of Selective. *Journal of Experimental Child Psychology*, **15**, 100–115. 12

Driver, J. and Spence, C. (1994). Spatial synergies between auditory and visual attention. In Umiltà, C. and Moscovitch, M., editors, *Attention and performance: conscious and unconscious information processing*, pages 311–331. MIT Press, Cambridge, MA. 36

Driver, J. and Spence, C. (1998). Cross-modal links in spatial attention. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, **353**(1373), 1319–1331. 36, 42

Duell, O. K. and Anderson, R. C. (1967). Pitch discrimination among primary school children. *Journal of educational psychology*, **58**(6), 315–318. 78, 90, 118

Enns, J. T. and Girgus, J. S. (1985). Developmental changes in selective and integrative visual attention. *Journal of experimental child psychology*, **40**(2), 319–337. 11, 21

Eriksen, B. A. and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, **16**(1), 143–149. 16

Escera, C., Corral, M. J., and Yago, E. (2002). An electrophysiological and behavioral investigation of involuntary attention towards auditory frequency, duration and intensity changes. *Brain research. Cognitive brain research*, **14**(3), 325–332. 42

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., and Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of cognitive neuroscience*, **14**(3), 340–347. 22, 23, 28, 102

Felleman, D. J. and Van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. *Cerebral cortex*, **1**, 1–47. 36

Fields, A. (2005). *Discovering statistics using SPSS*. Sage Publications, Beverley Hills. 30, 32

Francis, A. L. (2010). Improved segregation of simultaneous talkers differentially affects perceptual and cognitive capacity demands for recognizing speech in competing speech. *Attention, Perception, & Psychophysics*, **72**(2), 501–516. 77, 118

Giesbrecht, B., Woldorff, M. G., Song, A. W., and Mangun, G. R. (2003). Neural mechanisms of top-down control during spatial and feature attention. *NeuroImage*, **19**, 496–512. 37

Gomes, H., Barrett, S., Duff, M., Barnhardt, J., and Ritter, W. (2008). The effects of interstimulus interval on event-related indices of attention: An auditory selective attention test of perceptual load theory. *Clinical Neurophysiology*, **119**(3), 542–555. 76, 77

Gomes, H., Duff, M., Barnhardt, J., Barrett, S., and Ritter, W. (2007). Development of auditory selective attention: event-related potential measures of channel selection and target detection. *Psychophysiology*, **44**(5), 711–727. 56

Gomes, H., Molholm, S., Christodoulou, C., Ritter, W., and Cowan, N. (2000). The Development of Auditory Attention in Children. *Frontiers in Bioscience*, **5**, d108–120. 11, 57

Goodale, M. A. and Milner, A. D. (1992). Separate visual pathways for perception and action. [Review] [61 refs]. *Trends in Neurosciences*, **15**(I), 20–25. 36, 52, 55, 98, 115

Gronwall, D. and Wrightson, P. (1974). Delayed recovery of intellectual function after minor head injury. *Lancet*, **2**(7881), 605–609. 39

Guy, J., Rogers, M., and Cornish, K. (2012). Developmental changes in visual and auditory inhibition in early childhood. *Infant and Child Development*, **21**(5), 521–536. 59

Gyldenkærne, P., Dillon, H., Sharma, M., and Purdy, S. C. (2014). Attend to This: The Relationship between Auditory Processing Disorders and Attention Deficits. *Journal of the American Academy of Audiology*, **25**, 676–687. 113, 121

Halliday, L. F., Taylor, J. L., Edmondson-Jones, A. M., and Moore, D. R. (2008). Frequency discrimination learning in childrena). *The Journal of the Acoustical Society of America*, **123**(6), 4393–4402. 3

Hanania, R. and Smith, L. B. (2010). Selective Attention and Attention Switching: Toward a Unified Developmental Approach. *Developmental Science*, **13**(4), 622–635. 11, 21

Hansen, P. C., Stein, J. F., Orde, S. R., Winter, J. L., and Talcott, J. B. (2001). Are dyslexics' visual deficits limited to measures of dorsal stream function? *Neuroreport*, **12**(7), 1527–1530. 56

Haxby, J. V., Grady, C. L., Horwitz, B., Ungerleider, L. G., Mishkin, M., Carson, R. E., Herscovitch, P., Schapiro, M. B., and Rapoport, S. I. (1991). Dissociation of object and spatial visual processing pathways in human extrastriate cortex. *Proceedings of the National Academy of Sciences of the United States of America*, **88**, 1621–1625. 36

Hickey, C., Lollo, V. D., and Mcdonald, J. J. (2008). Electrophysiological Indices of Target and Distractor Processing in Visual Search. *Journal of cognitive neuroscience*, **21**(4), 760–775. 43, 52, 116

Hilimire, M. R., Mounts, J. R. W., Parks, N. a., and Corballis, P. M. (2009). Competitive interaction degrades target selection: An ERP study. *Psychophysiology*, **46**, 1080–1089. 43, 52

Hilimire, M. R., Mounts, J. R. W., Parks, N. a., and Corballis, P. M. (2011). Dynamics of target and distractor processing in visual search: evidence from event-related brain potentials. *Neuroscience letters*, **495**(3), 196–200. 43, 52, 116

Hill, K. T. and Miller, L. M. (2010). Auditory attentional control and selection during cocktail party listening. *Cerebral cortex*, **20**(3), 583–590. 37

Hillyard, S. A. (1993). Electrical and magnetic brain recordings : contributions to cognitive neuroscience. *Current Opinion in Neurobiology*, **3**(2), 217–224. 23, 37, 53, 116

Hillyard, S. A., Hink, R. F., Schwent, V. L., and Picton, T. W. (1973). Electrical Signs of Selective Attention in the Human Brain. *Science*, **182**, 177–180. 6

Huang-Pollock, C. L., Carr, T. H., Nigg, J. T., and Others (2002). Development of selective attention: Perceptual load influences early versus late attentional selection in children and adults. *Developmental Psychology*, **38**(3), 363–374. 71, 76, 91, 118

Hubel, D. H., Henson, C., Rupert, A., and Galambos, R. (1959). "Attention" Units in the Auditory Cortex. *Science*, **129**, 1279–1280. 6

Hugdahl, K. (2011). Fifty years of dichotic listening research - Still going and going and... *Brain and Cognition*, **76**(2), 211–213. 38

IBM Corp (released 2011). IBM SPSS Statistics, Version 20.0. 30

James, T. W., Culham, J., Humphrey, G. K., Milner, a. D., and Goodale, M. a. (2003). Ventral occipital lesions impair object recognition but not object-directed grasping: An fMRI study. *Brain*, **126**, 2463–2475. 36

Jensen, J. K. and Neff, D. L. (1993). Development of Basic Auditory Discrimination in Preschool Children. *Psychological Science*, **4**(2), 104–107. 11, 17, 79, 90

Jerger, J. (1998). Controversial issues in central auditory processing disorders. In *Seminars in Hearing*, volume 19, pages 393–398. Thieme Medical Publishers, Inc. 98

Jerger, J. and Musiek, F. E. (2000). Report of the Consensus Conference on the Diagnosis of Auditory Processing Disorders in School-Aged Children. *Journal of the American Academy of Audiology*, **11**(9), 467–474. 1, 2, 3

Jerger, S., Martin, R. C., and Pirozzolo, F. J. (1988). A developmental study of the auditory Stroop effect. *Brain Lang*, **35**(1), 86–104. 58

Johnston, W. a. and Heinz, S. P. (1978). Flexibility and capacity demands of attention. *Journal of Experimental Psychology: General*, **107**(4), 420–435. 9

Johnston, W. a. and Heinz, S. P. (1979). Depth of nontarget processing in an attention task. *Journal of experimental psychology. Human perception and performance*, **5**(1), 168–175. 9

Kaiser, H. F. (1960). The Application of Electronic Computers to Factor Analysis. *Educational and Psychological Measurement*, **20**, 141–151. 32

Kane, M. J. and Engle, R. W. (2003). Working-Memory Capacity and the Control of Attention: The Contributions of Goal Neglect, Response Competition, and Task Set to Stroop Interference. *Journal of experimental Psychology: General*, **132**, 47–70. 92

Karns, C. M., Isbell, E., Giuliano, R. J., and Neville, H. J. (2015). Auditory attention in childhood and adolescence: An event-related potential study of spatial selective attention to one of two simultaneous stories. *Developmental Cognitive Neuroscience*, **13**, 53–67. 57, 71

Katz, J. (1992). Classification of Auditory Processing Disorders. In Katz, J., Stecker, N., and Henderson, D., editors, *Central Auditory Processing: A Transdisciplinary View*, pages 81–91. Mosby Year Book. 97

Kessler, R. C., Adler, L., Ames, M., Demler, O., Faraone, S., Hiripi, E., Howes, M. J., Jin, R., Secnik, K., Spencer, T., Ustun, T. B., and Walters, E. E. (2005). The World Health Organization adult ADHD self-report scale (ASRS): a short screening scale for use in the general population. *Psychological Medicine*, **35**(2), 245–256. 80

Killion, M. C., Niquette, P. A., Gudmundsen, G. I., Revit, L. J., and Banerjee, S. (2004). Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *Journal of Acoustical Society of America*, **116**, 2395–2405. 44

Kinomura, S., Larsson, J., Gulyás, B., and Roland, P. E. (1996). Activation by attention of the human reticular formation and thalamic intralaminar nuclei. *Science (New York, N.Y.)*, **271**(5248), 512–515. 23

Kiss, M., Grubert, A., Petersen, A., and Eimer, M. (2012). Attentional Capture by Salient Distractors during Visual Search Is Determined by Temporal Task Demands. *Journal of Cognitive Neuroscience*, **24**, 749–759. 43

Koldewyn, K., Whitney, D., and Rivera, S. M. (2010). The psychophysics of visual motion and global form processing in autism. *Brain*, **133**(2), 599–610. 56

Krumbholz, K., Nobis, E. A., Weatheritt, R. J., and Fink, G. R. (2009). Executive control of spatial attention shifts in the auditory compared to the visual modality. *Human brain mapping*, **30**(5), 1457–1469. 36

Kubovy, M. (1981). Concurrent-pitch segregation and the theory of indispensable attributes. In Kubovy, M. and Pomerantz, J. R., editors, *Perceptual organization*. Lawrence Erlbaum Associates, Hillsdale, NJ. 78

Lamers, M. J. M., Roelofs, A., and Rabeling-Keus, I. M. (2010). Selective attention and response set in the Stroop task. *Memory & cognition*, **38**(7), 893–904. 23

Lane, D. M. and Pearson, D. A. (1982). The development of selective attention. *Merrill-Palmer Quarterly*, **28**(3), 317–337. 12, 57

Larson, M. J., Kaufman, D. A. S., and Perlstein, W. M. (2009). Neural time course of conflict adaptation effects on the Stroop task. *Neuropsychologia*, **47**, 663–670. 44

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, **21**(3), 451–468. 9, 16, 71, 75, 76, 96, 111, 115

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in cognitive sciences*, **9**(2), 75–82. 76

Lavie, N., Hirst, A., de Fockert, J. W., Viding, E., and Others (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology-General*, **133**(3), 339–353. 10

Lee, A., Rajaram, S., Xia, J., Bharadwaj, H., Larson, E., Hämäläinen, M. S., and Shinn-Cunningham, B. G. (2013). Auditory selective attention reveals preparatory activity in different cortical regions for selection based on source location and source pitch. *Frontiers in neuroscience*, **6**(January), 190–199. 6, 36, 37, 115

Lee, A. K. C., Larson, E., Maddox, R. K., and Shinn-Cunningham, B. G. (2014). Using neuroimaging to understand the cortical mechanisms of auditory selective attention. *Hearing Research*, **307**, 111–120. 11, 21

Lee, K. and Choo, H. (2013). A critical review of selective attention: an interdisciplinary perspective. *Artificial Intelligence Review*, **40**(1), 27–50. 21

Leibold, L. J. and Neff, D. L. (2007). Effects of masker-spectral variability and masker fringes in children and adultsa). *The Journal of the Acoustical Society of America*, **121**(6), 3666–3676. 56

Liddle, E. B., Batty, M. J., and Goodman, R. (2009). The Social Aptitudes Scale: an initial validation. *Social psychiatry and psychiatric epidemiology*, **44**(6), 508–513. 61, 80, 101

Liotti, M., Woldorff, M. G., Perez, R., and Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia*, **38**(5), 701–711. 43, 44, 53, 116

Litovsky, R. Y. (1997). Developmental changes in the precedence effect: estimates of minimum audible angle. *The Journal of the Acoustical Society of America*, **102**(3), 1739–1745. 91

Lund, J. S. (1988). Anatomical organization of macaque monkey striate visual cortex. *Annual review of neuroscience*, **11**(1), 253–288. 55, 78

Maccoby, E. E. and Konrad, K. W. (1966). Age trends in selective listening. *Journal of experimental child psychology*, **3**(2), 113–122. 12

Macleod, C. M. (1991). Haifa Century of Research on the Stroop Effect: An Integrative Review. *Psychological bulletin*, **109**(2), 163–203. 58

Markela-Lerenc, J., Ille, N., Kaiser, S., Fiedler, P., Mundt, C., and Weisbrod, M. (2004). Prefrontal-cingulate activation during executive control: Which comes first? *Cognitive Brain Research*, **18**(3), 278–287. 43, 44, 53

McClain, L. (1983). Stimulus-response compatibility affects auditory Stroop interference. *Perception & psychophysics*, **33**(3), 266–270. 22

McDermott, J. M., Pérez-Edgar, K., and Fox, N. a. (2007). Variations of the flanker paradigm: assessing selective attention in young children. *Behavior research methods*, **39**(1), 62–70. 58, 98, 102

McDonald, J. J. and Ward, L. M. (1999). Spatial relevance determines facilitatory and inhibitory effects of auditory covert spatial orienting. *Journal of Experimental Psychology: Human Perception and Performance*, **25**(5), 1234–1252. 38

McLennan, D., Barnes, H., Noble, M., Davies, J., Garratt, E., and Dibben, C. (2011). The english indices of deprivation 2010. 60

Mendelson, M. and Hath, M. (1976). The relation between audition and vision in the human newborn. *Monographs of the Society for Research in Child Development*, **41**(4), 1–72. 10

Merzenich, M. M., Colwell, S. A., and Andersen, R. A. (1982). Auditory forebrain organization. In Woolsey, C. N., editor, *Cortical Sensory Organization: Volume 3: Multiple Auditory Areas*. Humana, Clifton, NJ. 55, 78

Michie, P. T., Solowij, N., Crawford, J. M., and Glue, L. C. (1993). The effects of between-source discriminability on attended and unattended auditory erps. *Psychophysiology*, **30**(2), 205–220. 41, 43, 52, 116

Mishkin, M., Ungerleider, L. G., and Macko, K. A. (1983). Object vision and spatial vision: Two cortical pathways. *Trends in Neurosciences*, **6**, 414–417. 36, 52, 55, 98, 115

Moore, D. R. (2006). Auditory processing disorder (APD): Definition, diagnosis, neural basis, and intervention. *Audiological Medicine*, **4**(1), 4–11. 2

Moore, D. R. (2011). The diagnosis and management of auditory processing disorder. *Language, speech, and hearing services in schools*, **42**(3), 303–308. 1, 2, 3

Moore, D. R. (2012). Listening difficulties in children: bottom-up and top-down contributions. *Journal of communication disorders*, **45**(6), 411–418. 4

Moore, D. R. (2015). Sources of pathology underlying listening disorders in children. *International journal of psychophysiology*, **95**(2), 125–134. 12

Moore, D. R., Ferguson, M. A., Edmondson-Jones, A. M., Ratib, S., and Riley, A. (2010). Nature of Auditory Processing Disorder in Children. *Pediatrics*, **126**(2), E382–E390. 2, 3, 4, 13, 95, 113, 121

Moore, D. R., Ferguson, M. A., Halliday, L. F., and Riley, A. (2008). Frequency discrimination in children: Perception, learning and attention. *Hearing Research*, **238**(1), 147–154. 104

Moore, D. R., Rosen, S., Bamiou, D.-E., Campbell, N. G., and Sirimanna, T. (2013). Evolving concepts of developmental auditory processing disorder (APD): A British Society of Audiology APD Special Interest Group 'white paper'. *International journal of audiology*, **52**(1), 3–13. 1, 2, 4

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly journal of experimental psychology*, **11**(1), 56–60. 8

Most, S. B., Sorber, A. V., and Cunningham, J. G. (2007). Auditory Stroop reveals implicit gender associations in adults and children. *Journal of Experimental Social Psychology*, **43**(2), 287–294. 58

Muir, D. and Field, J. (1979). Newborn infants orient to sounds. *Child development*, **50**(2), 431–436. 10

Mullane, J. C., Lawrence, M. a., Corkum, P. V., Klein, R. M., and McLaughlin, E. N. (2014). The development of and interaction among alerting, orienting, and executive attention in children. *Child neuropsychology : a journal on normal and abnormal development in childhood and adolescence*, **7049**, 1–22. 58

Muller-Gass, A. and Schröger, E. (2007). Perceptual and cognitive task difficulty has differential effects on auditory distraction. *Brain research*, **1136**, 169–177. 77

Münte, T. F., Spring, D. K., Szycik, G. R., and Noesselt, T. (2010). Electrophysiological attention effects in a virtual cocktail-party setting. *Brain research*, **1307**, 78–88. 41

Näätänen, R., Gaillard, A. W., and Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta psychologica*, **42**(4), 313–329. 42

Näätänen, R., Paavilainen, P., Rinne, T., and Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical Neurophysiology*, **118**(12), 2544–2590. 42

Näätänen, R., Porkka, R., Merisalo, A., Ahtola, S., Naatanen, R., Porkka, R., Merisalo, A., and Ahtola, S. (1980). Location vs. frequency of pure tones as a basis of fast discrimination. *Acta Psychologica*, **44**(1), 31–40. 78, 90, 118

Nardini, M., Bedford, R., and Mareschal, D. (2010). Fusion of visual cues is not mandatory in children. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(39), 17041–6. 93, 120

Norman, D. A. and Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive psychology*, **7**(1), 44–64. 112

Partanen, E., Kujala, T., Näätänen, R., Liitola, A., Sambeth, A., and Huotilainen, M. (2013). Learning-induced neural plasticity of speech processing before birth. *Proceedings of the National Academy of Sciences of the United States of America*, **110**(37), 15145–15150. 10

Pashler, H., Johnston, J. C., and Ruthruff, E. (2001). Attention and performance. *Annual review of psychology*, **52**(1), 629–651. 6

Pazo-Alvarez, O., Cadaveira, F., and Amenedo, E. (2003). MMN in the visual modality: a review. *Biological psychology*, **63**, 199–236. 42

Pearson (1986 thesis). *Rapid reorientation of attention in children with and without attention deficits*. PhD thesis, Rice University. 56

Pearson, D. A. and Lane, D. M. (1991). Auditory attention switching: A developmental study. *Journal of Experimental Child Psychology*, **51**(2), 320–334. 11

Petersen, S. E. and Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual review of neuroscience*, **35**, 73–89. 16, 22, 23, 70, 96, 116

Picton, T. W., Van Roon, P., Armilio, M. L., Berg, P., Ille, N., and Scherg, M. (2000). The correction of ocular artifacts: A topographic perspective. *Clinical Neurophysiology*, **111**(1), 53–65. 45

Plude, D. J., Enns, J. T., and Brodeur, D. (1994). The development of selective attention: A life-span overview. *Acta psychologica*, **86**(2), 227–272. 11, 21

Posner, M. I. and Petersen, S. E. (1990). The attention system of the human brain. *Annu. Rev. Neurosci*, **13**, 25–42. 16, 22, 70, 96, 116

Posner, M. I. and Rothbart, M. K. (2007). Research on attention networks as a model for the integration of psychological science. *Annu. Rev. Psychol.*, **58**, 1–23. 57

R Core Team (2012). R: A language and environment for statistical computing. 30

Rauschecker, J. P. and Tian, B. (2000). Mechanisms and streams for processing of "what" and "where" in auditory cortex. *Proceedings of the National Academy of Sciences of the United States of America*, **97**(22), 11800–11806. 36, 42, 52, 55, 98, 115

Rees, G., Frith, C. D., and Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science*, **278**(5343), 1616–1619. 10

Repp, B. H. (1977). Measuring laterality effects in dichotic listening. *The Journal of the Acoustical Society of America*, **62**(3), 720–737. 12

Ridderinkhof, K. R. and Molen, M. W. (1995). A psychophysiological analysis of developmental differences in the ability to resist interference. *Child Development*, **66**(4), 1040–1056. 12

Ridderinkhof, K. R., van der Molen, M. W., Band, G. P., and Bashore, T. R. (1997). Sources of interference from irrelevant information: a developmental study. *Journal of experimental child psychology*, **65**(3), 315–341. 58

Ridderinkhof, K. R. and Van der Stelt, O. (2000). Attention and selection in the growing child: Views derived from developmental psychophysiology. *Biological Psychology*, **54**(1-3), 55–106. 57, 92

Roberts, K. L. and Hall, D. A. (2008). Examining a supramodal network for conflict processing: a systematic review and novel functional magnetic resonance imaging data for related visual and auditory stroop tasks. *Journal of cognitive neuroscience*, **20**, 1063–1078. 23, 24

Roberts, K. L., Summerfield, A. Q., and Hall, D. A. (2006). Presentation modality influences behavioral measures of alerting, orienting, and executive control. *Journal of the International Neuropsychological Society*, **12**(04), 485–492. 22, 23, 28, 37, 38, 39, 41

Robertson, I. H., Ward, T., Ridgeway, V., and Nimmo-Smith, I. (1994). *The test of everyday attention*. Thames Valley Test Company, Bury St. Edmunds, UK. 29, 39

Robertson, I. H., Ward, T., Ridgeway, V., Nimmo-Smith, I., and Others (1996). The structure of normal human attention: The Test of Everyday Attention. *Journal of the International Neuropsychological Society*, **2**, 525–534. 22, 29, 30, 39

Roebuck, H. and Barry, J. G. (submitted). Listening difficulties and everyday listening: An interaction between attention and language weaknesses. . 95, 113, 121

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., and Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia*, **42**(8), 1029–40. 12, 56, 58, 60, 70

Sætrevik, B. (2012). The right ear advantage revisited: Speech lateralisation in dichotic listening using consonant–vowel and vowel–consonant syllables. *Laterality: Asymmetries of Body, Brain and Cognition*, **17**(1), 119–127. 11

Sams, M., Aulanko, M., Hamalainen, R., Hari, R., Lounasmaa, O., Lu, S., and Simola, J. (1991). Seeing speech: visual information from lip movements modifies activity in the human auditory cortex. *Neuroscience Letters*, **127**, 141–145. 42

Sawaki, R., Geng, J. J., and Luck, S. J. (2012). A common neural mechanism for preventing and terminating the allocation of attention. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, **32**(31), 10725–36. 43, 52

Sawaki, R. and Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: electrophysiological evidence for an automatic attend-to-me signal. *Attention, perception & psychophysics*, **72**(6), 1455–1470. 43, 52, 116

Schmithorst, V. J., Farah, R., and Keith, R. W. (2013). Left ear advantage in speech-related dichotic listening is not specific to auditory processing disorder in children: A machine-learning fMRI and DTI study. *NeuroImage: Clinical*, **3**, 8–17. 12

Schröger, E. and Wolff, C. (1998). Behavioral and electrophysiological effects of task-irrelevant sound change: a new distraction paradigm. *Brain research. Cognitive brain research*, **7**(1), 71–87. 42

Sharma, M., Dhamani, I., Leung, J., and Carlile, S. (2014). Attention, memory and auditory processing in 10-15 year old children with listening difficulties. *Journal of Speech, Language, and Hearing Research*, **57**(6), 2308–2321. 5, 13, 95, 96, 97, 112, 121

Sharma, M., Purdy, S. C., and Kelly, A. S. (2009). Comorbidity of auditory processing, language, and reading disorders. *Journal of speech, language, and hearing research : JSLHR*, **52**(3), 706–722. 12, 101

Shepp, B. E. and Barrett, S. E. (1991). The development of perceived structure and attention: Evidence from divided and selective attention tasks. *Journal of Experimental Child Psychology*, **51**(3), 434–458. 57

Shinn, J. B., Chermak, G. D., and Musiek, F. E. (2009). GIN (Gaps-In-Noise) performance in the pediatric population. *Journal of the American Academy of Audiology*, **20**(4), 229–238. 3

Shinn-Cunningham, B. G. (2008). Object-based auditory and visual attention. *Trends in cognitive sciences*, **12**(5), 182–186. 6, 7, 11, 21, 111, 115

Shinn-Cunningham, B. G. (2009). Object-based auditory and visual attention. *Trends in cognitive sciences*, **12**(5), 182–186.

Simonds, J., Kieras, J. E., Rueda, M. R., and Rothbart, M. K. (2007). Effortful control, executive attention, and emotional regulation in 7–10-year-old children. *Cognitive Development*, **22**(4), 474–488. 58

Slagter, H. A., Giesbrecht, B., Kok, A., Weissman, D. H., Kenemans, J. L., Woldorff, M. G., and Mangun, G. R. (2007). fMRI evidence for both generalized and specialized components of attentional control. *Brain Research*, **1177**, 90–102. 37

Smith, D. V., Davis, B., Niu, K., Healy, E. W., Bonilha, L., Morgan, P. S., and Rorden, C. (2010). Spatial Attention Evokes Similar Activation Patterns for Visual and Auditory Stimuli. *Journal of cognitive Neuroscience*, **22**(2), 347–361. 36

Smith, L. B. and Katz, D. B. (1996). Activity-dependent processes in perceptual and cognitive development. In Gelman, R. and Au, T. K.-F., editors, *Perceptual and Cognitive Development*, pages 413–445. Academic Press, San Diego, CA. 10

Smith, L. B., Kemler, D. G., and Aronfreed, J. (1975). Developmental trends in voluntary selective attention: Differential effects of source distinctness. *Journal of Experimental Child Psychology*, **20**(2), 352–362. 71, 92, 93

Spagna, A., Mackie, M.-A., and Fan, J. (2015). Supramodal executive control of attention. *Frontiers in Psychology*, **6**(February), 1–14. 23, 24, 38

Spence, C. (2001). Crossmodal attentional capture: a controversy resolved? In Folk, C. and Gibson, B., editors, *Attention, Distraction and Action: Multiple Perspectives on Attentional Capture*, pages 231–262. Elsevier Science BV, Amsterdam. 23

Spence, C. and Driver, J. (1996). Audiovisual links in endogenous covert spatial attention. *Journal of experimental psychology. Human perception and performance*, **22**(4), 1005–1030. 23

Spence, C. and Santangelo, V. (2010). Auditory attention. *Oxford Handbook of Auditory Science: Hearing*, **3**, 249–270. 8

Stevens, C. and Bavelier, D. (2012). The role of selective attention on academic foundations: A cognitive neuroscience perspective. *Developmental Cognitive Neuroscience*, **2**(Suppl 1), 1–32. 6

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, **18**, 643–662. 43, 57

Sturm, W. and Willmes, K. (2001). On the functional neuroanatomy of intrinsic and phasic alertness. *Neuroimage*, **14**(1), S76–S84. 23

Sussman, E. and Steinschneider, M. (2009). Attention effects on auditory scene analysis in children. *Neuropsychologia*, **47**(3), 771–785. 111

The MathWorks (2008). MATLAB 7.6. 25

Treisman, A. and Geffen, G. (1967). Selective attention: perception or response? *The Quarterly journal of experimental psychology*, **19**(1), 1–17. 8

Treisman, A. M. (1960). Contextual cues in selective listening. *Quarterly Journal of Experimental Psychology*, **12**(4), 242–248. 8

Turatto, M., Benso, F., Galfano, G., and Umiltà, C. (2002). Nonspatial attentional shifts between audition and vision. *Journal of Experimental Psychology: Human Perception and Performance*, **28**(3), 628–639. 36, 42

Watson, C. S. and Kidd, G. (2006). Associations Between Auditory Abilities, Reading and Other Language Skills, in Children and Adults. In Cacace, A. T. and Mcfarland, D. J., editors, *Controversies in Central Auditory Processing Disorder*, chapter 13, pages 217–242. Plural Publishing. 3, 13

Watson, C. S., Qiu, W. W., Chamberlain, M. M., and Li, X. (1996). Auditory and visual speech perception: confirmation of a modality-independent source of individual differences in speech recognition. *The Journal of the Acoustical Society of America*, **100**(2), 1153–1162. 3

Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence*. Psychological Corporation. 101

Werner, L. A. (2007). Issues in human auditory development. *Journal of Communication Disorders*, **40**(4), 275–283. 11

Wertheimer, M. (1961). Psychomotor coordination of auditory and visual space at birth. *Science*, **134**(3491), 1692–1692. 10

West, R. (2003). Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. *Neuropsychologia*, **41**, 1122–1135. 43, 44, 53

West, R. and Alain, C. (1999). Event-related neural activity associated with the Stroop task. *Cognitive brain research*, **8**(2), 157–164. 43, 44, 53

Woldorff, M. G. and Hillyard, S. A. (1991). Modulation of early auditory processing during selective listening to rapidly presented tones. *Electroencephalography and Clinical Neurophysiology*, **79**(3), 170–191. 6

Wood, N. and Cowan, N. (1995). The cocktail party phenomenon revisited: how frequent are attention shifts to one's name in an irrelevant auditory channel? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **21**(1), 255–260. 8

Woods, D. L. and Alain, C. (2001). Conjoining three auditory features: an event-related brain potential study. *Journal of cognitive neuroscience*, **13**(4), 492–509. 78, 90, 118

Zachariou, V., Klatzky, R., and Behrmann, M. (2013). Ventral and Dorsal Visual Stream Contributions to the Perception of Object Shape and Object Location. *Journal of Cognitive Neuroscience*, **26**(1), 189–209. 36

Zelazo, P. D., Frye, D., and Rapus, T. (1996). An age-related dissociation between knowing rules and using them. *Cognitive development*, **11**(1), 37–63. 69, 117

Zhang, Y.-X., Barry, J. G., Moore, D. R., and Amitay, S. (2012). A New Test of Attention in Listening (TAIL) Predicts Auditory Performance. *PloS one*, **7**(12), e53502. 12, 15, 16, 21, 23, 70, 78, 116