Auditory Processing, Attention and Memory in School Aged Children with Listening Difficulties in Noise

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Contents

Declaration

I certify that the work in this thesis entitled "**Auditory Processing, Attention and Memory in School Aged Children with Listening Difficulties in Noise**" has not been previously submitted for a degree nor it has been submitted as a part of requirements for a degree to any other university or institution other than Macquarie University. I also certify that thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. The research presented in the thesis was approved by Macquarie University Ethics Review Committee, reference number: **5201000678** on 11th November 2010.

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Thesis Abstract

In this research we aimed to investigate auditory processing, attention and memory skills in children (10-15 years) with persistent listening difficulties in background noise despite having clinically normal hearing sensitivity. We conducted 3 studies in this research project. Study 1 was aimed to design or modify tasks to assess selected auditory processing abilities that are considered important for listening in noise but not routinely assessed in clinics. In study 2 we designed a novel task to examine the auditory selective attention and attention switching ability. Auditory processing ability was also assessed using a set of clinically recommended as well as the additional tasks designed in the study 1. The results were suggestive of poor attention switching and inhibitory control ability in the LD group. In the study 3, we invited more children with listening difficulties in background noise (LD group; n=21) and assessed them in three phases. First, we examined their attention switching ability using the task designed in the second study. The results were consistent with those in the early study. Secondly, we tested them on a set of recommended clinical tests to identify the presence of an auditory processing disorder (APD). The results indicated that five children could be diagnosed with APD (APD group) and were considered separately for further comparisons. Lastly, we evaluated both the LD and APD groups on additional tasks to examine their auditory processing as well as short term and working memory ability and found poor frequency resolution and working memory skills for the APD group. In summary, all the children who reported with listening difficulties in noise showed deficits in their attention switching and inhibitory control ability which may suggest a possible top down (central) information processing deficit in these children.

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Overall Introduction

Listening, in contrast to hearing can be referred to as a conscious process by which we attach meaning to the sounds that we hear (Nichols, 1947; Parrott, 1984). It denotes the act of understanding and making sense of the auditory information which requires attention, orientation and focus (Roth, 2012). Listening is an essential skill especially for school aged children in order for them to understand the information provided to them in classrooms and other learning environments. Noise which consists of speech and/or non-speech sounds is present as a potential distractor in a majority of listening situations (Crandell & Smaldino, 2000; Shield & Dockrell, 2008).

Previous studies have reported that some children despite having clinically normal hearing sensitivity may have a difficulty in listening to speech especially in presence of background noise(Hind et al., 2011; Lagacé, Jutras, & Gagné, 2010; Moore, 2012; Moore, Rosen, Bamiou, Campbell, & Sirimanna, 2012). It has been suggested that these children may have a deficit in auditory processing ability that lead to their listening difficulties (Bamiou, Musiek, & Luxon, 2001; Chermak, Tucker, & Seikel, 2002; Keith, 1999; Lagacé, et al., 2010; Moore, 2011; Moore, et al., 2012; Musiek & Chermak, 1995). Recent studies, however, also suggest a possible involvement of deficits in cognitive abilities such as attention and memory in this population (Moore, 2011; Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010; Moore, et al., 2012).

The main aim of this study was to evaluate children who reported persistent listening difficulties in presence of background noise for their auditory processing, attention and memory ability. Auditory processing is a broad term that encompasses spectral, temporal and binaural processing abilities (American Academy of Audiology, 2010; Catts et al., 1996). Spectral processing involves skills such as frequency resolution, intensity resolution and frequency selectivity (Moore, 1997; Moore, 1987) while temporal processing involves integration, sequencing and resolution skills (Shinn, 2003). Binaural processing requires integration, interaction and localization skills (Catts, et al., 1996; Moore, 1991). Various clinical tests have been designed and recommended to assess some of these processing skills in populations with listening difficulties (American Speech-Language-Hearing & Association, 2005; Moore, et al., 2010; Moore, 2012). Currently, however, test battery selection for populations with listening difficulties lacks a gold standard (Musiek, Bellis, & Chermak, 2005; Schow, Seikel, Chermak, & Berent, 2000). However, various guidelines (American Academy of Audiology, 2010; Catts, et al., 1996) do exist on the diagnostic approach. While these guidelines have some differences in their approach or philosophy, there are similarities as well. All guidelines suggest a test battery approach that targets spectral, temporal and binaural skills assessment. In this research we have taken the viewpoints of the various guidelines and explored new tasks in addition to the commonly used (Emanuel, 2002; Emanuel, Ficca, & Korczak, 2011) and recommended clinical tests to determine the spectral, temporal and binaural processing skills for children with listening difficulties.

The recommended clinical tests (American Academy of Audiology, 2010) that we used were the frequency pattern (Musiek, 2002), dichotic digits (Musiek, Gollegly, Kibbe, & Verkest-Lenz, 1991), gap detection in noise (Jerger & Musiek, 2000), masking level difference(Wilson, Moncrieff, Townsend, & Pillion, 2003) and listening in spatialized noise(Cameron & Dillon, 2007) tests while the additional tests assessed auditory stream segregation(Darwin, 2008; McDermott, 2009), frequency resolution (Darwin, 2008; Peters, Moore, & Baer, 1998), localization (Bronkhorst, 2000; Grothe, Pecka, & McAlpine, 2010; Hawley, Litovsky, &Culling, 2004; Kerber & Seeber, 2012) as well as temporal envelope and fine structure perception (Rosen, 1992; Zeng et al., 2004) skills. The rationale for inclusion of the additional tests has been discussed in the chapter 3. Although the assessment of all of these additional skills has been suggested by various guidelines for populations with listening difficulties, the tasks to assess them have not yet been transformed for routine clinical use (American Academy of Audiology, 2010; Catts, et al., 1996; Jerger & Musiek, 2000).

In addition to the assessment of auditory processing skills, a majority of clinical guidelines also suggest evaluation of attention and memory abilities in populations with listening difficulties (Cacace & McFarland, 2009; Cacace & McFarland, 1998; Jerger & Musiek, 2000; Keith, 1999; Moore, 2006; Moore, et al., 2012). Attention (George et al., 2007; Houtgast & Festen, 2008; Mattys, Davis, Bradlow, & Scott, 2012) and memory (Conway, Cowan, & Bunting, 2001; Meister et al.; Rönnberg, Rudner, Lunner, & Zekveld, 2010) have also been suggested to play an important role in understanding speech in presence of background noise.

Attention can be classified into various forms such as phasic alertness, selective attention, divided attention, sustained attention and attention switching (Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000; Sturm, Willmes, Orgass, & Hartje, 1997). Amongst these forms of attention, a majority of studies have evaluated sustained attention for children with listening difficulties (Riccio, Cohen, Hynd, & Keith, 1996; Sharma, Purdy, & Kelly, 2009) except a few (Martin, Jerger, & Mehta, 2007; Moore, 2010). Selective attention and attention switching ability have been suggested to be crucial for listening especially in situations involving background noise or multiple talkers (Bronkhorst, 2000; Koch, Lawo, Fels, & Vorländer, 2011; McDermott, 2009; Shinn-Cunningham & Best, 2008). In the current study, in addition to assessing sustained attention, we also designed a task to evaluate selective attention and attention switching abilities for the participants.

Auditory short term and working memory ability has also been suggested to be important for listening in noise by temporary storage and processing of the auditory information in order to form coherent information representations across time while ignoring irrelevant distraction

(Conway, et al., 2001; Kraus, Strait, & Parbery-Clark, 2012; Lunner, 2003; Meister, et al.; Pichora-Fuller, Schneider, & Daneman, 1995; Rudner, Lunner, Behrens, Sundewall Thorén, & Rönnberg, 2012). We used a digit span test in the current study to evaluate short term and working memory ability for the participants.

Children aged between 10-15 years, who reported listening difficulty in presence of background noise (LD group) as well as those without listening difficulty (Control group) were invited to participate in this study. Overall, 12 adults and 15 children with no listening difficulty and 21 children with listening difficulty in background noise participated in the study. All children in the LD group had a history of recurrent OME. On the basis of a clinical test battery consisting of recommended tests, five out of the twenty one children from the LD group could be diagnosed as APD and were considered separately for comparisons (APD).

The overall results indicated that all the children who reported with listening difficulties in noise (LD and APD group) had deficits in their attention switching and inhibitory control ability suggesting a possible top down information processing deficit in these children. Additionally, the APD group also showed poor frequency resolution and working memory. In summary, the results suggest the need to include tasks to assess attention switching, frequency resolution and memory abilities in the clinical test battery for populations with listening difficulties Further research is required in order understand the underlying cause of such deficits and to contemplate training and management programmes based on these novel findings.

Organization of Thesis

The referencing style for the two papers that consisted of Chapter 2 and Chapter 4 were kept similar to that of the published paper (Chapter 3), whereas for other sections of the thesis, we used the recommended by the American Psychological Association (6^{th} edition).

The overall thesis has been divided into 4 chapters namely:

Chapter 1

In this chapter, we briefly discuss about the recommended and routinely used clinical tests that are used to evaluate children with listening difficulties. The evaluation has been discussed in 3 domains namely 1) Interview and Questionnaire 2) Auditory processing assessment and 3) Cognitive assessment.

Chapter 2

This chapter consists of the study in which we tested a group of children (n=15; 10-15 years) and adults (n=12; 18-30 years) with no reported listening difficulty and clinically normal hearing sensitivity in order to collect performance benchmarks for the newly designed tasks for assessing auditory processing skills. The tasks included in this study aimed to examine skills such as frequency resolution, auditory stream segregation, localization and temporal envelope perception. The results indicated no significant differences between the 2 groups for any of the tasks used in the assessment. The findings from this study suggested that the performance of children with adult-like for all the tasks used in this experiment and were consistent with the findings of some of the earlier studies.

Chapter 3

This chapter consists of a published study (Dhamani, Leung, Carlile, & Sharma, 2013) (published version attached as pdf format in the appendix) in which we designed a test to assess auditory selective attention and attention switching ability in children with reported persistent listening difficulty in background noise. The main aim was to assess these two abilities for children (n=12, 10-15 years) who reported with listening difficulties in presence of background noise. The results indicated substantially longer attention re-orientation time and higher false alarm rate in children with listening difficulties compared to age matched controls. The findings were suggestive of poor attention switching and inhibitory control abilities in children with listening difficulties.

Chapter 4

This chapter includes the study in which we invited more children who reported with listening difficulties in presence of background noise (n=21; 10-15 years) with an aim to evaluate their attention, memory and auditory processing abilities. The study was conducted in 3 phases.

In phase 1, we tested the participants for their attention switching ability using the same test used in study 2. The results were consistent with our previous findings and indicated notably longer attention re-orientation time and false alarm rates for children with listening difficulties compared to the controls. Phase 2 of the study involved administration of a set of recommended clinical tests on the participants in order to identify the presence of an APD amongst the children with listening difficulties. The results of this phase indicated that a relatively small subset of children (n=5) amongst those with listening difficulties could be diagnosed with APD. Based on these findings we further divided the children with listening difficulties in 2 subgroups namely those with (APD group) or without APD (LD group) for further testing in phase 3. In phase 3, we assessed the 3 groups of participants (Control, LD and APD) for additional tasks to assess their auditory localization, frequency resolution, temporal envelope/fine structure perception, stream segregation, short term memory and working memory abilities. The results revealed poor frequency resolution and short working memory ability for the APD group in comparison to the other 2 groups. There was no significant difference between the LD and Control group for any of the tasks. In summary, the results of this study suggested attention switching and inhibitory control deficits in all the children who reported listening difficulties. Additionally a subset of these children who had APD also showed poor frequency resolution and working memory ability.

Author contributions

Imran Dhamani and Mridula Sharma conceived the concept for the overall research project. Imran Dhamani, Johahn Leung and Simon Carlile designed the selective attention and attention switching task. Imran Dhamani with the help of Mridula Sharma, Johahn Leung and Simon Carlile designed the auditory sequential stream segregation, localization, frequency discrimination and amplitude modulation detection tasks. Imran Dhamani recruited the participants and collected the data. Imran Dhamani performed the analysis of the data with inputs from Mridula Sharma, Johahn Leung and Simon Carlile. The manuscript for study 1 (Chapter 2) was prepared by Imran Dhamani with inputs from Mridula Sharma. The manuscript for study 2 (Chapter 3) was mainly prepared by Imran Dhamani and Johahn Leung with input from Simon Carlile and Mridula Sharma. The manuscript for study 3 (Chapter 4) was mainly prepared by Imran Dhamani and Mridula Sharma with inputs from Simon Carlile and Johahn Leung.

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Chapter 1

Audiological Assessment of Children with Listening Difficulties

Audiological Assessment of Children with Listening Difficulties

In this chapter, we will mainly discuss the abilities and skills that are routinely evaluated in audiology clinics for children who report with listening difficulties despite having clinically normal hearing sensitivity. In addition to this, we will also briefly mention about the other skills which, although crucial for listening, have not yet become part of the routine clinical test battery.

Listening to a single talker in a noisy background is one of the complex tasks that we accomplish with relative ease in most communication settings consisting of a complex mixture of speech and non-speech sounds. This is, however, not the case for some children who in spite of having normal hearing sensitivity, have persistent listening difficulties, and find it extremely challenging to listen effectively against distraction in their day to day listening environments such as classrooms (Hind et al., 2011; Lagacé, Jutras, & Gagné, 2010; Moore, Rosen, Bamiou, Campbell, & Sirimanna, 2012). The comprehensive evaluation of children who report with such listening difficulties has been suggested by various clinical guidelines to involve a multi-disciplinary team approach which involves assessment of cognitive, linguistic and auditory processing abilities (Canadian Association of Speech-Language Pathologists and Audiologists, 2012; American Academy of Audiology, 2010; British Society of Audiology, 2011).

The assessment of auditory processing abilities is usually done by audiologists through a battery of clinical tests (Emanuel, 2002; Jerger & Musiek, 2000; Moore, 2012; Moore, et al., 2012). If the children perform poorly on these clinical tests, then they are usually diagnosed as having an auditory processing disorder (APD). APD has been defined as a difficulty in processing auditory information via the central auditory nervous system and the associated neurobiological activity (American Academy of Audiology, 2010; Emanuel, 2002; Jerger

&Musiek, 2000; Moore, 2012; Moore, et al., 2012; Musiek et al., 2010). Although the exact aetiology of APD is still under debate (Cacace & McFarland, 1998; Dawes, Bishop, Sirimanna, & Bamiou, 2008), it has been suggested that APD is often associated with neurological conditions such as tumours, cerebrovascular disorders, infections and seizures; delayed central nervous system maturation; or other developmental disorders (Bamiou, Musiek, & Luxon, 2001; Catts et al., 1996; Moore, et al., 2012; Sharma, Purdy, & Kelly, 2009).

Clinical guidelines (Canadian Association of Speech-Language Pathologist and Audiologists, 2012; American Academy of Audiology, 2010; British Society of Audiology, 2011) have been suggested for different countries regarding the test battery that should be used for evaluating auditory processing ability but, to date there is no universal gold standard for the tests that need to be included in the test battery (Dawes, et al., 2008; Moore, 2006). The evaluation of auditory processing ability in children that is routinely performed in clinics (Emanuel, 2002; Emanuel, Ficca, & Korczak, 2011) can mainly be divided into 3 domains namely 1) Interview and Questionnaire 2) Behavioural tests 3) Electrophysiological tests.

Interview and Questionnaire

An interview with the parents and the child is of significant importance in order to acquire information regarding the main complaint, related symptoms as well as the presence of other co-morbid conditions such as dyslexia, autism, attention deficit disorder or language impairment. The interview usually involves collecting a detailed medical, social and academic history of the child. The history-taking process also includes procuring information regarding the child’s developmental milestones, family history of hearing difficulties, psychological aspects, auditory behaviour as well as cultural and linguistic background. This information is often useful for the clinicians in order to avoid any influence of extraneous factors during the subsequent testing. In addition to the interview, the administration of a questionnaire involving rating and/or description of the listening and other related difficulties for a range of different situations has also been shown to be an important aspect of the assessment (Cacace & McFarland, 1998; Dawes, et al., 2008; Jerger & Musiek, 2000; Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010). Recent literature has emphasized the importance of parental report and questionnaire for the diagnosis of listening difficulties in children (Dillon, Cameron, Glyde, Wilson, & Tomlin, 2012; Moore, et al., 2012). Additionally, checklists based on auditory and listening behaviour rating are also available for screening children for APD such as the Children's auditory performance scale (Smoski, Brunt, & Tannahill, 1992) and the Fisher's auditory processing checklist (Willeford & Burleigh, 1985).

Behavioural Tests

One of the main aims of administering these tests is to identify the children who have auditory processing difficulty compared to those who don't have such difficulty. The basic understanding in the comprehensive evaluation of auditory processing abilities for children is to get their best response after minimizing the confounding factors like environmental distraction, motivation, attention and fatigue (American Academy of Audiology, 2010; Dillon, et al., 2012; Moore, 2011). A majority of behavioural tests that are used in clinics for diagnosis of APD were initially developed to identify lesions in the central auditory nervous system for adults and were gradually transformed to clinical use in testing children with listening difficulties (Chermak & Musiek, 2011; Dillon, et al., 2012). The approach towards behavioural assessment of children for APD is usually based on the assumption of a developmental immaturity or abnormality of the central auditory system (Keith & Jerger, 1991; Keith, 2000b). The behavioural tests that are used for clinical assessment mainly aim to examine abilities such as spectral, temporal and binaural processing as well as speech recognition in degraded or competing noise situations (Canadian Association of Speech-

Language Pathologists and Audiologists, 2012; American Academy of Audiology, 2010; British Society of Audiology, 2011). There is still some ongoing debate on the issue of use of verbal tasks that involve linguistically loaded test materials for behavioural assessment (Catts, et al., 1996; Moore, 2012; Moore, Rosen, Bamiou, Campbell, & Sirimanna, 2013). Despite lack of consensus about the type of stimuli to be used in testing, many clinicians still use a combination of speech and non-speech materials in the test battery (Emanuel, 2002; Emanuel, et al., 2011). The interpretations of the results of clinical tests are based on comparisons with age appropriate normative data which are available for most tests that are commercially available. Various diagnostic criteria have been suggested in literature in order to decide abnormality of scores (Wilson & Arnott, 2013). These criteria range from a strict (two standard deviations below the mean of the normative data for both the ears on at least two or more tests - American Academy of Audiology, 2010) to a relatively lenient (two standard deviations below the normative mean in at least one ear on any one of the behavioural tests - Dawes & Bishop, 2009) criterion. There is however, still a lack of a universally accepted diagnostic criterion for APD (Wilson & Arnott, 2013).

Spectral processing

Spectral processing refers to the analysis of the absolute and relative changes in the sound spectrum and is frequently assessed by examining the frequency and intensity resolution skills (Moore, 2003). Frequency resolution skill relates to the ability of the listener to analyse and discriminate the different frequency components of the auditory signal and can be assessed using tasks to measure frequency discrimination and psychophysical tuning curves (Moore, 1995). Intensity resolution on the other hand is the ability of the listener to detect subtle intensity related changes and can be assessed through tasks that measure intensity discrimination. The assessment of frequency and intensity resolution skills has not yet been popular in clinical test batteries for assessing children with listening difficulties (American

Academy of Audiology, 2010; Emanuel, et al., 2011). Although most of the clinical guidelines and position statements for evaluation of APD emphasize the importance of assessing spectral processing ability, there is a lack of valid clinical tests to assess this ability (Canadian Association of Speech-Language Pathologists and Audiologists, 2012; American Academy of Audiology, 2010; British Society of Audiology, 2011).

Temporal processing

The analysis of the slow and rapid changes in the spectrum of sound across time is known as temporal processing (Moore, 1997). Temporal processing ability encompasses skills such as sequencing, resolution, integration and masking (Shinn, 2003). Temporal sequencing is the process of stringing together ongoing streams of complex sounds, based on their time of occurrence, in order to perceive coherent streams of information (Fitzgibbons & Gordon-Salant, 1998; Shinn, 2003). It is commonly assessed in clinics using pattern perception tasks such as frequency and duration pattern tests in which children are asked to verbalize the order of a sequence of three tones that may vary in pitch or duration (Musiek, 2002; Musiek, Baran, & Pinheiro, 1990). Temporal resolution, on the other hand, is the ability of a listener to discriminate sounds based on the time gap between them as well as to process the slow and fast moving (envelope and fine structure) changes in the sound spectrum across time (Shinn, 2003). Clinical assessment of temporal resolution usually involves gap detection (Dias, Jutras, Acrani, & Pereira, 2011; Musiek et al., 2005; Phillips, Comeau, & Andrus, 2010) tasks.

Temporal integration refers to the ability of the listener to integrate sound energy within a certain time window (200-300 ms), thus leading to summation and overall increase in sound intensity (Moore, 1987; Shinn, 2003). Temporal integration can be assessed using tasks that measure and compare the audibility of signals at short and long durations. To date however, there are no clinical tests available to evaluate temporal integration skills in children (American Academy of Audiology, 2010).

The change in the detectability of a sound due to the presence of another stimulus presented immediately before or after it is called temporal masking (Moore, 1997; Moore, 1987). Earlier studies have examined temporal masking for children with listening difficulty using tasks that involved examining the effect of forward or backward masking on the detection of target sounds (Rosen, Cohen, & Vanniasegaram, 2010; Vanniasegaram, Cohen, & Rosen, 2004). However, these tasks have not yet been popular in routine clinical evaluations (Emanuel, 2002; Emanuel, et al., 2011).

Binaural processing

Binaural processing involves the analysis of cues, such as inter-aural time and intensity differences, that are generated due to the presence of two ears (Moore, 1991). These cues assist in locating the sound source in space, integrating information received from the two ears to make a coherent stream of information as well as separating speech from noise (Akeroyd, 2006; Durlach, Thompson, & Colburn, 1981). Binaural processing can be evaluated by tasks that measure spatial localization, dichotic listening and binaural release from masking (Catts, et al., 1996; Parthasarathy, 2006). Spatial localization is the ability of a listener to identify the location of a sound source in space and has been traditionally been examined in literature using target localization tasks with or without the presence of a masker (Kopčo, Best, & Carlile, 2010; Middlebrooks & Green, 1991). Although it is one of the crucial auditory processing skills that facilities listening especially in presence of distractors, valid clinical tests for assessing localization are still not available for testing children with listening difficulties (American Academy of Audiology, 2010).

Binaural release from masking is usually assessed in audiology clinics using a task that involves the detection of a low frequency pure tone in presence of noise (Emanuel, et al., 2011; Kelly-Ballweber & Dobie, 1984; Wilson, Moncrieff, Townsend, & Pillion, 2003). The signal threshold that is obtained from the listener is compared in different masking conditions. These masking conditions involve determining the threshold of the signal when it is either in phase (SoNo condition) or out of phase (SpiNo condition) with the masker in the two ears. The masking level difference is usually calculated by subtracting the threshold obtained in the SpiNo condition from that obtained in the SoNo condition. Another clinical test which also aims to assess binaural masking release has recently become commercially available (Cameron & Dillon, 2007a). This test involves comparison of speech recognition thresholds in presence of spatially separated and co-located competing talkers.

Listening in presence of degraded or competing acoustic signals

Speech perception in presence of challenging listening situations such as background noise is one of most common complaints in children with listening difficulties (Dawes, et al., 2008; Lagacé, et al., 2010). It is thus important for the inclusion of tests that examine the ability to listen in difficult situations such as in presence of acoustical distortions and competing signals. The behavioural tests that are designed to assess this ability often involve perception of speech sounds which are distorted in their spectral or temporal characteristics to reduce the redundancy of the stimulus through manipulations such as filtering (Bornstein, Wilson, & Cambron, 1994), time compression (Beasley, Schwimmer, & Rintelmann, 1972) and reverberation (Wilson, Preece, Salamon, Sperry, & Bornstein, 1994). Additionally, some tests also involve speech perception in presence of competing distraction such as noise (Bentler, 2000; Decker & Nelson, 1981; Jerger, 1987; Keith, 2009).

Electrophysiological tests

As electro-physiological tests are mainly based on measurement of objective responses, they have immense potential for use in early identification of APD (American Academy of Audiology, 2010; Jirsa, 1992; Jirsa & Clontz, 1990). Auditory evoked potential (AEP) measurement is one of the most commonly utilized electro-physiologic assessment tools in audiology clinics. Based on their time of occurrence, AEPs are usually categorized into 3 different types, namely short, middle and late latency potentials (Burkard, Don, & Eggermont, 2006). While the short latency potentials are mainly used to examine auditory processing at the level of auditory nerve and brainstem, the middle and late latency potentials are used to assess higher level processing of sounds at the midbrain and cortical level (Burkard, et al., 2006). Currently, however, there are no set clinical protocols for recording and measurement of AEPs with regards to auditory processing assessment (American Academy of Audiology, 2010). Moreover, there is a lack of normative data with respect to the amplitude and latency of occurrence of the different types of AEPs for different age groups of children (American Academy of Audiology, 2010). Despite these drawbacks, AEP measurement is often suggested to be useful in children who are suspected to have APD (Keith, 2000b; Parthasarathy, 2006). Recent studies have also suggested the potential for using speech in contrast to non-speech stimulus in identifying children with auditory processing disorders (Hornickel & Kraus, 2011; Johnson, Nicol, & Kraus, 2005; Rocha-Muniz, Befi-Lopes, & Schochat, 2012).

Summary

A comprehensive evaluation of listening difficulties in children should include the assessment of auditory processing, cognitive and linguistic skills. Such an evaluation usually requires a multi-disciplinary team approach that involves health professionals such as audiologist, paediatrician, speech-language pathologist, psychologist and general practitioner. The audiological assessment of listening difficulties in children mainly comprises of evaluation of auditory processing ability. Parental and child interview which also involves taking a detailed medical, social and academic history is an important aspect of auditory processing evaluation. Currently the diagnosis of APD is based on poor performance on a range of behavioural tests that have been designed to assess specific auditory processing skills. A poor performance on these set of tests is suggestive of APD. Currently, there is no gold standard for which tests to be included in the test battery as well as for the diagnostic criterion. Overall, there is still a need for further research in order to develop suitable clinical tests to assess children with listening difficulties as well as to set universal gold standards for diagnosis and evaluation.

Table 1: This table summarizes some of the routinely administered clinical tests for auditory processing assessments

Ability	Tests
Spectral processing	Wepman's auditory discrimination (Reynolds, 1987) Goldman-Fristoe-Woodcock test of auditory discrimination (Goldman, 1970)
Temporal processing	Random gap detection (R. W. Keith, 2000a) Gap detection in noise (Musiek, et al., 2005) Auditory fusion (McCroskey & Keith, 1996) Frequency pattern (Musiek, 2002) Duration pattern (Musiek, et al., 1990)
Binaural processing	Dichotic digits (Musiek, 1983) Binaural fusion (Hayashi, Ohta, & Morimoto, 1966) Rapidly alternating speech perception (Bellis, 2003) LISN-S (Cameron & Dillon, 2007a) Masking level difference test (Wilson, et al., 2003)
Listening in presence of degraded and competing acoustic signals	Synthetic sentence identification (Decker & Nelson, 1981) Paediatric speech intelligibility (S. Jerger, 1987) Speech in Noise (Bentler, 2000) Low pass filtered speech (Bellis, 2003) High pass filtered speech (Bellis, 2003) NU6- time compressed speech (Grimes, Mueller, & Williams, 1984) SCAN- Filtered words (Amos & Humes, 1998) SCAN- Auditory figure ground (Amos & Humes, 1998) NU6 – time compressed speech with reverberation (Baran et al., 1985)

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Chapter 2 (Study 1)

Evaluation of Selected Auditory Processing Abilities in School-aged Children and Adults

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Evaluation of selected auditory processing abilities in school-aged children and adults

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Abstract

The present exploratory study was conducted on a group of adult and child participants to test for auditory stream segregation, localization, frequency resolution and temporal envelope perception ability. All these abilities are known to be crucial for understanding speech in noise. The main aim of this study was to design tasks to assess these abilities in children with listening difficulties and to collect performance benchmarks. Twelve adults (18-30 years) and fifteen children (10-15 years), with clinically normal hearing sensitivity and no reported listening difficulty, participated in this study. The results indicate no significant differences between the adults and children for any of these tasks suggesting that these processes assessed through these tasks may operate similarly in children and adults.

Key words:

Auditory stream segregation, localization, frequency resolution,

Introduction

The main aim of this study was to design tasks to assess a selected set of auditory processing abilities in school aged children who despite having normal hearing sensitivity report of listening difficulties especially in presence of background noise. Although all the abilities that were evaluated as part of this study have been suggested to be crucial for listening in presence of background noise, appropriate tasks to assess them have not yet become part of the routine clinical test battery used to assess children with listening difficulties. The rationale for the selection of the abilities and tasks is as follows.

Auditory stream segregation is an important ability which facilities listening by the separation of different stream of auditory information in a noisy environment based on the various spectral, temporal and binaural cues[1,2]. The separation of information overlapping in time is usually referred to as simultaneous stream segregation whereas the separation which occurs sequentially across time is termed as sequential stream segregation[3]. Sequential stream segregation involves grouping of sounds that arise from the same source across time[4,5]. Previous studies have suggested sequential stream segregation to be important to understand speech in noise[2,6-8]. Amongst the various cues that facilitate sequential stream segregation, pitch cues have been suggested to be of foremost importance[7,9-11]. The ABA_ paradigm[12] is one of the most commonly used tasks to examine auditory sequential stream segregation ability and focusses on measuring the temporal coherence or segregation boundary. In the present study, we designed a task based on the ABA_ paradigm in order to measure temporal coherence boundary. The task was designed in such a way as to predominantly provide only pitch based cues to the participants for segregation of streams.

Auditory localization refers to the identification of the location of sound source in space which is an important ability to understand speech in presence of background noise[13]. A majority of real life listening environments require identification of the location of the relevant talker in presence of distracters. In spite of its ecological validity, very few studies have examined localization of speech stimulus in presence of noise or competing talkers[14-17]. In the present study, we focussed on designing a task to examine localization of a speech stimulus (syllable) in presence of competing maskers using a single-source localization task in free-field.

Frequency resolution is the ability to discriminate between two difference frequencies[72] and has often been reported to be an area of difficulty for individuals who have listening difficulty in noisy backgrounds[18,19]. It is commonly examined by tasks that measure auditory filter shapes or frequency discrimination thresholds[20,21]. The measurement of auditory filter shapes is usually a lengthy and tedious task demanding substantial vigilance and thus may not be suitable for children[22]. We thus designed a task to measure frequency discrimination thresholds. Earlier studies have measured frequency discrimination using tasks that utilize relatively long (≥200 ms) in contrast to short duration sounds[23-27]. The ability to discriminate short duration sounds (< 200 ms) based on their frequency differences is important in processing transient cues in the speech signal such as voice onset time, formant transitions, plosive burst duration and aspirations[23,28] and is thus crucial to understanding speech in noisy backgrounds. We thus aimed at designing a task to measure the frequency discrimination thresholds for short duration (100 ms) pure tones.

Temporal envelope perception refers to the analysis of the relatively slow fluctuations in the overall amplitude (2-500 Hz) of sounds and has been suggested to facilitate the processing of auditory cues in speech such as manner of articulation, voicing and prosodic information including intonation and stress[29,30]. Amplitude modulation detection has been one of the tasks commonly used in the literature to examine temporal envelope processing ability[31-33]. In the present study, we thus designed an amplitude modulation detection task to assess the temporal envelope processing ability for the participants.

Method

Participants

Twelve adults (18-30 yrs., Mean age- 25.16±2.31 yrs.) and fifteen children (10-15 yrs., 12.53±0.40 yrs.) with no reported listening difficulty (normal adults and children) participated in this study. All subjects spoke Australian English as their first language and had normal hearing sensitivity (250-8000 Hz) as assessed using pure-tone audiometry. None of the participants presented with a middle ear pathology at the time of testing which was confirmed by clinically normal findings for otoscopy, tympanometry and acoustic stapedial reflex thresholds. Medical history did not suggest any history of ADHD or middle ear infections.

Procedure

A short questionnaire was given to the adult participants and the parents of the child participants to procure information regarding their academic, hearing, listening and behavioural history. Each test session was of 3 hours duration and all the testing was distributed across 3 sessions within 2 weeks duration. Care was taken to avoid participant fatigue and loss of motivation by constant engagement with the participants and positive reinforcement. We also ruled out the presence of a auditory processing disorder for all the participants by comparing their performance with previously published age based normative data[34,35] on a set of clinical tests recommended by the American Academy of Audiology (2010)[36].The test order was randomized and counter-balanced to avoid any bias. Informed consent was obtained from all the participants and the study was conducted in compliance with the guidelines of the Human Research Ethics committee at Macquarie University. All the sounds used in the experiments were generated on a PC at 48000 Hz sampling rate (16 bits) and routed via a USB based computer sound interface (RME Fireface 400) connected to headphones (Beyerdynamic DT 990 pro) or loudspeakers (Audience A3/Tannoy V6).

Auditory Stream Segregation

Stimulus preparation

We used the ABA_ paradigm as suggested by Van Noorden (1975) along with a constant-stimuli procedure. Each stimulus sequence comprised of two loudness equalized pure tones Loudness equalization was done using filters based on equal loudness contours (ISO 226:2003). The loudness equalization ensured that the stream segregation task would be predominantly dependent on pitch based differences in the tones. Stimulus ‘A’ was a 100 Hz pure tone and stimulus ‘B’ consisted of a variable pure tone from 100-500 Hz. The tone duration was 100 ms with a 10 ms rise/fall time (raised cosine ramp). There was a silence of 20 ms between stimulus ‘A’ and ‘B’ and 100 ms between the ABA triplets. As logarithmic rather than linear step sizes in frequency separation have been speculated to be suitable for such tasks[37], the intermittent (logarithmic) frequency steps for the variable tones were calculated by dividing the highest frequency to the lowest frequency in the desired range and then a 14th root of the resultant value was used to get the multiplier for the reference frequency through which the 14 frequency components were obtained (Albert Bregman, personal communication). A total of 12 ABA sequences were strung together to form each test sequence. Each participant was presented 150 trials in a random order binaurally at 70 dB SPL. We used a repetitive and long loop of sequences in order to facilitate the build-up of stream segregation and to avoid bias in the responses due to formation of memory traces of the initial or last part of the sequence[4].

Procedure

The participants were presented the ABA_ sequences at a sufficiently high rate with a variable frequency separation between the A and B tones until they could no longer perceive the sequence as a single stream with an aim to measure their temporal coherence boundary[4,7,12,38]. The presentation of the test sequences was done using a custom program using the Alvin2 software[39]. A practice trial was given to all subjects using the test sequences whose patterns were easily perceptible to demonstrate the two patterns (galloping or non-galloping). The participants were asked to listen for the pattern/rhythm of the test sequences and judge them being either in a galloping or a non-galloping pattern. The practice trial continued until the participants demonstrated an acceptable level of accuracy for the recognition task. The response was collected via a yes/no button press task. The stimulus presentation order was randomized. Care was also taken to instruct the participants to base their judgements on the complete test sequence in order to allow for the build-up of segregation[3]. Moreover, in order to allow for the build-up of segregation, the test was designed in such a way as to allow button press response only after each stimulus sequence ended. The children were reinforced using animation that appeared on the computer screen after each response to keep them motivated for the task. The reinforcement was contingent to the participant's response of pressing the button (yes/no). Additionally, tangible reinforcement in the form of cookies/candies (with parents' permission) was also given to the participants after the end the test. As the cues for the separation of the two streams in this experiment involve ambiguity in perceiving coherent or non-coherent streams, the participants would always be able hear two streams voluntarily, by directing attention to only one of the types of tones (A's or B's). We therefore asked the participants to attempt to listen for the galloping rhythm and to report "no" when they couldn't hear it. This procedure measures the "temporal coherence boundary" (compelling level of segregation even though the listener is biased against hearing it) rather than the "fission boundary" (segregation when the listener is trying to hear it) [3].

The responses for each participant was collected and quantified in terms of the percentage 'Yes' (gallop) responses for each frequency combination and generated using a bootstrapping and maximum likelihood Gaussian line fit of data (gamma =0.031). The temporal coherence boundary (TCB) was estimated by taking the 50 % point from the psychometric curve. Further, in order to correct for possible response bias, we also analysed the results using signal detection theory. The number of 'Yes' (gallop) responses given by the participants when the frequencies of A and B tones were the farthest apart (i.e. B-tone at 499 Hz) was used to estimate a 'false-alarm' rate. We measured the performance in terms of sensitivity (d') using these hit and false alarm rates. Hit or false alarm rate values of 0 or 1 were adjusted by 1/2n or 1-1/2n respectively where n is the number of trials at each epoch to compensate for extreme values (i.e. 0 and 1) in the calculation of d'. We also measured response bias (criterion) which is a measure of the participants' decision variable to respond to a target. Response bias was measured using the criterion (criterion = - [Z (Hit rate) + Z (False alarm rate)]/2). A liberal criterion (negative value) would suggest a bias of the participant towards responding yes (i.e. gallop) regardless of the stimulus and a conservative criterion (positive value) would indicate a bias towards responding no (i.e. no gallop).

Localization

Stimulus preparation

The target speech syllable (/da/) spoken by a female speaker with Australian English as her first language was recorded in a sound treated room at a sampling rate of 44100 Hz, 16 bits resolution using a high quality audio recorder. The duration of the syllables were shortened to 150 ms using audio processing software (Adobe Audition 2.0). The relatively short duration of the target sound also ensured minimal role of head movements to aid in the source localization task[40]. A spectral analysis of the target stimuli indicated maximum spectral energy in the stimuli up to about 4000 Hz. The maskers were created using recorded sentences with heterogeneous context and content taken from standardized passages ("The Rainbow" and "My Grandfather" passage) spoken either by the same female speaker or by another native English female speaker (to avoid giving pitch based cues for segregation). The presentation level of the target syllable was kept at 60 dB SPL (calibrated in free field using a sound level meter) and the signal to masker ratio was kept constant at approximately 0 dB. This signal to masker ratio was 5 dB above the mean threshold (70% correct identification) on a syllable identification task in presence of the same competing maskers that was administered to all the participants as part of another experiment to ensure adequate audibility and identification of the target syllable.

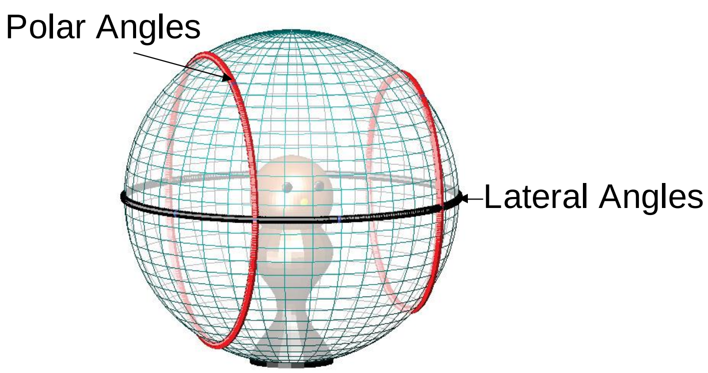
Procedure

The target speech syllable was presented from one of the 7 possible horizontal plane locations in an anechoic chamber against a background of a 2 competing talkers. The target and maskers were presented through loudspeakers in a triple walled sound attenuated anechoic chamber (working area 2.5 x 2.5 x 2.5 meters). The moving robotic arm and hoop speaker apparatus used by Carlile, Leong and Hyams (1997) was used for testing. A two way intercom system was kept in the testing chamber to facilitate communication between the participant, parents and the experimenter and to monitor any signs of discomfort or inconvenience to the participants during the testing session. The target syllable (/da/) was presented in each trial through the hoop loudspeaker along with the 2 competing talkers narrating stories from the front 2 loudspeakers (kept at ±45 degrees Azimuth) and the participant's task was to point their nose to the perceived location of the target and press a response button. The nose pointing task was used based on the premise that turning face or head towards the sound source is a highly ecological behaviour compared to other tasks such as hand pointing[42]. Moreover, the localisation errors measured using the nose pointing task has also been shown to have similar degree of variability compared to other commonly used tasks such as hand pointing[42]. The nose pointing task using a moving hoop speaker used in the current study also has advantages over verbal reporting tasks that use different speakers to measure relative localization ability and the participants may thus be able to use speaker-specific, non-spatial cues to perform the localisation task. The target and maskers were presented using custom developed scripts through the Playrec[41] utility in Matlab 2009b and routed via an external USB driven computer sound interface (RME - Fireface 400) to Audience A3 (frequency response = 40-22000 Hz) and Tannoy V6 (frequency response - 87 Hz to 35000 Hz) loudspeakers respectively. The maskers were gated along with the target stimuli with an onset and offset time of 800 ms.

Participants stood on a platform at the centre of the testing chamber with their head aligned roughly in the centre of the platform. The target speech syllable was played via the loudspeaker and its position was varied using a computer controlled positioning system with a suspended double hoop design[42]. A tracking device (Intersense IC3) which was fitted on the head of each of the participants using an adjustable plastic frame constantly monitored their head position from a calibrated reference point in the centre to record the localization responses. We examined the localization for 7 different locations viz. 0, ±30, ±60, ±90 Azimuth in the horizontal plane. All participants underwent 1 training trial using visual feedback for accurate pointing in which the nose pointing response method was demonstrated and practised which may have assisted in reducing the extent of errors due to eye pointing especially at the extreme positions (±90).

The responses were measured in terms spatial co-ordinates of the participants by nose pointing to the position of the target in a spherical coordinate system (See figure 1). The localization errors were defined as the difference between the actual target location and that indicated by the participants. We measured the lateral angle errors (LAE) as the root mean square (RMS) errors in horizontal plane (Left-Right) localizations, and the polar angle errors (PAE) were the RMS errors in vertical plane corresponding to those positions in the horizontal plane[43,44]. The polar angle errors were also corrected for inflation due to the relative differences in the dimensions of the cone of confusion at different positions.

Figure 1: The spherical polar co-ordinate system depicting the polar and lateral angles that were used in the measurement of localization accuracy



Brief Tone Frequency Discrimination

Stimulus preparation

Frequency discrimination was assessed using short duration (100 ms; 20 ms raised cosine ramp) pure tone stimuli at 2 different frequencies (100 and 1000 Hz). The level of presentation was constant at 70 dB SPL. The stimulus intensity was calibrated using a Bruel and Kjaer artificial ear and type 1 sound level meter assembly using a linear frequency weighting scale. The stimuli were presented using an AXB paradigm and a 1 up, 3 down transformed up-down staircase procedure (Levitt, 1971). The AXB paradigm was used based on its advantages such as reduced short term memory demand and resistance to bias over other designs such two or three alternative forced choice[45,46]. The initial frequency difference at the start of the test was intentionally kept large (i.e. 30 Hz and 100 Hz) in order to orient the participants to the task.

Procedure

The task was implemented in Matlab 2009b using custom made graphical user interface (Psychophysics Software Suite) designed by Goldberg, Lvovsky and Banai (2010). This interface is a child friendly and uses animations. A response contingent feedback was provided after each trial to the participants. The frequency difference between the fixed and reference frequencies (delta) changed adaptively based on a pre-defined set of rules. The delta for the reference frequency of 100 Hz initially changed in larger steps (5 Hz), progressing to intermediate steps (2 Hz) and later in small steps (1 Hz), whereas that for the reference frequency of 1000 Hz varied from large steps of 10 Hz to intermediate steps of 5 Hz and lastly smaller steps of 1 Hz in order to reach the threshold. The experiment continued until 10 reversals were obtained. The participants were instructed to listen to all the 3 tones that were presented in a trial and then determine which of the tones (1^{st} or 3^{rd}) was not identical to the reference tone (2^{nd}). The participants responded by clicking the appropriate 'graphic' (animated picture of a mouse or dragon) on the computer screen. We also monitored each participant’s performance based on the variability of their track widths (standard deviations) in the tests and repeated the tests if there was an evidence of variable track width suggesting a possible attention lapse[47,48]. The threshold was calculated from the staircase using the arithmetic mean of the last 5 reversals. This threshold would converge approximately at the 77% point on the psychometric function.

Temporal envelope perception

Based on the procedure from Rocheron et al[32], we used a sinusoidal amplitude modulation rate (SAM) detection task at a low (4 Hz) and high (128 Hz) modulation rate as a measure to examine temporal envelope processing. The stimulus was a sinusoidally amplitude modulated broad band noise (BBN) (0-20KHz) with a duration of 500 ms (20 ms rise/fall time) with a modulation frequency of 4 and 128 Hz respectively. The modulation depth of the BBN was varied to determine the detection threshold for amplitude modulation. The intensity of the unmodulated reference sound was normalized such that the overall power was the same for the reference and variable (modulated) sound. The task design (AXB paradigm; 1 up-3 down transformed staircase procedure) and implementation was similar to that used in the frequency discrimination experiment. The participants' task was to detect the modulation and determine which interval had the modulated noise. The modulation detection thresholds were expressed in decibels ($dB = 20 \log_{10}$ (modulation detection threshold)) for comparisons.

Results and Discussion

We performed a 2 tailed independent samples t-test to compare the performance on the three tasks across the 2 groups of participants. The data for each task was found to be normally distributed (based on 2 tailed Shapiro-Wilk test and Q-Q plots). The overall results of this experiment indicated no significant differences ($p>0.05$) in performance between the 2 groups of participants on any of the tasks.

Auditory Stream Segregation

The results indicated no significant differences across the 2 groups for temporal coherence boundary measured in Hz as well as for the sensitivity (d') and criterion (C) measures (See Table 1, figure 2 and figure 3). The analysis of the response criterion as a function of the frequency separation between the A and B tones (See figure 3) indicated a gradual change from a relatively neutral criterion at smaller frequency separations to a more conservative criterion at larger values of separation for both group of participants.

In contrast to the findings of an earlier study which reported poorer performance for sequential stream segregation task based on frequency separation cues for 9-11 year old children in comparison to adults[49], the results of the current study indicated no significant differences in performance between the adult and child participants. The differences between our results and that of Sussman et al (2007) can be attributed to factors such as differences in age range of participants (10-15 Vs. 9-11 years), reference frequency (100 Vs. 1000 Hz) and the measure used (temporal coherence Vs. fission boundary). Additionally, the mean temporal coherence boundary obtained from the adult and child participants in our study (11.41 and 9.48 semitones respectively) were higher than that reported in earlier studies[4,12,49,50]. This discrepancy is most likely due to procedural variations and the fact that unlike the previous studies, we used loudness balanced pure tones which relatively diminished the intensity based cues that may have further facilitated segregation. Moreover, consistent with the findings of previous studies[49,51-53], we found a gradual reduction in the temporal coherence percept (gallop) as the frequency separation between the 2 tones increased.

Figure 2: Mean temporal coherence scores (d') for the 2 groups measured as a function of frequency separation (Hz) between A and B tones. The error bars represent the standard error of means.

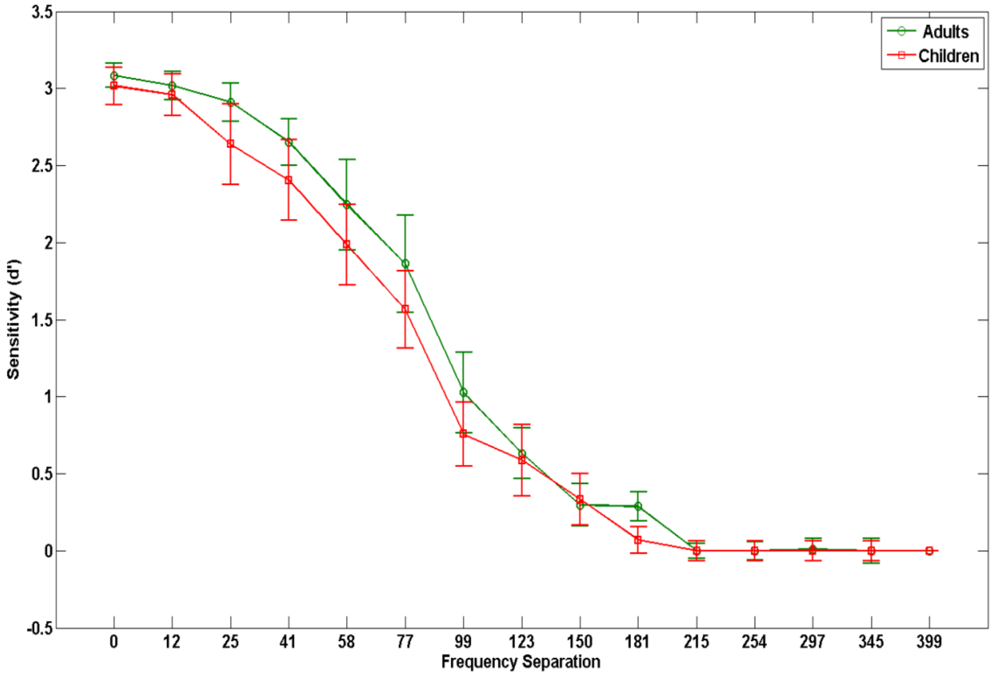
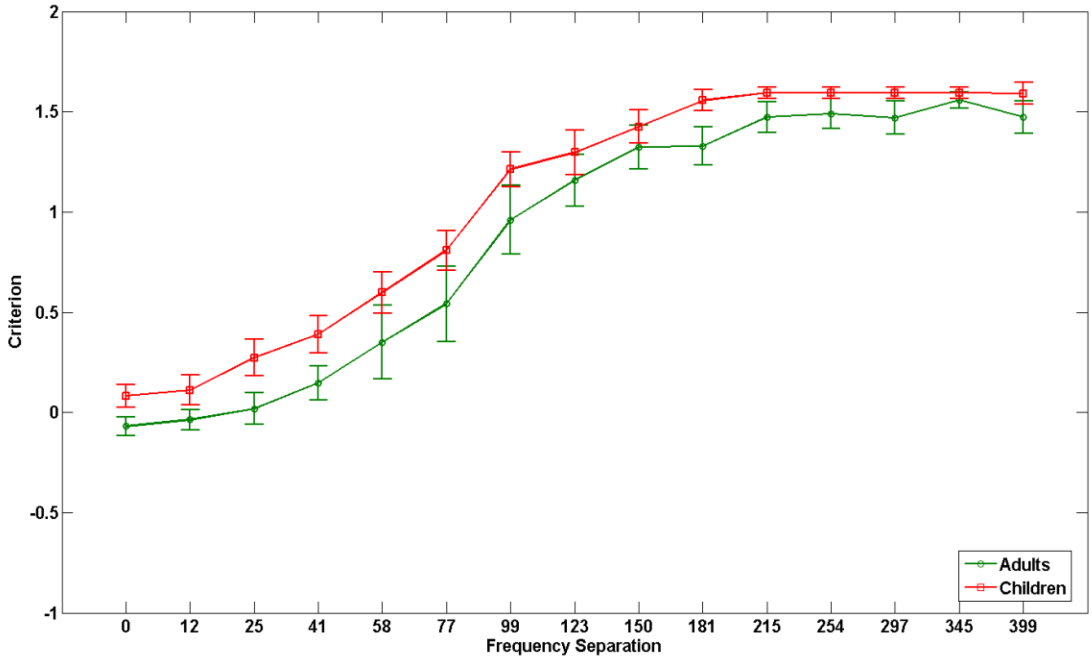


Figure 3: Mean response criterion (c) for the 2 groups measured as a function of frequency separation between A and B tones in Hz. The error bars represent the standard error of means.



Localization

We found no statistically significant differences between the 2 groups for the measures of lateral and polar angle errors (see Table 1). The distribution of the azimuth errors was much larger for the children compared to the adults (See figure 4, 5 and 6). Additionally, we also compared the data collected from the adult participants for the lateral and polar angle errors with the mean data from another study in our laboratory that consisted of 20 adults (unpublished) who were highly trained localisers and found no significant differences ($p>0.05$) between the means of the two data. These results indicate no significant differences in the auditory localization ability between the normal adults and children. This finding is consistent with that of earlier studies which reported adult-like auditory localization abilities in children by 5-6 years of age[54-59].

Figure 4: Scatterplots for the 2 groups representing the actual position of the target on the abscissa and the mean of the perceived position of the target on the ordinate axis.

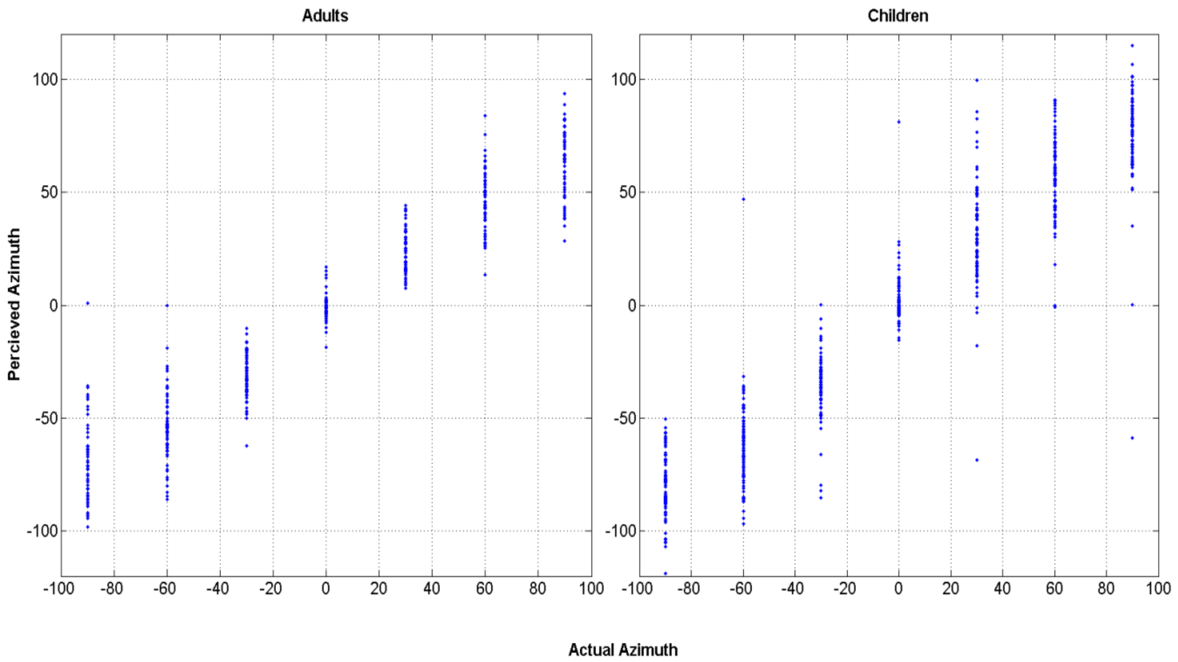


Figure 5: Individual localization test data from 2 youngest participants from the 2 groups. The data for each participant are plotted at actual and perceived azimuths for locations in the front, right and left of the participant on a scatter plot.

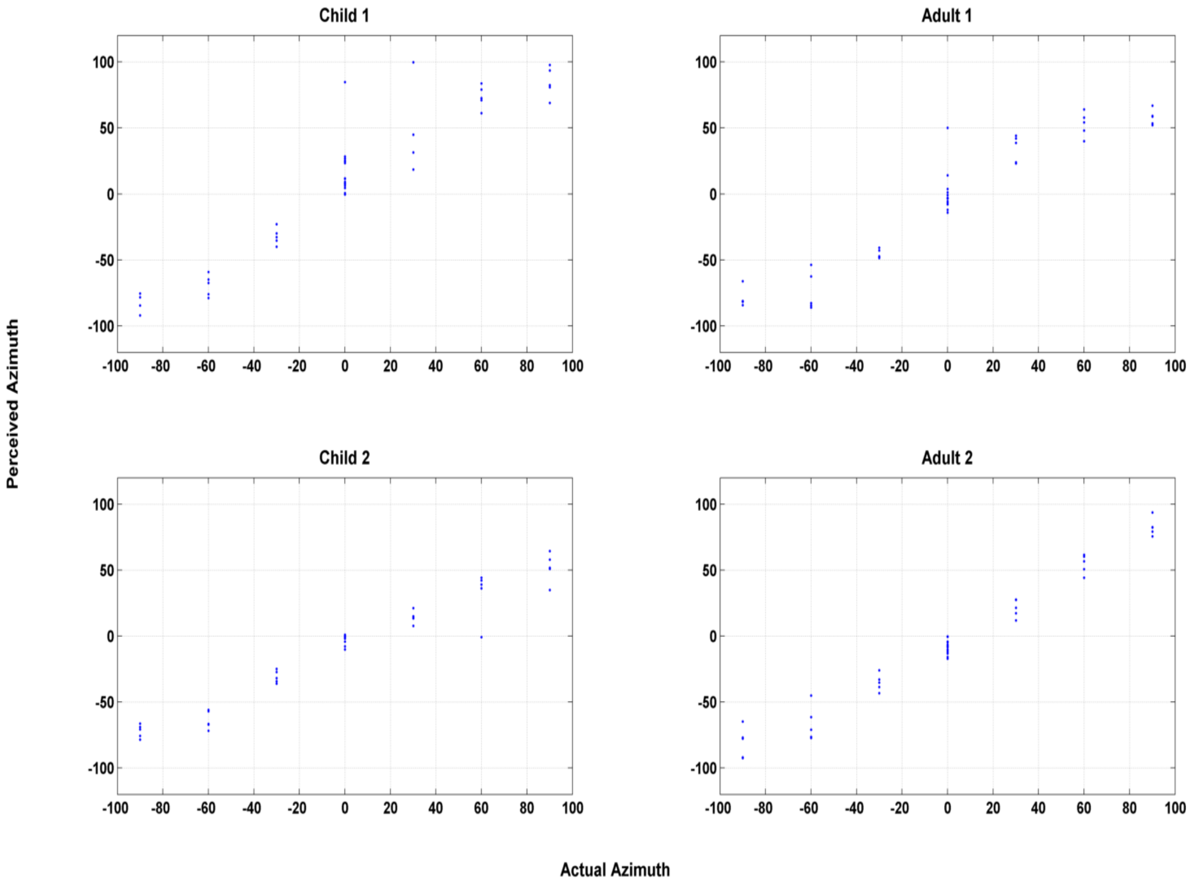
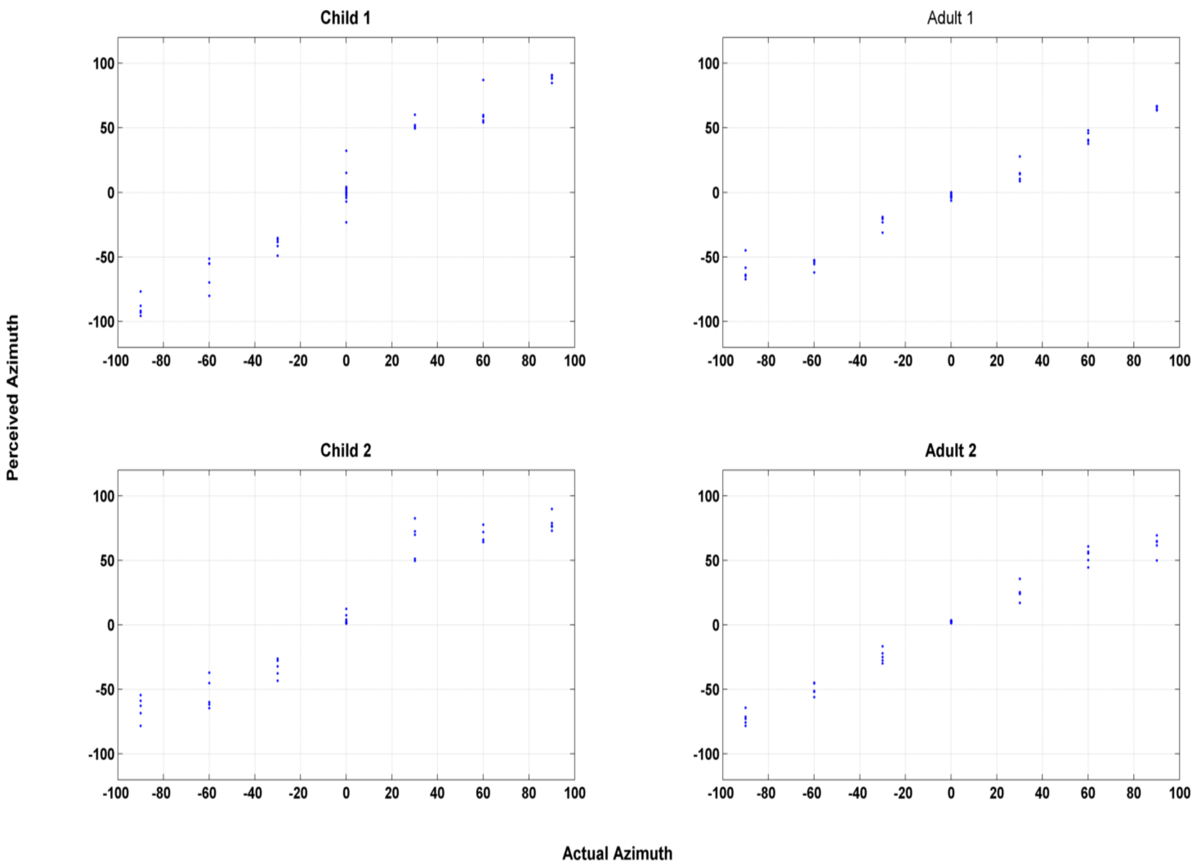


Figure 6: Individual localization test data from 2 oldest participants from the 2 groups. The data for each participant are plotted at actual and perceived azimuths for locations in the front, right and left of the participant on a scatter plot.



Brief tone frequency discrimination

We found no differences between the 2 groups for frequency discrimination thresholds obtained at 100 and 1000 Hz (See table 1). These results are consistent with the result of an earlier study which reported adult-like frequency discrimination ability for short duration pure tones such as those used in the present study, by 9 years of age[23].

Temporal envelope perception

The results for the amplitude modulation detection task (4 and 128 Hz) indicated no significant differences between the 2 groups (See Table 1). These findings suggest adult-like temporal envelope processing ability in the children evaluated in this study. Earlier studies done to examine speech perception based on temporal envelope cues have reported that the ability to encode these cues matures and becomes adult-like by the age of 10 years[60,61]. Moreover, amplitude modulation detection thresholds have been shown in earlier studies to be similar to adults by the age of 10-12 years[33,62]. Our results are consistent with these earlier findings.

Conclusion

The overall results suggest no significant difference for performance on any of the tasks between the 2 groups. This may suggest that the processes that have been assessed using these tasks namely auditory sequential stream segregation, localization, frequency discrimination and temporal envelope perception may operate similarly in school aged children (>10 years) and adults. These results can be used as benchmarks to compare the performance of school-aged children with listening difficulties on these tasks.

Table 1: The table shows the mean scores along with the standard error of mean for the three tasks in Adults and Children

Tests	Adults	Children
Brief-tone frequency discrimination		
100 Hz	5.7 (1.07)	6.17 (0.65)
1000 Hz	5.56 (0.76)	5.76 Hz (1.05)
Localization		
Lateral angle error	15.14 Az (1.71)	12.95 Az (0.66)
Polar angle error	8.91 Az (1.97)	12.73 Az (1.63)
Sequential stream segregation		
Temporal coherence boundary (Hz)	94.81 (9.17)	69.54 Hz (8.03)
Amplitude modulation detection		
4 Hz	-23.73 dB (1.22)	-24.46 dB (0.51)
128 Hz	-19.73 dB (0.93)	-21.05 dB (0.69)

Additional Note:

* On further analysis of the localization data, we also observed some intra and inter-subject variability in the localization performance of children which is consistent with the results of an earlier study conducted on a younger group of children[63] (See figure 5 and 6).

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Chapter 3 (Study 2)

Switch Attention to Listen

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Switch Attention to Listen

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Abstract

The aim of this research was to evaluate the ability to switch attention and selectively attend to relevant information in children (10-15 years) with persistent listening difficulties in noisy environments. A wide battery of clinical tests indicated that children with complaints of listening difficulties had otherwise normal hearing sensitivity and auditory processing skills. Here we show that these children are markedly slower to switch their attention compared to their age-matched peers. The results suggest poor attention switching, lack of response inhibition and/or poor listening effort consistent with a predominantly top-down (central) information processing deficit. A deficit in the ability to switch attention across talkers would provide the basis for this otherwise hidden listening disability, especially in noisy environments involving multiple talkers such as classrooms.

Introduction

Listening and understanding a single talker in the presence of other talkers or distracters requires adequate hearing sensitivity, processing of the spectral (frequency and intensity) and temporal (time) cues, separating the information into coherent streams as well as selectively attending to the relevant talker and ignoring the distracters[1]. Selective auditory attention and re-orientation in a noisy environment is a basic yet complex behavior[2,3,4]. Most of our listening experiences in the environment are dynamic and the sources as well as information change constantly in time and space. Therefore the listener needs to orient attention when there is relevant information and rapidly re-orient attention from one stream of information to another as the situation demands[2].

There have also been suggestions that the deficits in auditory processing skills and speech perception in noise, which are most often observed in children who have a history of recurrent otitis media (middle ear infection) with effusion (OME)[5], are associated with poor attention abilities[6]. We have focused our research to study the attentional mechanisms in such a population in order to gain further insight into the underlying cause of the listening difficulties in background noise.

Auditory attention can involve both top-down and bottom-up processing based on the types and demands of a listening task[7,8,9]. A task which requires a voluntary selection of targets amongst distracters would involve top down (cognitive) control, whereas that requiring involuntary focus of attention due to factors such as salience will recruit bottom up (sensory) processing resources[10]. From a functional perspective, listening to speech in a noisy background requires a listener to remain alert and responsive to relevant cues (intrinsic and phasic alertness), orient attentional focus to important or salient signals (orienting) and selectively focus attention on the sounds of interest while ignoring the distracters (selective attention)[11,12]. In addition, there may also be a need to simultaneously focus attention on two or more signals (divided attention) and/or disengage and switch attentional focus between multiple sources of information based on relevance or salience (attention switching/re-orientation)[13,14].

Selective auditory attention in the time domain is especially important in situations where speech and noise sources overlap in space and where the listeners are required to constantly switch attentional focus in time[15]. A number of studies have demonstrated that tone detection in the presence of background masking noises improved significantly when the temporal interval of target occurrence was expected or cued[16-19]. An extension to this notion of temporal selective attention is the time required for the subjects to *re*-orient their attention after attending to the expected time window. This has been studied in vision where the temporal re-orientation time varied between 200-500ms[20]. However to our knowledge, this has yet to be examined in audition.

In this study, we designed a task to examine the relative roles of top-down and bottom-up control of attention and the time taken to re-orient attention in the auditory domain. Based on a combination of the multi-probe signal method[21] and Posner's cueing paradigm[22], this method involved priming a target signal at a specific time interval in a stimulus sequence (temporal epoch) by cueing, followed by frequent presentations of the target at the cued epoch. This ensured the focus of attention on the expected epoch. To identify attention specific effects, in addition to presenting targets at the expected interval, stimuli were also presented infrequently at unexpected epochs. Importantly we also allowed for the presentation of catch trials to facilitate bias correction and sensitivity analysis. Here, we used a target identification task involving the discrimination and identification of a target syllable from a string of five syllables in the presence of a two-talker speech babble (see Figure 1). The duration of the five temporal windows (epochs) was based on the subject's individual reaction time via button press responses in a control experiment. This ensured a correlation between attention and reaction, while also providing a means to quantify the subject's response accuracy over time and allowed us to model the patterns of attentional re-orientation. Additionally, by changing the temporal position of the priming cue and the expected epoch between the first and last stimulus windows, we were able to gain insights into the subject's auditory selective attention abilities.

Performance benchmarks were collected from two control groups of subjects with normal hearing sensitivity and no reported listening difficulty (adults and children). We then applied this paradigm on a third (experimental) group of children who presented with persistent listening difficulties in noise. In particular, apart from parental and teacher concerns about their listening difficulties and a concomitant medical history of recurrent OME, this last group of children otherwise performed similar to the control (children) group when assessed using a wide range of clinical tests for hearing sensitivity and auditory processing. Apart from the standard test battery recommended by the American Academy of Audiology (2010)[23], they were also examined on additional tests (See Table 1) that ruled out deficits in peripheral hearing, auditory short-term memory, auditory sustained attention and auditory processing (See Table 2).

Previous studies, although using shorter observation time windows than the current experiment, have demonstrated a reduction in sensitivity to targets outside a certain time window around an expected epoch[16,18]. Detection of the targets occurring earlier than expected has been shown to involve involuntary shifts of attention requiring bottom-up processing resources; whereas the detection of targets later than expected involves voluntary disengagement and switch of attention from the expected temporal epoch requiring top-down processing resources[9,10]. Furthermore, we anticipate a gradual improvement in sensitivity over time at the unexpected epochs following the epoch when a target was expected but not presented[24]. We assessed the difference in sensitivity to identify a target for expected and unexpected targets presented at the first epoch as a measure of selective attention and the time taken to relatively recover the sensitivity for the unexpected targets as a measure of attention switching. All the participants were tested on 2 conditions, an “Early” condition in which the target syllable occurred frequently (60%) in Epoch 1 and a “Late” condition in which the target occurred frequently in last epoch (Epoch 5). That is, for the “Early” condition the target syllables occurred infrequently at the unexpected epochs (2-5) while the converse was true for the “Late” condition where target occurrence at epochs 1-4 was unexpected. The “Early” condition allowed us to examine the voluntary attention re-orientation mechanisms that are distinct from the involuntary attentional processes of the “Late” condition[25].

To our knowledge, this is the first investigation and demonstration of temporal attentional re-orientation in children. Most importantly, these results indicated a significantly longer attentional re-orientation time for children who reported with persistent listening difficulties and a history of recurrent OME, in contrast to an age matched control group.

Results

Adults and Children with no Listening Difficulty

<u>*Early Condition*</u>

We examined subjects with normal hearing and no reported listening difficulties (12 adults and 12 children). We observed several distinct patterns in hit rate and false alarm responses. Overall, the hit rates at the expected epoch were considerably higher than those at the unexpected epochs in children but not for adults (Figure 2, blue and green bars). For the children, the hit rates dropped substantially immediately after Epoch 1 (from 0.82 ± 0.01 to

0.39 ± 0.07) in the "Early" condition, then gradually improved consistent with a reorientation/re-preparation process[24] (Figure 2A, blue and green bars), reaching 0.69 ± 0.05 in Epoch 5. This did not occur for the adult subjects, where there was no notable drop in their hit rates after the expected epoch, maintaining a hit rate of 0.72 ± 0.06 at Epoch 2 (0.51 ± 0.01 seconds, see Methods).

The considerable reduction in hit rate for the normal children after the expected epoch coupled with a relatively slow reorientation time meant that there remained a notable difference in hit rate between Epoch 1 and Epoch 5, the last temporal window. In order to compare the reorientation time between normal adults and children, we extrapolated the hit rates using a simple line of best fit ($y=0.089*x+0.22$, adjusted $R^2 = 0.81$) and projected that normal children will only regain sensitivity at 3.32±0.08 seconds with a hit rate of 0.84±0.18 (see Figure 2A). In the expected epoch (Epoch 1), there was no notable difference in hit rates for the normal adults and children, however, there was a considerably higher number of false alarms committed by the children (Figure 2B, blue and green): 0.17 ± 0.02 versus 0.06 ± 0.01 respectively - suggesting a reduction in sensitivity (see below for d' analysis).

Late Condition

In the "Late" condition (Figure 3); the hit rates were substantially higher for the adults in all epochs with a consistently lower false alarm rate. While there was a notable difference in hit rates between adults and children in Epoch 5, both groups performed above the 75% threshold, with adults reaching 0.94 ± 0.00 and children 0.87 ± 0.01. In comparison between Early and Late conditions, the hit rates at the expected epoch showed a similar pattern. There was a higher hit rate for adults in the "Late" condition; however, a commensurate increase in false alarm rate was also observed, suggesting a similar level of sensitivity for target identification at the expected epoch for both groups of participants. That was not true for children though, where a considerable increase in false alarm rate was observed in the Late condition (from 0.13 ± 0.02 to 0.46 ± 0.03), suggesting a lower level of sensitivity. Similar to the finding in the "Early" condition, there was no notable difference between the false alarm rates for the unexpected epochs within each of the two groups (See Figures 2B and 3B, blue and green bars).

Selective Attention

The hit rate and false alarm results were summarized with a sensitivity (d') analysis (See Method and Supplement 1 for further details). We compared the target identification sensitivity at the first temporal epoch when the target was expected at that epoch ("Early" condition) to when it was unexpected ("Late" condition) as a measure of temporal selective attention ability[24] and found a notably higher sensitivity for target identification at the first epoch in the "early" condition (Expected) compared to that at the first epoch in the "Late" condition (Unexpected) suggesting a marked effect of focusing attention selectively on the expected epoch for both groups of participants. Further we also compared the sensitivity for identifying the target at the expected epochs for both Early and Late conditions (Figure 4). In the Early condition, normal adults had a sensitivity of 2.49, 95% CI of [2.2 2.75] while normal children were considerably lower at 1.87, 95% CI of [1.62 2.11]. In the Late condition, normal adults had a sensitivity of 2.64, 95% CI of [2.35 2.91], with the normal children dropping in sensitivity to 1.04, 95% CI of [0.82 1.25]. In summary, sensitivity for the adult population did not vary between conditions and was consistently considerably higher than that of normal children. However, the converse was true for the normal children tested, where we observed a notable decrease in sensitivity between the Early and Late conditions.

Children with listening difficulties

Early Condition

This group of subjects consisted of 12 children, age-matched ($p<0.005$) against the children in the control group, who presented with persistent listening difficulties especially in a noisy environment (see Methods). Consistent with the results from the children in the control group and from previous research[16,18], the hit rates for target identification was considerably higher when the target syllable occurred at the expected epoch and poorer elsewhere for all the participants (See Figures 2A and 3A, red bars). A comparison between the children in the experimental and control group showed no notable difference in hit rates at Epoch 1. Substantially more false alarms were committed by children in the experimental group (0.41 ± 0.03 versus 0.17 ± 0.02 (normal children) and 0.06 ±0.01 (normal adults)).

Similar to the responses in the control group of children, there was a substantial drop in pooled hit rate immediately after the expected epoch – from 0.79 ± 01 (Epoch 1) to 0.16 ± 0.05 (Epoch 2). Additionally, hit rates were considerably lower for all the unexpected epochs when compared with the control group and the normal adults, only reaching 0.30 ± 05 at Epoch 5; However, a trend of recovery can still be seen, albeit at a much slower rate (Figure 2A). Again, we extrapolated the hit rates from Epoch 2 to 5 and estimated that the experimental group would have recovered their sensitivity at 9.47 ± 0.25 seconds, reaching a hit rate of 0.78 ± 0.27; a notable increase in duration from the control group.

Late Condition

In the Late condition the hit rate at the expected epoch was notably lower for the children in the experimental group. Interestingly, the false alarm rates in the expected epoch for the experimental group did not vary significantly when compared with the "Early" condition, maintaining at 0.47 ± 0.01, even though a substantial increase was observed for children in the control group.

Selective Attention

Similar to the results obtained in the previous experiment, we observed considerably higher sensitivity for target identification at the expected epoch compared to the unexpected epoch for both groups of children suggesting that similar to the children in the control group, the children in the experimental group showed an advantage for identifying the target based on its expectancy. Further comparison of target identification sensitivity between the 2 groups at the expected epochs for both "Early" and "Late" conditions showed a notably higher sensitivity for the children in the control group in the Early condition but there was no substantial difference in sensitivity between the two groups in the "Late condition (See Figure 4).

Discussion

In these experiments, we used a modified probe-signal method to analyze the rate of recovery in attention and extrapolated the time course necessary for subjects to regain attentional focus. In addition to segmenting each trial into equal response windows (epochs) based on each individual's minimal response times, false alarms were also recorded to ensure the validity of the task and to calculate the sensitivity for target identification across the epochs. The catch trials used in the task also played an important role of reducing the attentional preparation of the listeners for targets presented at the unexpected epochs[24]. The role of the catch trials in context of this paradigm would be to generate a degree of uncertainty regarding the occurrence of target which may relax the participants' state of preparation for responding to the target especially at the unexpected temporal epochs[24]. Although the proportion of catch trials used in the current study was relatively small (20%), it has been shown previously that such dis-preparation due to the presence of catch trials is an 'all or none' process, such that even a small percentage of catch trials is sufficient for the effect to be observed[24]. By combining a rigid time response window with hit rates and false alarm measures we were able to derive bias-free sensitivity measures at the expected epochs.

We also found enhanced sensitivity for target identification at expected vs. unexpected epoch indicating an ability to attend selectively to the target at the expected time interval for all 3 groups of participants. From the present data we are unable to compare and contrast the magnitude or strength of selective attention abilities between these groups.

While other studies have also shown a reduction in sensitivity after the expected epoch, here we also quantified the recovery rate. Such recovery can be attributed to the process of "re-preparation" by which the listener develops a new state of preparation across the unexpected epochs, due to the absence of targets at the expected epoch[24]. Despite the temporary disruptions in re-preparation caused by the presence of catch trials', the participants gradually recover their sensitivity. This recovery would require a goal driven mental effort for the listeners[26] involving predominantly top down voluntary control of shift in attention across time[25] with possibly some involuntary bottom-up processing [10,24].

Interestingly, the results showed that our adult participants had an essentially flat distribution of hit rates across the five epochs in the "Early" condition. Given the similarities in hit rate, the results may suggest that adults reoriented faster than could be detected using a button press response paradigm. The duration of the epochs was tailored individually based on the response times derived from a set of control experiments (see Methods), which for adults was 360±15.56 ms. These results suggest a relatively rapid attention switching time in the time domain for adults. This is consistent with earlier studies pertaining to the recovery of the "attentional blink" phenomenon in which the detectability of the second target in a dual target detection task was substantially reduced if it occurred within 200-500ms from the first and improved thereafter[27]. This has been observed in audition as well as vision[20,28] and indicates that the listeners' attention is captured by the first target and thus unable to rapidly switch to the next. While this may provide a tentative explanation to the results from the adult population, "attentional blink" in the auditory modality has not been examined in children.

In contrast, the hit rates for normal children dropped significantly between Epoch 1 and Epoch 2 - before increasing slowly in Epoch 5. A linear extrapolation projected a reorientation time of 3.32 ± 0.08 seconds to attain parity with the expected epoch, which is significantly slower than adult behaviour. To our knowledge, this is the first report that quantified the differences in attentional reorientation between adults and children and suggests that this process continues to mature into adulthood.

Most significantly, when we applied this testing methodology on a cohort of children who reported with persistent listening difficulties (Experimental group), their hit rates, false alarm rates and temporal re-orientation time were respectively lower and longer than that of the normal children and adults. A comparison of sensitivity in the expected epochs (Figure 4) clearly demonstrates this trend. Interestingly, there was a significant difference in d' between the Control and Experimental cohorts only in the "Early" condition, with the d' for the Control cohort reduced to the level of the Experimental subjects in the "Late" condition. The difference in hit rate responses between the cohorts could not account for such a drop in sensitivity. Rather, there was a highly significant difference in false alarm rates between the expected epochs for the children in the Control group, where a much smaller number of false alarms were committed in the "Early" condition. This suggests that the Experimental cohort were less able to inhibit their responses in the expected epoch of the "Early" condition, rather than representing a decrease in sensitivity of the Control group.

The substantially higher false alarm rate in the Experimental group at the expected epoch in the "Early" condition may be due to a combination of excessive facilitation effect due to a reflexive shift of attention at the expected epoch along with poor response inhibition[29]. Moreover, the total number of false alarms across the five epochs was significantly higher for these subjects, suggesting a general reduced ability to avoid responding in a catch trial. Previous work has shown that such intentional or voluntary inhibitory control processes are vital in regulating the allocation of attention[29,30]. A poor control of response inhibition as observed may also be related to poorer working memory capacity[31]. This inability to intentionally inhibit the allocation of attention to irrelevant stimuli may lead to increased distractibility of these children especially in noisy listening environments and may thus partly explain their difficulties in listening.

The results seen with the experimental group are consistent with the idea that there are differences in the ability to rapidly shift attention in the group of children with persistent listening difficulties compared to their age matched peers. This difference could involve a combination of top-down and bottom-up processing deficits. Listening in a noisy background or in a multi-talker environment, like a group discussion, not only requires efficient peripheral hearing, auditory processing and memory but also rapid switching of the focus of the listeners attention from one talker to another based on the changing relevance of information[32,33]. This requires the application of listening effort to attend to the expected as well as unexpected sources of information and the ability to inhibit responding to distracting stimuli. Deficits in any of these abilities may affect an individual's ability to listen effectively in a noisy or multi-talker situation. Previous brain imaging studies indicate the involvement of predominantly frontal and parietal cortical areas of the brain in attention switching, listening effort and response inhibition control which further suggests a more central or top down processing deficit in the experimental group tested in this study[8,34-36].

Previous work involving children with listening difficulties has reported variable performance on psychoacoustic tasks meant to measure their auditory processing abilities. This has also been attributed to poor auditory attention and is the consistent with the findings reported here[37,38]. Interestingly, all the participants in our experimental group reported a history of recurrent otitis media. While the data does not speak directly to any definitive links with OME, it may be that due to the transient disruptions in hearing associated with recurrent OME[39,40]the experimental group may have learnt to allocate most of their cognitive resources to selectively focus attention on expected information and the remaining resources are insufficient for them to switch their attention to any unexpected stimulus. Future studies are needed to evaluate this hypothesis. Further research should also explore whether these attention switching deficits are specific to the auditory modality or are modality independent general cognitive deficits.

This work has described an auditory attention switching deficit in a group of school-aged children with persistent listening difficulties in noisy environments. As the current set of standard clinical tests was unable to discriminate this group of listeners from normal controls, the test reported here may provide a good candidate test for children with listening difficulties. As attention switching requires predominantly top down control, the data is consistent with the suggestion that this deficit represents a more central pathology in contrast to a peripheral auditory processing deficit. An aspect of considerable interest will be the capacity of training or practice regimes to assist in overcoming this deficit. In a similar study, we are currently focusing on assessing children diagnosed with an auditory processing disorder to determine if it is part of the broader spectrum of listening difficulties and to gain insights into its underlying cause.

Method

Participants

We examined three groups of participants – 12 normal adults (mean age 21.09, SD 3.52), 12 normal children (control group) (mean age 12.5, SD 1.55) and 12 children with persistent listening difficulties (experimental group) (mean age 11.38, SD 1.48). All subjects spoke Australian English as their first language, had normal hearing sensitivity and did not present with any middle ear pathologies. We ruled out any auditory memory, sustained attention or processing deficits for all the participants based on a comprehensive clinical test battery[23,41] (See Table 1 and 2). The test scores for each of the normal children on the standardized clinical tests were within the previously published norms[42,43]. All the children in the experimental group presented with persistent listening difficulties that were based on parental, teacher and participant reports of concerns regarding their listening abilities especially in noisy environments.

Children with a history or formal diagnosis of attention deficit/hyperactivity disorder (ADHD) were excluded from the study. Furthermore, all children were tested on the auditory continuous performance task[44] and there was no significant difference (See Table 2) between the control and experimental group children. Earlier studies have reported the continuous performance task as a screening test for ADHD[45]. Interestingly, their medical history also revealed a history of recurrent (>2 episodes, Mean= 2.91, SD=0.51) otitis media with effusion between the ages of 2-5 years that was absent in the control group. Both the control and experimental groups were age matched ($p<0.05$). Informed consent was obtained from all the participants in accordance with procedures approved by the Human Research Ethics Committee at Macquarie University. For every child participant, care was taken to avoid participant fatigue and loss of motivation[46] by constant positive reinforcements and dividing the tests across multiple sessions within a span of 2 weeks.

The modified multi-probe signal method

The multi-probe signal method examines the allocation of attentional resources by examining a subject's target detection sensitivity in expected and unexpected time windows. It focused the subject's attention to the expected epoch by 1) presenting an auditory priming cue and 2) repeated presentations of the target signal, at the primed epoch. Target signals were then presented at the unexpected temporal epochs. This allowed us to examine the subject's attention reorientation time by comparing the target detection sensitivity between the time windows. Here, we examined five temporal epochs with the following target presentation ratio: 60% in the expected epoch, 5% in the four unexpected epochs and 20% catch trials. All the participants were tested on two conditions, an "Early" condition in which Epoch 1 was the expected epoch, where the target syllable occurred frequently and a "Late" condition in which Epoch 5 was the expected. This allowed us to compare between voluntary endogenous attention re-orientation mechanisms ("Early") and involuntary exogenous process ("Late")[9,25]. The duration of the epochs was set based on the subject's response time (RT) derived from a series of training trials (see below), where

Epoch duration = $RT_{mean} + RT_{STD}$

This ensured a reasonably high level of test difficulty within the motor constraints of the participants. The mean inter-stimulus interval for each group of participants was: Adult: 360±15.56ms, Control group: 404.16±13.84ms, Experimental group: 410.83±14.3ms.

Stimuli and Procedure

The experiments were performed in a darkened anechoic chamber. Stimuli consisted of five speech syllables from the list (/da/pa/ga/ka/ba) each 150ms long spoken in a male voice, presented from a loud speaker (Audience A3) located 1m directly in front of the subjects (0°Azimuth). Maskers in the form of female "babble speech" were presented from two speakers (Tannoy V6) placed 1m in front at ±45°Azimuth at a constant intensity level of 70 dB SPL. The target to masker ratio varied between subjects (by varying the intensity of the syllable train) to keep a 75-85% target detection threshold. Speech syllable stimuli were used to emulate a natural listening environment within the constraints of linguistic load. It has been shown in an earlier study that attention can be specifically allocated to a single syllable[47]. The stimulus duration was kept short to preserve a narrow listening window[18].

Each trial began and ended with 800ms of masker followed the syllable train that was mixed pseudo-randomly, with /da/ being the target. A priming cue (100ms, 2.5 kHz tone) always preceded the expected epoch by 100ms (see Figure 1). Previous research suggests that such cues may facilitate detection and help orient attention involuntarily even if the listener is unaware of its presence[22]. The cue frequency was chosen based on the premise that the key differences in the acoustics of the syllables used are in the 2nd and 3rd formant transitions and may enhance identification of target syllable at the cued epoch[48]. The duration between the cue and the onset of a syllable (stimulus onset asynchrony (SOA)) was maintained at 100ms to avoid the phenomenon of inhibition of return at longer SOAs which is known to impair the speed and accuracy of target identification at the cued epoch[49,50].

Auditory stimulus was generated using Matlab (version 2009b, The MathWorks Inc., Natick, Massachusetts) on a PC connected to an external sound card (RME FireFace 400). The subject's task was to press the response button as quickly as possible when the target syllable

/da/ was detected. Subject's also received instantaneous visual feedback (a red or green LED light) for correct target and false alarm identifications. A head tracker (Intersense IC3) constantly monitored the subject's position to ensure they directly faced the front speaker and a TDT System 2 (Tucker Davis Technologies) recorded the button press responses. Button presses that occurred 50ms prior to the occurrence of target in a trial were rejected from the analysis with an assumption that they were random guesses.

Each subject participated in two training and test blocks. Each training block consisted of 25 trials which had both cued and un-cued targets presented in a randomized order. They were initially presented at a target to masker ratio of -10 dB and subsequently varied in 1 dB steps to reach a hit rate threshold of 75-85% and <40% false alarm rate on catch trials[18]. Each test block examined the "Early" and "Late" conditions separately and was further divided into two split halves of 60 trials each of approximately 5 minutes in duration, short enough to avoid participant fatigue (See Appendix 2). The first 10 trials always had the syllable /da/ presented at the expected epoch (priming trials) to focus the attention of the participant and were excluded from subsequent analysis. The remaining 50 trials were presented in a pseudo-random order that preserved position of the expected epoch (either "Early" or "Late").

<u>Analysis</u>

The results were analysed using hit and false alarm rates of target identification at each epoch, as well as d' analysis at the first epoch. The hit rate was the proportion of correct responses, while the false alarm rate was the proportion of responses (button presses) in catch trials. The false alarms were assigned to the epochs based on the subject's response time[51]. Since the number of trials across the five epochs was uneven, the proportion of catch trials allocated to each epoch was based on the distribution probability of the targets; i.e., 60% of false alarms would be committed in the expected epoch. A control study corroborated this assumption by showing that uniform target presentation rates lead to a uniform false alarm distribution (see Supplement 2). Subsequent analysis was performed on the pooled hit rate and false alarm rates by combining the results across participants in each group[18,52,53]. Sensitivity (d') was calculated using the pooled hit and false alarm rates only at the first temporal epoch for both conditions in order to assess selective attention ability. The 95% CI for the sensitivity measures were calculated using Miller's approach[54] (see Figure 4). Also, hit or false alarm rate values of 0 or 1 were adjusted by 1/2n or 1-1/2n respectively where n is the number of trials at each epoch to compensate for extreme values (i.e. 0 and 1) in the calculation[52].

In order to predict the temporal reorientation time, we modelled the hit rate from the unexpected epochs with a line of best fit (linear least square interpolation) and extrapolated to the epoch at which the hit rate reached 1 standard error of the expected epoch (see Figure 2A). An adjusted chi-square test was used to calculate the goodness of fit.

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Author Contributions Statement

I.D. and M.S conceived the overall concept for the project. I.D. and J.L. designed the experiments. I.D. recruited the participants, collected the data and performed the analysis. The manuscript was mainly prepared by I.D. and J.L. with input from S.C. and M.S. I.D. created the figures. All authors reviewed the manuscript.

Competing financial interests

The authors declare no competing financial interests.

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Figure 1: A time domain view of the stimulus presented in a test trial within an experimental block ("Early" Condition) in which the target was presented frequently and cued at the first temporal epoch. **A** – Cue-Tone (2500 Hz); **B** – Target (da) validly cued and occurs in 60% of trials at this epoch; **C** – 2 Talker Babble (Female); **D** – Target (da) invalidly cued and occurs in 20% of trials at these epoch

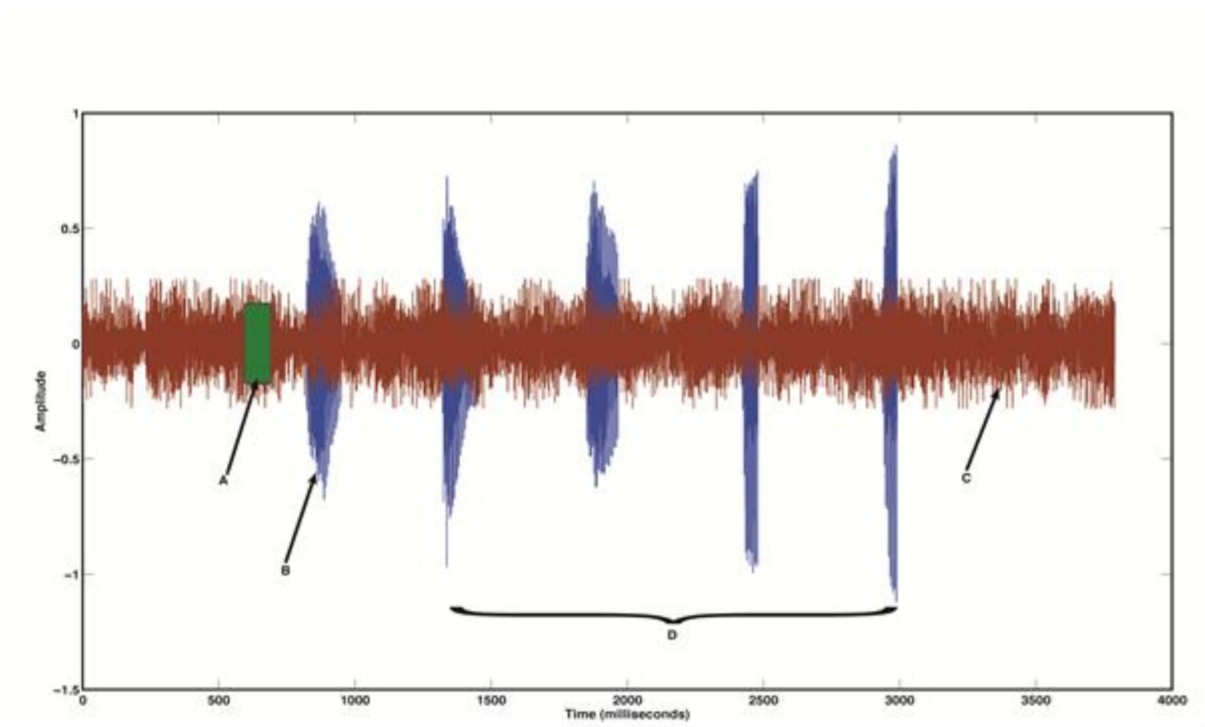

Figure 2A and 2B: Pooled hit and false alarm rates for target identification for the 3 groups in the "Early" Condition across the 5 temporal epochs. The blue bars represent the data for the adult participants with no listening difficulty, the green bars for the children with no listening difficulty and the red bars for children with listening difficulty. The green and red dashed line in figure 2A are the lines of best fit used to extrapolate the attention re-orientation time for children without and with listening difficulties respectively. Error bars represent standard errors of the mean.

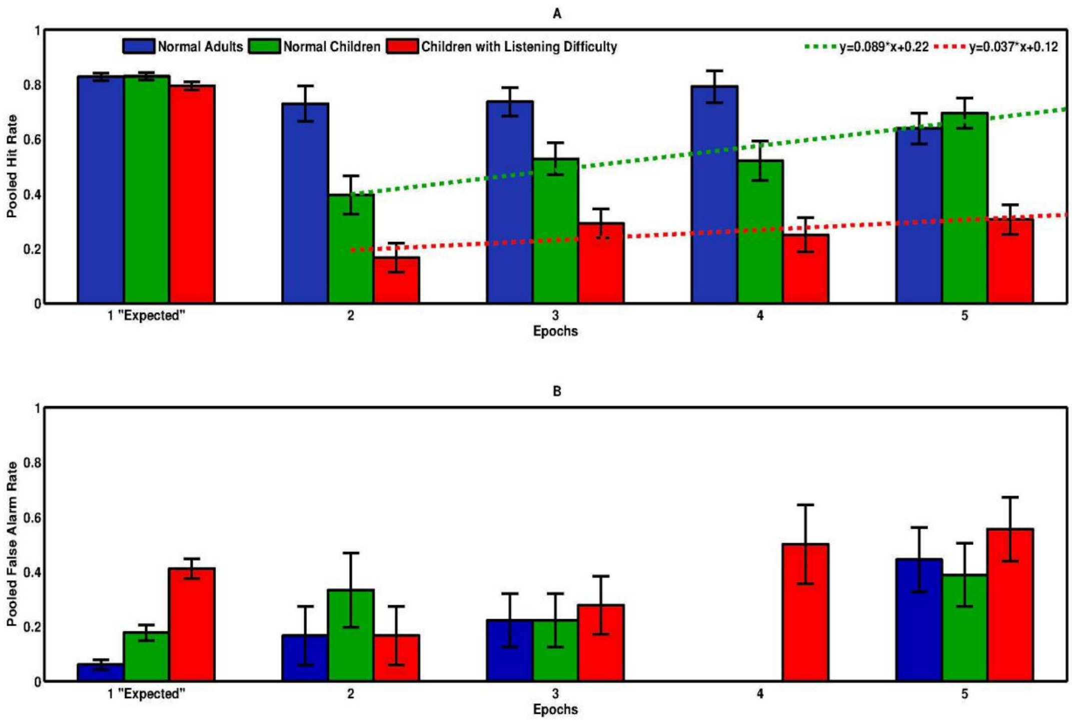

Figure 3A and 3B: Pooled hit and false alarm rates for target identification for the 3 groups in the "Late" Condition across the 5 temporal epochs. The blue bars represent the data for the adult participants with no listening difficulty, the green bars for the children with no listening difficulty and the red bars for children with listening difficulty. Error bars represent standard errors of the mean.

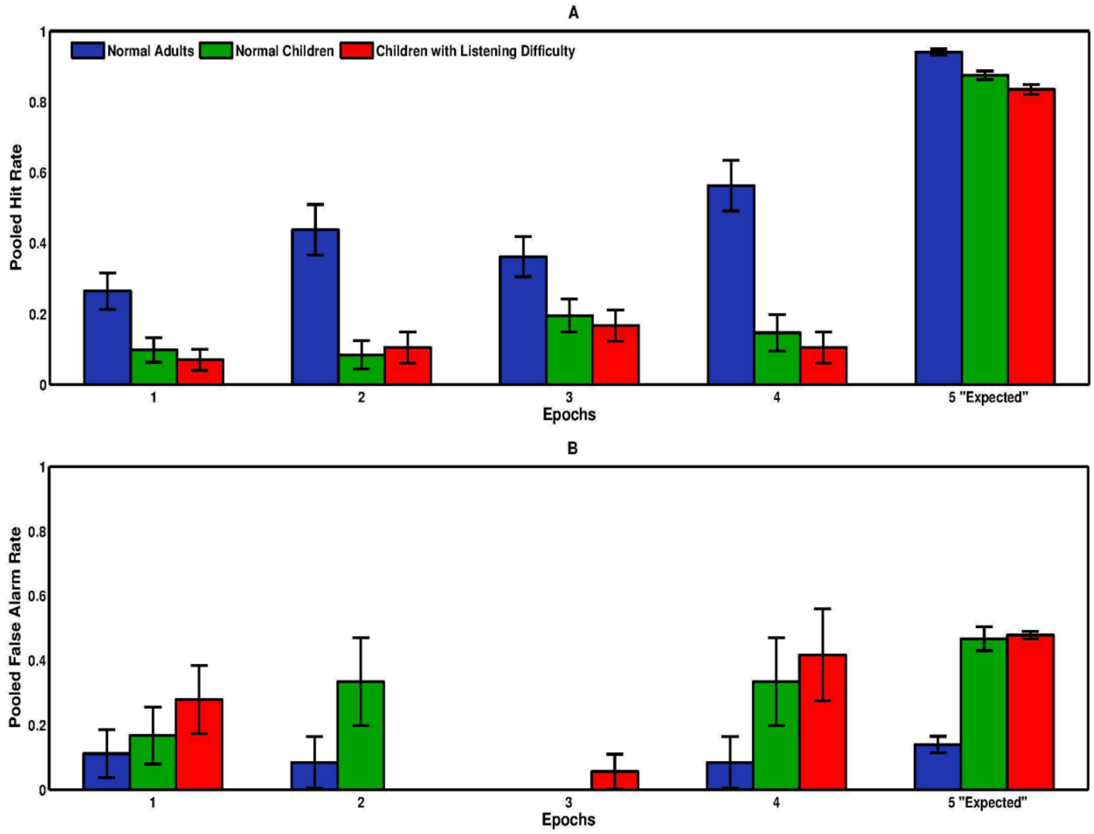

Figure 4: Pooled sensitivity (d') for target identification at the expected epochs for the 3 groups for "Early" and "Late" conditions. The blue bars represent the data for the adult participants with no listening difficulty, the green bars for the children with no listening difficulty and the red bars for children with listening difficulty. Error bars represent the 95% confidence intervals. * – Substantial Difference; NS – Non-substantial difference

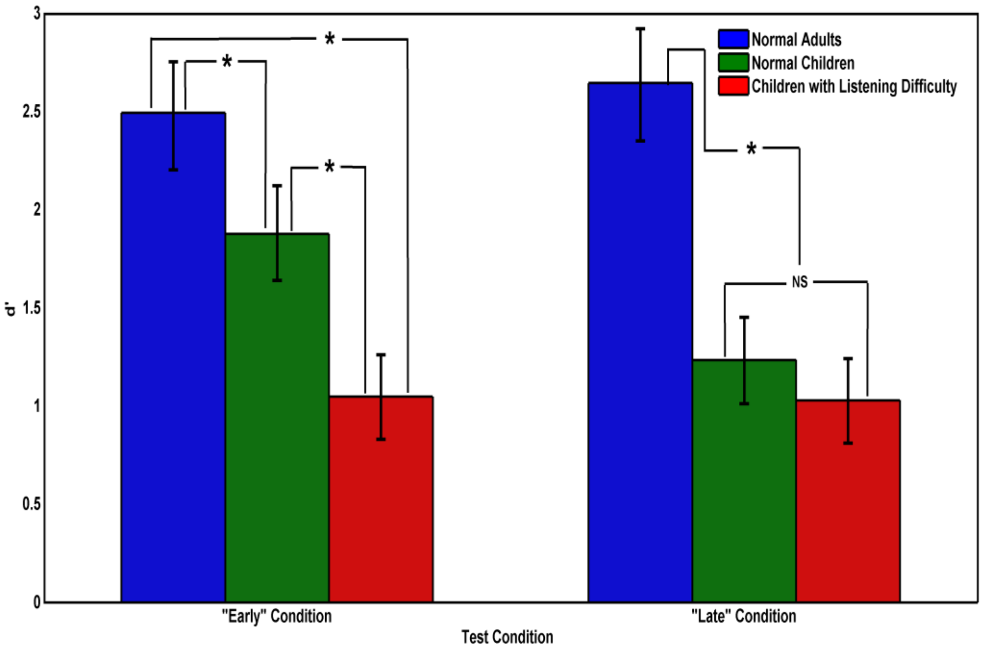

Table 1: Details of assessment measures, skills and tests undertaken in the current study to investigate peripheral hearing, auditory processing skills, auditory memory and attention

Measures	***Skills***	***Tests***
Peripheral Hearing	*Hearing sensitivity*	*Pure tone audiometry*
	Middle ear integrity	*Immittance audiometry*
Spectral Processing	*Frequency Discrimination*	*Brief tone frequency discrimination test*[55]
Temporal Processing	*Temporal resolution*	*Gap detection in noise test*[56]
	Temporal ordering	*Pitch pattern test*[23]
	Temporal envelope processing	*Sinusoidal amplitude modulation detection threshold*[57]
	Temporal fine structure processing	*Low frequency fine structure - Inter aural phase sensitivity (TFS-LF)*[58]
		High frequency fine structure - phase shifted harmonic discrimination (TFS1)[58]
Binaural Processing	*Binaural integration*	*Dichotic digits test*[23]
	Binaural separation	*Binaural masking level difference test*[23]
	Localization	*Speech localization in presence of 2 talker babble*[59]
Auditory Stream Segregation	*Sequential stream segregation*	*ABA_ paradigm (temporal coherence boundary)*[60]
	Spatial stream segregation	*Listening in Spatialized noise test (LiSN-S)*[46]
Speech Perception in Noise	*Speech recognition in presence of Spatialized noise.*	*High Cue SRT condition of LISN-S test*[46]
Auditory Memory	*Short term and working memory*	*Forward and Backward Digit span test*[41]
Auditory Attention	Sustained attention	*Auditory Continous Performance Test*[42]
	Selective attention and Attention switching	*Test Developed in the current study*

Table 2: Mean scores with standard errors for auditory processing, memory and attention tests. There was no significant difference between the 2 groups for any of the tests (p>0.05). For the tests marked with an asterisk the individual scores for normal children were also within the previously published[42,43]age based normative data.

Tests	***Normal Children***	***Children with Listening Difficulty***
Brief tone frequency discrimination (threshold in Hz)	100 Hz: 6.15 Hz (0.84) 1000 Hz: 5.43 Hz (1.04)	100 Hz: 6.54 Hz (1.05) 1000 Hz:6.70 Hz (1.37
Gap detection in noise (threshold in ms)	2.92 ms (0.27)	3 ms (0.30)
Pitch pattern (Percentage correct score)*	Right: 92.21% (2.14) Left: 92.76% (1.91)	Right:91.93% (2.85) Left: 92.2% (1.85)
SAM detection (threshold in dB)	4 Hz: -23.79 dB (0.55) 128 Hz: -20.97 dB (0.71)	4 Hz: -22.21 dB(0.78) 128 Hz: -19.59 dB (1.34)
TFS-LF[58] (Interaural phase difference threshold in degrees)	44.05 deg (5.05)	35.23 deg (3.04)
TFS1[58] *(score in Hz)*	24.5 Hz (4.43)	28.39 Hz (3.41)
Dichotic digits (Percentage correct score)*	Right: 98.49% (0.89) Left: 94.81% (2.3)	Right:95.23% (1.31) Left: 93.24% (1.70)
*Binaural masking level diffference** (difference in dB)	12 dB (1.2)	12.08 dB (0.80)
Localization (Root mean square lateral and polar angle errors (LAE and PAE) in Azimuth)	LAE:11.5 Az (0.9) PAE: 14.25 Az (0.72)	LAE: 14.58 Az (1.43) PAE: 13.08 Az (0.57)
Sequential stream segregation (temporal coherence boundary in Hz)	60.92 Hz (9.90)	80.90 Hz (9.69)
Spatial stream segregation (spatial advantage raw score)*	11.90 (0.70)	11.44 (0.56)
*Speech Recognition in Noise** (Signal to masker ratio threshold in dB)	SRT: -15 dB (0.6)	SRT:-13.74 dB (0.78)
Digit Span (Forward and backward digit span raw score)*	Forward: 9.33 (0.54) Backward: 7.08 (0.49)	Forward: 8.5 (0.59) Backward: 5.57 (0.25)
Auditory Continous Performance (raw scores)*	Inattention: 2.25 (0.65) Impulsivity: 1.08 (0.66) Vigilance: 0.66 (0.28)	Inattention: 4.08 (1.08) Impulsivity: 1.5 (0.59) Vigilance: 1 (0.30)

Switch Attention to Listen

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Supplementary Information

Supplement 1

Auditory Processing Assessment

The psychophysical test paradigm for assessing auditory stream segregation, frequency discrimination and amplitude modulation detection (See Table 1 for details) consisted of 10 trials at random intervals in which the stimulus difference was kept intentionally large to monitor attentional lapses. We also monitored each participant's performance based on the variability of their track widths (standard deviations) in the tests and repeated the tests if there was an evidence of attentional lapse or variable track width[1,2].

Additional Analysis

The data for hit and false alarm rates was pooled across participants within the same group based on the finding of similar response bias across participants within the same group. We assessed the data for normality using a 2 tailed Shapiro–Wilk test and found the data to be normally distributed. Although, the statistical test used to test the hypothesis did not allow us to get specific significance level values (p values), to our knowledge, there is only a limited scope of comparison of such data otherwise.

To the best of our knowledge, there is no literature suggesting an appropriate procedure for calculating d primes in the test paradigm that we have used in this study. The confidence intervals observed were much larger at the unexpected temporal epochs in contrast to the expected ones due to the fewer number of trials at those epochs an thus were not graphically represented. During the calculation of target identification sensitivity, we observed few negative d' values at the unexpected temporal epochs which were normalized to zero based on previous treatment of such data and the fact that the 95% confidence intervals for sensitivity on those epochs included zero suggesting a sampling error[3].

The presence of negative d' values for target identification at the unexpected temporal epochs suggest that the false-alarm rate was greater than the hit rate at those epochs. If the participants had responded only on the basis of the expected epoch, it would have yielded chance (very low) unexpected interval d' values. However, the observation of some negative d' values at the unexpected epochs suggested that the participants responded on the basis of the full interval and shifted their response criterion consistent with target expectation.

In addition to comparing pooled hit and false alarm rates, we also compared the mean derived from individual participant's results and found similar results as obtained with pooled rates. We also measured response bias, which was calculated in terms of the criterion and is a measure of the participants' decision variable to respond to a target[4]. A liberal criterion (negative value) would suggest a bias of the participant toward responding yes, regardless of the stimulus and a conservative criterion (positive value) would indicate a bias towards responding no[3,4]. The analysis of the response criterion across the 5 epochs indicated shifts in response criterion ranging from a relatively lax criterion to a more conservative criterion, consistent with target expectancies for both the group of participants suggesting that they responded to the target on the basis of the full trial interval and not only on the basis of the expected epoch, whereby they chose a relatively neutral criterion at the expected epoch and became gradually more conservative in their responses till epoch 4. A gradual increase in the hit rates across the epochs may further indicate that the listeners may soon realize the in-appropriateness of this strategy and re-adopt a more cautious listening strategy towards the later epochs. Alternatively it is also possible that the listeners may not have a voluntary control of their selective listening window in time[5].

There was a sudden change in the response criterion observed at the last epoch in which the participants became more liberal in their response criterion perhaps due to an inability to sustain the listening efforts in the task for the entire listening interval. In contrast to the controls, the participants in the experimental group chose a stricter criterion (i.e. bias towards responding no) for responding to targets presented in the 2nd temporal epoch suggesting that they may have momentarily employed a listening strategy that required relatively less effort[5], thereby missing unexpected information especially in a noisy background. As the participants were clearly instructed to press the response button when they identified the target syllable regardless of when it occurs in a trial, the probability of the participants not responding to the target presented at the unexpected interval despite identifying it, would be minimal[5,6].

Supplement 2

Control experiments

As part of additional control experiments, we also analyzed the reliability (internal consistency) of the test, the effect of target occurrence probability on the distribution of false alarms at different epochs, the possibility of interfering (forward masking) effects of the cue on target identification and the effect of serial position of the target on identification.

Split-half reliability (Internal consistency)

In order to assess the reliability of the test we assessed both the test blocks in two split halves of 60 trials each in a randomized order for all the participants (i.e. adult, control and experimental groups). We measured the split-half reliability by correlating (re-adjusted using the spearman-brown formula) the hit rates between the two halves due to constraints of testing time and found the test to be highly reliable ($r>0.8$).

False Alarm Distribution

This experiment was conducted on a small group of children (10-15 years; 8 controls and 8 experimental) in order to measure the distribution of false alarms on each temporal epoch when the target was equally probable to occur (20%) at each of the epochs. This was done to facilitate the allocation of catch trials for test blocks in which the target was unequally distributed at the various epochs. We compared the false alarm rate across the 5 epochs in such a control block in which the target was cued but occurred with equal probability at each of the epochs. No notable differences ($p>0.05$) were found across the epochs and between the two groups suggesting approximately equal distribution of false alarms. This suggests that the distribution of false alarms at the epochs would vary as a function of probability of target occurrence at that epoch.

Forward masking interference of the cue

We tested this by comparing the hit rates for 2 control blocks administered on 8 control and 8 experimental group participants. The target had equal probability of occurrence at each epoch for both the blocks. In the first block the target was cued whereas in the second block it was not. We observed a noticeable improvement in hit rates across the five epochs in the cued block compared to the un-cued block which rules out the possibility of the tonal cue reducing the hit rates for target identification, possibly due to a forward masking effect.

Reaction Time advantage and Serial position effect

We administered 5 test blocks in a random order on a smaller subgroup of 6 adult participants (18-30 years; Mean age=21.2; SD=2.68) in which the target was cued and frequently presented (60% trials) at each of the 5 epochs (Similar in structure to the test blocks used in "Early" and "Late" conditions in the main experiment). These test blocks were administered to study the effect of serial position of target on hit rates. As we had compared blocks in which the target was expected at the first and last serial position in experiment 2 with an aim to assess selective attention, a possibility of a bias in hit rates at those extreme positions compared to the middle ones due to limitation in short term memory capacity must be ruled out (primacy and recency effect). The results indicated no substantial difference in hit rates at each of the epochs when it was expected ($p>0.05$). This finding rules out the possibility of either an inherent reaction time advantage or the contribution of the serial position effect at a specific epoch due to short term memory capacity limitations[7]. In part, this was also facilitated by our experimental design using a go/no-go button press response to a rapidly presented auditory stimulus.

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Chapter 4 (Study 3)

Evaluation of Auditory Attention, Processing and Memory in School-aged Children with Listening Difficulties in Noisy Environments

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Evaluation of Auditory Attention, Processing and Memory in School-aged Children with Listening Difficulties in Noisy Environments

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Abstract

The aim of this study was to examine selected auditory attention, processing and memory skills for children who present with difficulties listening in noisy environments despite having clinically normal hearing sensitivity. Twenty-one children with listening difficulty in background noise (LND group) and fifteen children with no listening concerns (Control group) participated in the study. The research was conducted in three phases. Phase 1 involved evaluating all the children for their auditory attention switching ability. Results revealed that LND group were significantly slower in switching their auditory attention and had poorer inhibitory control. In Phase 2 we administered a set of recommended clinical tests with an aim to determine if the children in the LND group also had auditory processing disorder (APD). Only 5 (out of 21) showed significantly poor performance on the frequency pattern test and were subsequently diagnosed to have APD. Phase 3 further explored additional auditory processing as well as memory skills. Results revealed that the subset of children diagnosed with APD showed poorer frequency resolution and working memory ability. In summary, consistent with the results of our previous study, all the children in the LND group showed deficits in attention switching and inhibitory control and only a subset of these had APD involving frequency resolution and working memory deficit.

Keywords: Listening difficulties, auditory processing disorder, attention switching, frequency discrimination, memory

Introduction

Some children in spite of normal hearing sensitivity, report persistent listening difficulties especially in noisy environments such as classrooms (Hind et al., 2011; Lagacé, Jutras, & Gagné, 2010; Moore, Rosen, Bamiou, Campbell, & Sirimanna, 2012). In addition to hearing sensitivity, listening in presence of background noise has been suggested to also depend upon abilities such as auditory attention, processing and memory (Bronkhorst, 2000; Brungart & Simpson, 2007; Conway, Cowan, & Bunting, 2001; Haykin & Chen, 2005; McDermott, 2009). In the current study, the aim was to evaluate auditory attention, processing and memory ability in children with reported listening difficulty in the presence of background noise (LND group). The study was conducted in 3 phases. In Phase 1 we assessed auditory attention, specifically auditory attention switching ability (Dhamani, Leung, Carlile, & Sharma, 2013). Phase 2 involved testing a range of auditory processing abilities using a set of standard clinical tests (American Academy of Audiology, 2010; Emanuel, 2002; Jerger & Musiek, 2000). Lastly, in Phase 3 we assessed an additional set of auditory processing skills including frequency resolution as well as short term and working memory skills.

It has been suggested that auditory attention is an important factor influencing the ability to listen in the presence of background noise (Fritz, Elhilali, David, & Shamma, 2007; Sturm, Willmes, Orgass, & Hartje, 1997). Evidence for attention deficits in children with listening difficulties has been shown in two recent studies (Dhamani, et al., 2013; Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010). Auditory attention can be classified into different forms such as phasic alertness, sustained attention, selective attention and attention switching ability (Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000; Sturm, et al., 1997). In a majority of listening situations involving multiple talkers and distractors, there is often an overlap of different relevant sources of auditory information in space. Such situations require the listener to selectively focus attention to the target information (selective attention) and switch his focus between different sources of information (attention switching) in time based on their relevance (Astheimer & Sanders, 2009). In an earlier study (Dhamani, et al., 2013), we designed a psychophysical paradigm that revealed substantially longer attention re-orientation time and hence poor attention switching ability in children with listening difficulties in presence of background noise. In Phase 1 of the current study, we applied this novel test on the current group of participants to determine if they had attention re-orientation difficulties.

There have also been suggestions that a proportion of children who complain of listening difficulties especially in presence of noise may have deficits in auditory processing and subsequently get diagnosed with an auditory processing disorder (APD) (Bamiou, Musiek, & Luxon, 2001; Lagacé, et al., 2010; Moore, et al., 2012). Auditory processing disorder (APD) is characterized as a neural dysfunction which leads to deficits in processing speech as well as non-speech sounds (Moore, et al., 2012). The Phase 2 of the present study was aimed at identifying the presence of an auditory processing disorder for the children in the LD group based on their performance on a set of recommended clinical tests (American Academy of Audiology, 2010).

The recommended clinical test battery used by audiologists to evaluate children with listening difficulties usually encompasses the testing of a wide range of auditory processing and cognitive skills (American Academy of Audiology, 2010; Emanuel, 2002; Jerger & Musiek, 2000). However, some additional skills such as frequency resolution, auditory stream segregation, localization, temporal envelope/fine structure perception, auditory short term/working memory although suggested in literature to be crucial to listening in noise, are not routinely assessed for children with listening difficulties(American Academy of Audiology, 2010; Parthasarathy, 2006). Studies undertaken in populations with dyslexia and language impairment, who also often complain of listening difficulty in background noise (Alcántara, Weisblatt, Moore, & Bolton, 2004; Ziegler, Pech-Georgel, George, & Lorenzi, 2011; Ziegler, Pech-Georgel, George, & Lorenzi, 2009), suggest deficits in their auditory stream segregation (Démonet, Batty, Chaix, & Taylor, 2006; Helenius, Uutela, & Hari, 1999; Lepistö et al., 2009), frequency resolution (Halliday, 2006; McArthur & Bishop, 2004), temporal envelope processing (Cohen-Mimran & Sapir, 2007; Rocheron, Lorenzi, Füllgrabe, & Dumont, 2002) and memory (Gathercole & Alloway, 2005; Montgomery, Magimairaj, & Finney, 2010; Nelson & Warrington, 1980). In Phase 3 we assessed the children with listening difficulties on additional set of tasks to investigate their frequency resolution, auditory stream segregation, temporal envelope/fine structure perception, localization as well as short term and working memory skills.

Frequency resolution has often been reported to be an area of difficulty for individuals who have listening difficulty in background noise (Badri, Siegel, & Wright, 2011; Strelcyk & Dau, 2009). Frequency resolution in the current study was measured using a frequency discrimination task (Moore, 1997). Poor performance on frequency discrimination tasks using short duration pure tones has been observed in populations associated with central auditory dysfunction such as children with a history of recurrent otitis media with effusion (OME) (Cranford, Thompson, Hoyer, & Faires, 1997), children with reading disorders (Walker, Givens, Cranford, Holbert, & Walker, 2006), older age listeners (Cranford & Stream, 1991) and patients with temporal lobe lesions (Cranford, Stream, Rye, & Slade, 1982). We thus focussed on measuring the frequency discrimination thresholds for short duration (100 ms) pure tones in this study.

Temporal processing refers to the ability to analyse the time based cues within the sounds and includes envelope and fine structure encoding ability (Shinn, 2003). Temporal envelope encoding is important for the analysis of the relatively slow fluctuations in the overall amplitude (2-500 Hz) in speech which facilitate the processing of information related to the manner of articulation, voicing and prosodic information such as intonation and stress (Rosen, 1992; Zeng et al., 2004). Earlier studies have reported a deficit in encoding temporal envelope cues in children with disabilities such as dyslexia, specific language impairment and autism (Alcántara, Cope, Cope, & Weisblatt, 2012; Lorenzi, Dumont, & Fullgrabe, 2000; Rocheron, et al., 2002; Wright et al., 1997). Temporal fine structure encoding refers to the processing of rapid (500 Hz-10 kHz) amplitude fluctuations of speech (Rosen, 1992). The encoding of temporal fine structure is known to be important for pitch and timbre perception as well as for speech perception in degraded listening environments such as in presence of noise or reverberation (Assmann & Summerfield, 2004; Hopkins & Moore, 2009; Moore, 2008). Previous studies have reported a correlation between the performance on tasks to assess temporal fine structure processing and speech perception in noise ability (Strelcyk & Dau, 2009). Therefore, in the current study we aimed to assess the temporal envelope and fine structure encoding ability for the participants.

Auditory stream segregation that occurs sequentially across time is termed as sequential stream segregation and involves grouping of sounds from the same source across time (Bregman, 1994; Shamma & Elhilali, 2008). Previous studies conducted on adult participants have shown a correlation between sequential stream segregation and the ability to understand speech in noise (Mackersie, Prida, & Stiles, 2001; Oxenham, 2008). Amongst the factors that facilitate sequential stream segregation, pitch cues based on the frequency separation between sounds are known to be of paramount importance (Moore & Gockel, 2002; Oxenham, 2008). Studies have also indicated a weak but positive correlation between auditory stream segregation and frequency discrimination in normal and hearing impaired listeners (Rose & Moore, 2005). The focus of the present study was to examine auditory sequential stream segregation predominantly based on pitch cues.

Spatial localization of the sound source in addition to facilitating the separation of relevant speech from the distracters based on their location also assists in selective allocation of attention resources to the relevant information (Kidd, Arbogast, Mason, & Gallun, 2005; Middlebrooks & Green, 1991). Earlier investigations of localization ability (measured in quiet anechoic as well as reverberant environment) in children with a prolonged history of recurrent OME indicated poor localization accuracy (Besing & Koehnke, 1995; Hall 3rd, Grose, & Pillsbury, 1995; Hogan & Moore, 2003). We thus focussed on examining the ability to localize sound sources (speech syllable) in presence of competing maskers for the participants using a single-source localization task in free-field.

Auditory short term and working memory skills facilitate speech understanding in presence of noise by temporarily storing and actively processing the auditory information to link related information across time and form coherent representations while ignoring irrelevant distraction (Arlinger, Lunner, Lyxell, & Pichora-Fuller, 2009; Conway, et al., 2001; Kraus, Strait, & Parbery-Clark, 2012; Pichora-Fuller, Schneider, & Daneman, 1995). Previous studies have shown poor auditory short term memory for children with APD (Maerlender, 2010; Maerlender, Wallis, & Isquith, 2004). Moreover, earlier studies conducted on adult listeners indicated that the performance of participants on speech recognition in presence of competing speech has been reported to be strongly correlated to verbal working memory skills (Kraus, et al., 2012; Meister et al., 2013; Rudner, Lunner, Behrens, Sundewall Thorén, & Rönnberg, 2012). We used a digit span test (Spreen & Strauss, 1998) in the current study to assess the short term/working memory skills of the children.

Thus the overall aim of the current study was to investigate if children with listening difficulties in noise have attention switching, auditory processing and/or memory deficits.

Method

Subjects

Fifteen children (10-15 yrs.; 12.53±0.40 yrs.) with no listening difficulty (Control group) and twenty-one children (10-15 yrs.; 12.55±0.47 yrs.) with self, teacher and parental reports of listening difficulties in noisy backgrounds (LND group) participated in the current study. The participants with listening in noise difficulty were recruited through 2 main modes namely 1) advertisement published in local health magazine asking for parents who had concerns with their child's listening ability in noisy backgrounds to participate in this study 2) information brochures provided to parents who reported the Macquarie University Audiology clinic with concerns regarding their child's listening ability. All subjects spoke Australian English as their first language and had normal hearing sensitivity (250-8000 Hz) on clinical evaluation. None of the participants presented with a middle ear pathology at the time of testing which was confirmed by clinically normal findings for otoscopy, tympanometry and acoustic stapedial reflex thresholds. Participants who had a history or formal diagnosis of attention deficit/hyperactivity disorder (ADHD) were excluded from this study.

Procedure

A questionnaire was given to the parents of all the participants to acquire information regarding their academic, hearing, listening and behavioural history. Additionally, the parents were also asked to rate their child's hearing, listening, attention, and memory as well as reading ability on an informal rating scale (Scale of 0-5, where, 0 = very good and 5 = very poor). Each test session was of 3 hours duration and all the testing was distributed across 3-4 sessions within 2 weeks duration. Care was taken to avoid participant fatigue and loss of motivation by constant engagement with the participants, breaks and positive reinforcement. The test order within each phase of the study was randomized and counter-balanced to avoid any bias. All the sounds used in the experiments were generated on a PC at 48000 Hz sampling rate (16 bits) and routed via a USB based computer sound interface (RME Fireface 400) connected to either headphones (Beyerdynamic DT 990 pro) or loudspeakers (Tannoy V6). The stimuli that were used to assess auditory processing skills were selected with an aim to minimize the influence of prior linguistic knowledge or competency on the performance. All the participants underwent the same number of practice trials for each of the tasks to ensure that they were well understood. An informed consent was obtained from all the participants and the study was conducted in compliance with the guidelines of the Human Research Ethics committee at Macquarie University.

Phase 1

Selective attention and attention switching task

The stimulus, procedure and analysis for this task were the same as described in our previous study (Dhamani, et al., 2013). In summary, the task required the participants to identify the presence of a target syllable (/da/) amongst a sequence of 5 syllables in the presence of a competing two talker speech babble. We cued the targets using a short duration (100 ms) pure tone (2500 Hz) and presented the targets more frequently at the beginning of the stimulus sequence along with infrequent presentations of target at unexpected time windows (See figure 1). Additionally, there were also catch trials which did not have the presence of target within the sequence. The responses of the participants were then analyzed in the form of pooled hit and false alarm rates (Werner, Parrish, & Holmer, 2009). The values of hit and false alarm rates will be represented as mean ± standard error. We used pooled statistics to compare between different proportions (MacMillan & Creelman, 2005; Macmillan & Kaplan, 1985). The 2 proportion were considered significantly different ($p<0.05$) if their 95% confidence intervals did not overlap (Werner, et al., 2009). The attention re-orientation time was calculated by extrapolating the epoch in the "early" condition at which the participant's hit rate recovered to within 1 standard error of that on the expected epoch. This extrapolation was done using a simple line of best fit (linear least square interpolation).

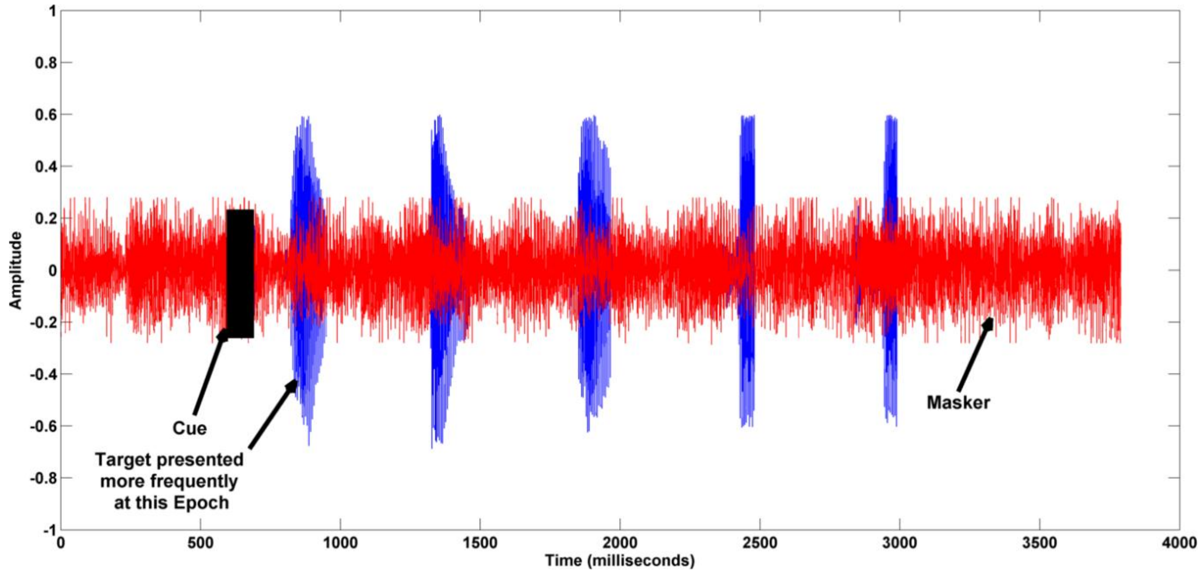

Figure 1: Schematic of a stimulus block used for the attention switching task.

Phase 2

In this experiment we used a battery of recommended clinical tests (American Academy of Audiology, 2010) with an aim to identify the presence of an APD in the participants. This test battery consisted of the frequency pattern (Musiek, 2002) (FPT), dichotic digits (Musiek, 1983), binaural masking level difference (Wilson, Moncrieff, Townsend, & Pillion, 2003), gap detection in noise (Baker, Jayewardene, Sayle, & Saeed, 2008), auditory continuous performance (Keith & Engineer, 1991; Riccio, Cohen, Hynd, & Keith, 1996) and the LISN-S (Dillon, Cameron, Glyde, Wilson, & Tomlin, 2012) test. The diagnostic criterion for APD was based on the guidelines suggested by American Speech-Language and Hearing Association (2005) and previously published age based normative data (Bellis, 2003; Kelly, 2007). The details regarding the stimuli, procedure, implementation and interpretation of these tests have been discussed extensively in previous literature (See Table 1). The participants were tested twice within a span of 2 weeks on tasks on which they showed poor performance to confirm the scores.

Phase 3

The objective in this phase was to assess frequency resolution, auditory stream segregation, spatial localization, temporal envelope perception, temporal fine structure perception as well as short term and working memory skills for the participants. The details regarding the stimulus and procedure for the tasks used in this phase have been summarized in Table 2 and the further details are provided in the supplementary material.

Results and Discussion

The analysis of the data from the questionnaire indicated that all participants in the LND group indicated a history of recurrent (>3 episodes, Mean = 3.42, SD = 1.43) OME. There were no reports of a history of OME for children in the Control group. All the participants were reported by their parents to have normal motor developmental milestones. There were also no significant difference ($p>0.05$) between the age of the participants in the Control and LND group. The statistical analysis (Mann-Whitney U test) of the rating scale data suggested that the parental rating for attention and memory concern ($p=0.001$), listening ability in quiet ($p=0.004$) and listening in noise ability ($p=0.000$) for the children in the LND group were significantly poorer than the control group (See figure 2).

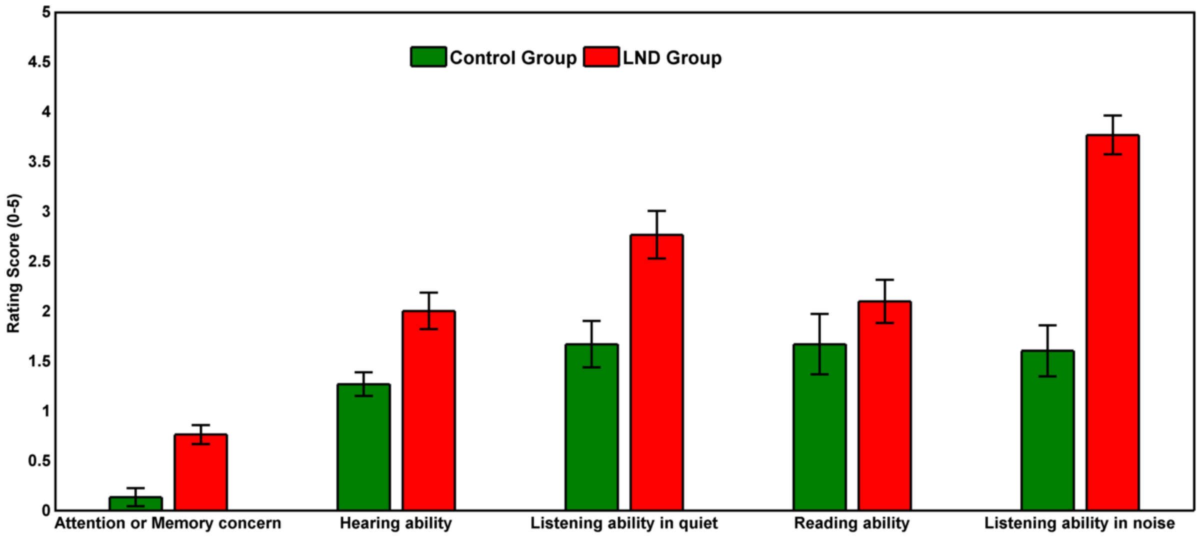

Figure 2: Mean and standard error of the parental rating scores for the 2 groups of participants.

Phase 1

As expected, the hit rates for both the groups (Control and LND) were significantly higher at the expected epoch compared to that at the unexpected epochs. The main aim was to measure the predicted time at which the participants would be able to recover their hit rate at the unexpected epochs. The extrapolation of the hit rates for the Control group ($y = 0.098*x + 0.26$, adjusted $R^2 = 0.93$) revealed that these participants would recover their hit rate from 0.8233 ±0.012 at the expected epoch to 0.851±0.12 at 2.75±0.067 seconds (See figure 3). On the other hand, the extrapolation of hit rates for the LND group ($y=0.045*x+0.14$, adjusted R^2

=0.88) indicated that they would recover their hit rate (from 0.80±0.01 at the expected epoch to 0.82±0.25) at 7.92±0.57 seconds. Thus, based on these findings, the LND group take substantially and significantly longer time (p=0.00) to re-orient their attention to the targets occurring at the unexpected epochs and subsequently recover their hit rates as compared to the Controls. These results are consistent with our earlier study where we reported longer attention re-orientation time for children with listening difficulties in noise (Dhamani, et al., 2013). Such a deficit in the ability to switch and rapidly re-orient attention may lead to a difficulty in monitoring incoming information from multiple relevant sources and thus partly explain the listening difficulties reported by the children in noisy or multi-talker environments.

Additionally, the comparison of false alarm rates between the 2 groups indicated significantly higher false alarm rate for the LND group (0.34±0.02 versus 0.16±0.02) at the expected epoch (See figure 4). Moreover the LND group also showed significantly higher overall false alarm rates (combined across the 5 epochs) than the Control group (0.33±0.02 versus 0.19±0.02). These findings may suggest poor ability to inhibit responses in the LND group. A poor inhibitory control in the LND group may affect their ability to voluntarily inhibit the allocation of attention to irrelevant stimuli in a noisy environment. This may then subsequently lead to increased distractibility and listening difficulties. Overall, the results of phase 1 of the study indicated poor attention switching and inhibitory control ability in the LND group compared to the Controls. Previous studies have also shown a link between attention switching and inhibitory control ability (Barrouillet & Camos, 2001; Berti & Schröger, 2003; Fillmore, Milich, & Lorch, 2009; Lépine, Bernardin, & Barrouillet, 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Redick, Calvo, Gay, & Engle, 2011). Both these abilities have been suggested in earlier studies to predominantly involve top-down processing ability (Coull, Vidal, Nazarian, & Macar, 2004; Dhamani, et al., 2013; Li, Huang, Constable, & Sinha, 2006) which may indicate a possible top down (central) information processing deficit in these children.

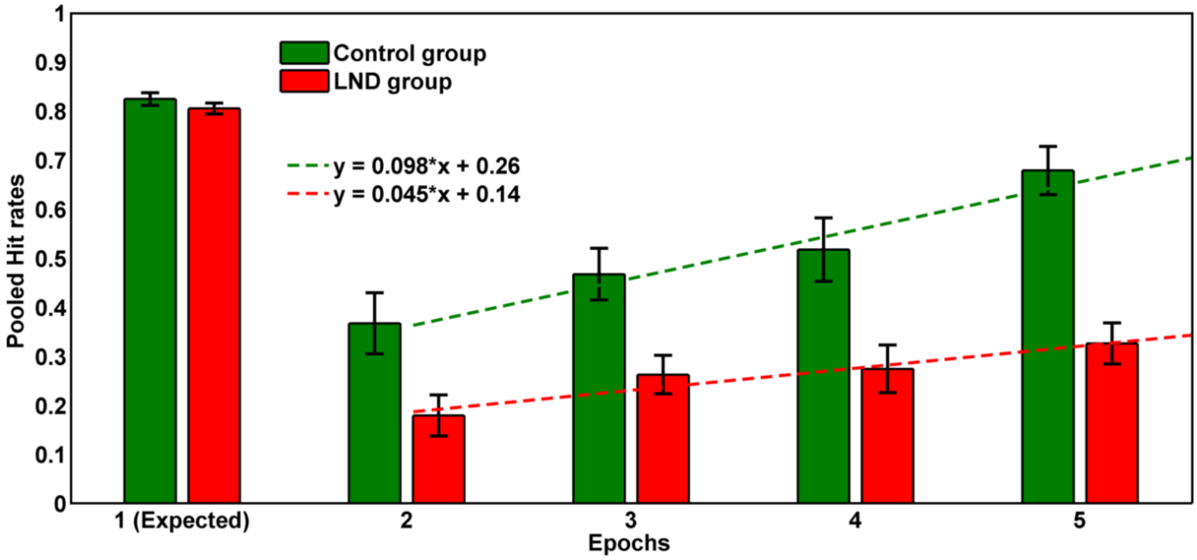

Figure 3: Pooled hit rates for target identification across the 5 temporal epochs. The green and red dashed line are the lines of best fits used to extrapolate the attention re-orientation time for the Control and LND groups respectively. Error bars represent standard errors of the mean.

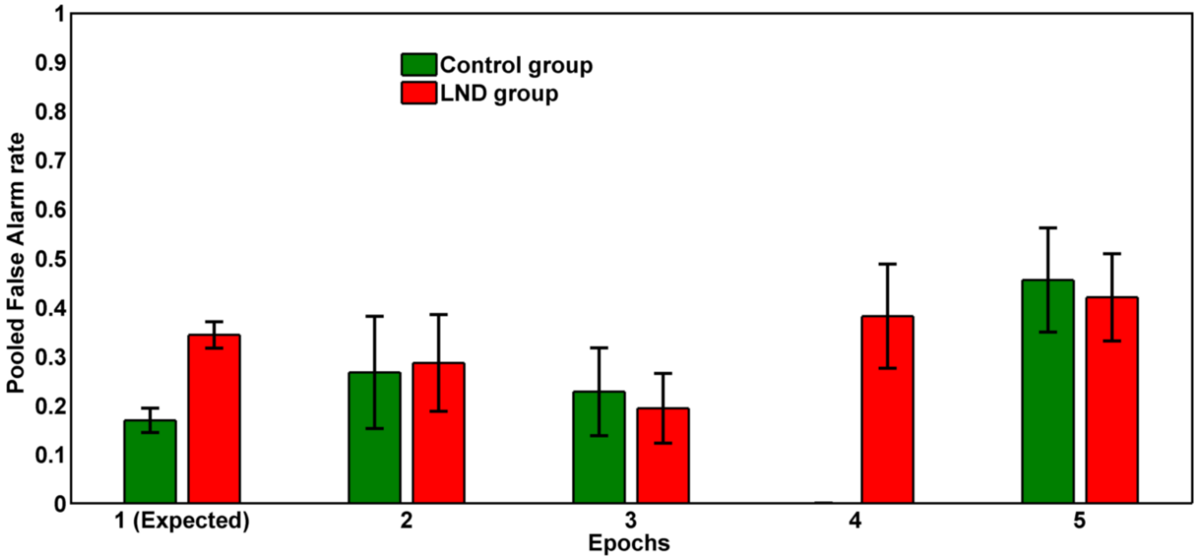

Figure 4: Pooled false alarm rates across the 5 temporal epochs. Error bars represent standard errors of the mean.

Phase 2

The main aim of this phase of research was to identify if the participants in the LND group could be identified as having an auditory processing disorder based on a set of recommended clinical tests (See Table 1). Only five children in the LND group performed poorly (performance scores lower than 3 standard deviations (SD) from the age based norm (Bellis, 2003; Kelly, 2007) on the frequency pattern test (FPT) and were subsequently diagnosed as having an APD. All the children who had difficulty on FPT task showed scores close to 3 SD below the norms. These children also had no significant differences between their FPT test scores (p=0.064) on a repeated test administered within 2 weeks from date of the first test. Additionally, none of the other children from the LND group could be diagnosed as APD despite using a relatively lax diagnostic criterion of 2 SD below norms. These children also had no significant differences between their FPT test scores (p=0.064) on a repeated test administered within 2 weeks from date of the first test. FPT requires skills such as frequency discrimination, temporal ordering, linguistic labelling, memory and attention (Musiek, 2002;

Musiek & Pinheiro, 1987). Poor performance on FPT could thus be attributed to a deficit in either of the above mentioned skills (Musiek, 2002; Musiek & Pinheiro, 1987). Based on these results, the LND group (n=21) who had shown attention switching and inhibitory control deficits in phase 1 then were further divided into 2 subgroups namely APD group (n=5) and LD group (n=16). Further, as expected, when compared to the LD and Control groups, the APD group showed significantly poorer FPT scores for both ears. [Right – $F(2, 33) = 44.03$, $p=0.00$; and Left ear – $F(2, 33) = 70.58$, $p=0.00$)] (See figure 5)

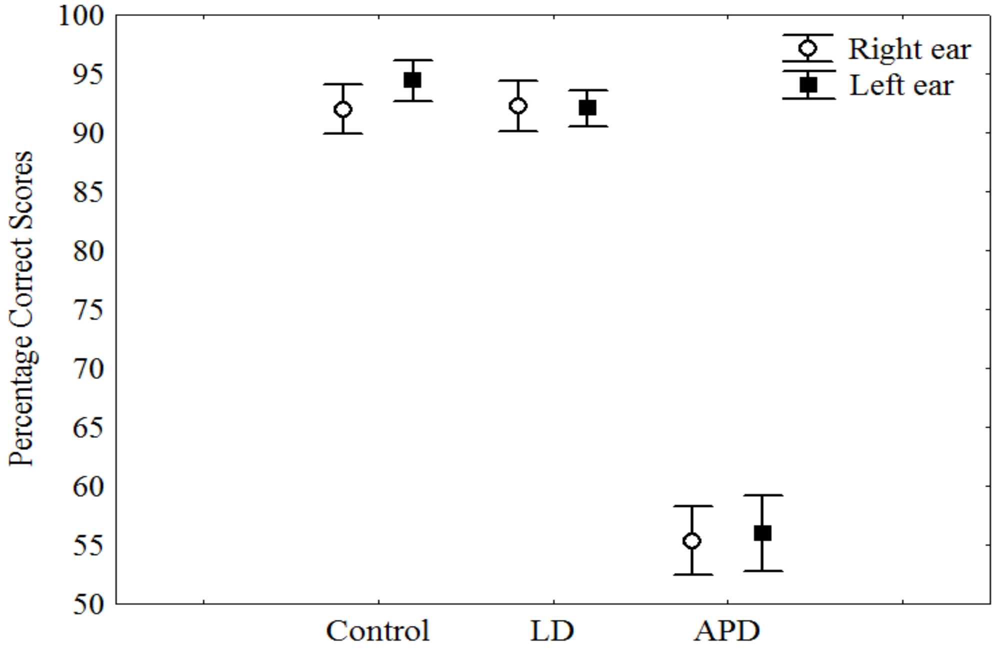

Figure 5: Mean scores for FPT for the 3 groups. The error bars represent the standard error of means

In order to test if the subgroup of children who were diagnosed with APD (n=5) in this Phase, behaved similar to the remaining LD group participants (n=16), we also analysed the results of Phase 1 separately for the 2 subgroups and compared them to the controls. The results of this analysis indicated that both the APD (n=5) and LD (n=16) groups showed significantly different attention re-orientation time in comparison to the Control group (F (2, 33) = 569.63, p=0.00). Further post hoc analysis indicated that in comparison to the Control group (2.75±0.067 seconds), the APD (8.43±0.25) and the LD group (7.37±0.13) took substantially longer time to re-orient their attention. Additionally, the analysis indicated that the APD group took significantly longer (p=0.00) than the LD group to reorient their attention. It would be interesting in future studies to test more children with APD (specifically those who have difficulties with FPT) and assess if their attention switching/re-orienting time is significantly longer than those in the LD group. In the current cohort however, the number of participants especially in the APD group are too small to conclude with any confidence.

Phase 3

In this phase, we now examined 3 groups (Control, LD and APD) on additional tests (See Table 2) to further examine auditory processing and memory abilities. The aim was to determine if we could differentiate the LD and APD groups from each other as well as from the Control group based on their performance on these tasks. The results of the normality test (2 tailed Shapiro-Wilk test and visual inspection of histograms and Q-Q plots) revealed normal distribution of the data within each group (p>0.05) for all the tasks. Moreover, we performed a Welch test for comparing the means instead of a one-way ANOVA for some tasks in which we found an inequality of variances (Levene's test) between the 3 groups. In summary, we found significantly poor performance on the frequency discrimination and memory tasks for the APD group compared to the Controls and LD groups. There were no significant differences (p>0.05) between the 3 groups for any other tasks (See Table 3). It is possible that the relatively small sample size and greater inter-subject variability of performance for the APD group may have obscured any possible differences for the other tasks.

Frequency Discrimination

The results indicate significant differences for frequency discrimination thresholds obtained at 100 Hz (Welch's F ratio = 6.18, p=0.02) and 1000 Hz (Welch's F ratio = 6.51, p=0.01) between the 3 groups (See figure 6). Post-hoc analysis (Games-Howell test) revealed that the APD group had significantly higher thresholds (p=0.04) in comparison to the other 2 groups. There was no significant difference between the Control and LD group (See figure 6). Furthermore, a post hoc power analysis indicated a high statistical power for the differences observed between the 3 groups for this task (100 Hz: effect size = 4.12, $\alpha = 0.05$, critical F = 3.28, power = 1.00; 1000 Hz: effect size = 12.29, $\alpha = 0.05$, critical F = 3.28, power = 1.00). Earlier studies conducted on children with dyslexia and specific language impairment have also shown difficulty in discrimination of rapidly presented short duration sounds (Hari & Renvall, 2001; Martino, Espesser, Rey, & Habib, 2001; Reed, 1989; Tallal, Miller, & Fitch, 1993; Wright, et al., 1997). These studies used short duration sounds (<75 ms) with a variable inter-stimulus interval (ISI) and found poor performance on temporal sequencing and discrimination tasks at short ISIs (<305 ms) in comparison to the Control group. The ISI in the current task was fixed at 300 ms. It is thus possible that the poor performance of the children with APD on this task may be associated with either the duration of stimuli, rate of presentation or their frequency resolution ability.

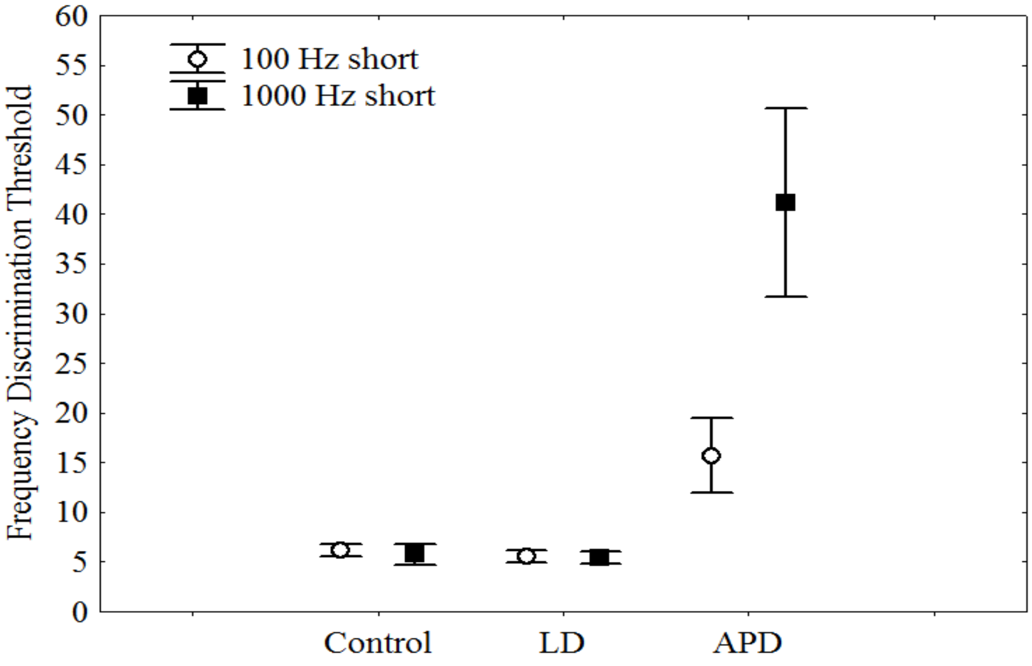

Figure 7- Mean frequency discrimination thresholds at 100 and 1000 Hz for the 3 groups. The error bars represent the standard error of means.

To determine if the ISI or the actual stimulus duration was the cause of this performance deficit, we conducted additional experiments in which we varied the ISI and stimulus duration. In this experiment, we also examined frequency discrimination using two additional stimulus conditions i.e. 1) longer stimulus duration (500 ms) and same ISI as used previously (300 ms) and 2) longer ISI (500 ms) but short stimulus duration (100 ms). Only a subset of participants from the original cohort consented to participate in this experiment. The participants included 5 participants each in the Control (mean age = 12.6 yrs., SD = 0.55), LD (mean age = 12.48 yrs., SD = 1.77) and APD (mean age = 13.13 yrs., SD = 2.48) group. The results from this experiment showed no significant difference (within group ANOVA, $p>0.05$) in thresholds between the 3 stimulus conditions for each group (See figure 7A and 7B). Notwithstanding the limited number of participants, this finding (although a pilot data) may suggest that the poor performance on the frequency discrimination task observed in APD group is not associated with the stimulus duration or rate of presentation. Caution should however be taken in interpreting the results of this pilot study due to the limitations in sample size.

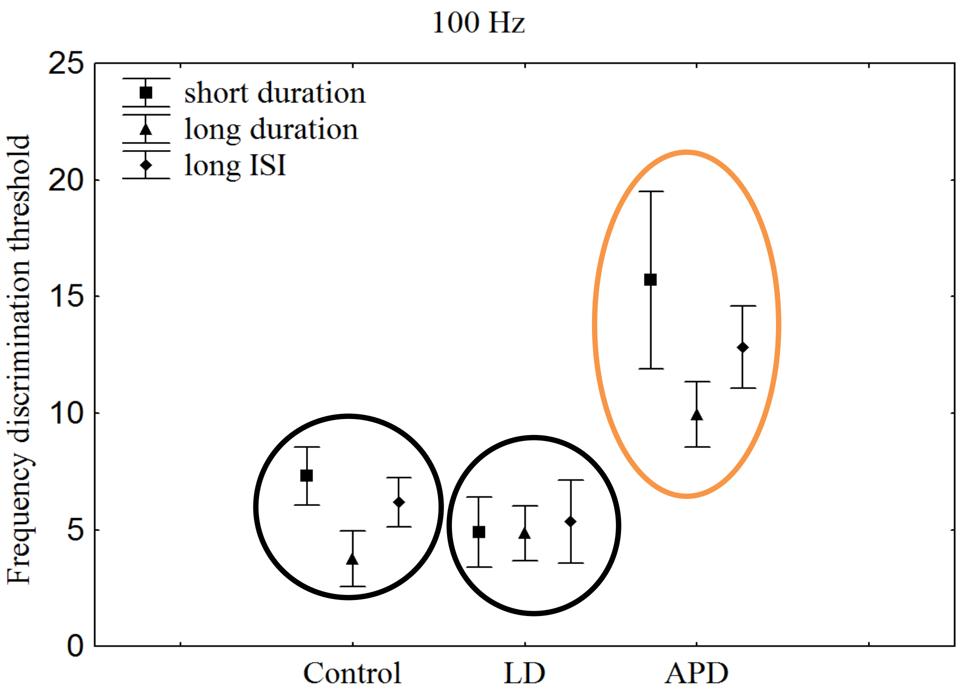

Figure 7A: Mean frequency discrimination thresholds at the base frequency of 100 Hz for the 3 different stimulus conditions. The error bars represent the standard error of means.

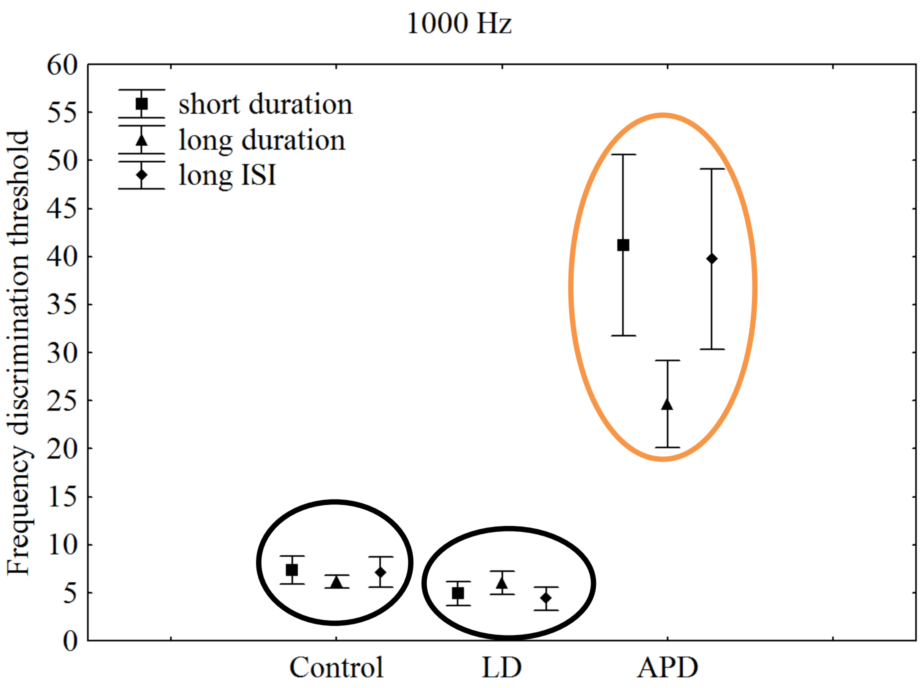

Figure 7B: Mean frequency discrimination thresholds at the base frequency of 1000 Hz for the 3 different stimulus conditions. The error bars represent the standard error of means.

Overall, it is unlikely, that the poor performance of APD group on the frequency discrimination task may be associated with the duration of the stimuli.

Auditory Memory

The digit span test used here is a measure of short term and working memory skills (Harris et al., 2012; St Clair-Thompson, 2010). It has been suggested that the backward digit recall task, when administered on children, may predominantly measure working memory capacity and requires attention control resources (Conklin, Curtis, Katsanis, & Iacono, 2000; Pisoni & Cleary, 2003; Pisoni & Geers, 2000; Reynolds, 1997; St Clair-Thompson, 2010). In the present study, the results for this task indicated no significant difference between the 3 groups for the scores on the forward digit span task ($p>0.05$). Backward digit span test scores however, were significantly different amongst the 3 groups ($F(2, 33) = 6.10$, $p=0.006$) (See figure 8 and Table 3). Post hoc analysis (Tukey-Kramer) revealed that APD group performed significantly poorer (p=0.005) than the other 2 groups. There was no significant difference (p>0.05) for the backward digit span scores between the Control and LD groups. Moreover, a post hoc power analysis revealed a high statistical power for the differences observed between the 3 groups for the backward digit span (effect size = 0.76, α = 0.05, critical F = 3.28, power = 0.98). This finding is consistent with the results of earlier studies that have shown poor auditory memory for children with APD (Maerlender, 2010; Maerlender, et al., 2004)

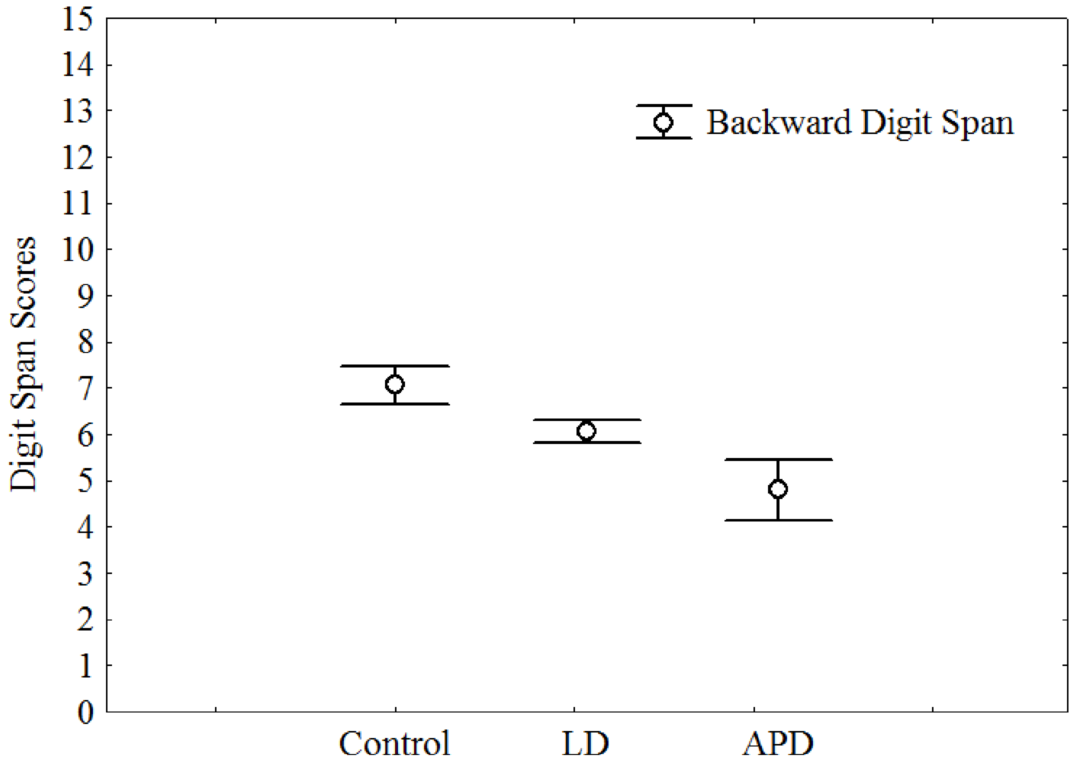

Figure 8 - Mean scores for the backward digit span test across the 3 groups. The error bars represent the standard error of means.

A listening difficulty in presence of background noise as a consequence of poor working memory skills may be explained on the basis of the information degradation hypothesis (Pichora-Fuller, 2003a, 2003b). In the context of listening in noise, a working memory deficit may mean that the task of listening to a single talker would engage most of the capacity for storage, processing and retrieval. The remaining capacity would then be inadequate to simultaneously monitor other inputs (Rudner, et al., 2012). Studies using functional-MRI have also reported evidence of involvement of common cortical areas such as the left ventral and dorsal prefrontal cortex (PFC) for speech perception in noise and function of working memory (Salat, Kaye, & Janowsky, 2002; Wong, Ettlinger, Sheppard, Gunasekera, & Dhar, 2010; Wong et al., 2009). It has also been suggested that the PFC may be responsible for inhibiting processing of competing sounds (Wong, et al., 2010) in noisy backgrounds.

Is there a link between the performance on auditory processing and memory tasks?

A correlational analysis using the Pearson's product moment test was performed on the complete data set (n=36) to determine any association between their scores on the tasks used to assess auditory processing, attention and memory (See Table 4 for the results of this analysis). This analysis revealed a modest negative correlation between the scores of the frequency discrimination and the backward digit span task. The scores of the FPT and dichotic digits test were positively correlated with those of the backward digit span test. We also found a strong negative correlation between the scores for the frequency discrimination and frequency pattern task. The modest correlations for the performance between the 3 tasks (digit span, frequency discrimination and frequency pattern) suggest a link between working memory, frequency resolution as well as pattern perception skills (Cranford, et al., 1997; Moore, Ferguson, Halliday, & Riley, 2008; Mukari, Umat, & Othman, 2010; Sharma, Purdy, & Kelly, 2009; Thompson, Cranford, & Hoyer, 1999). From the findings of the current study, it is however not possible, to show any causal link between working memory deficits observed in the APD group and their performance on frequency discrimination task and FPT. Moreover, the correlations also suggest an association between the performance on the FPT and frequency discrimination task. This may be attributed to the involvement of the common ability of frequency resolution for the two tasks. However, the poor performance of the APD group for the FPT cannot be completely attributed to their poor frequency discrimination/resolution ability due to the fact that the frequency separation between the stimuli used for the FPT was much higher (880 Hz and 1120 Hz) than the range of the frequency discrimination thresholds that were obtained. It is thus possible that, in addition to the poor frequency resolution ability, additional cognitive factors such as memory and attention may have contributed to the poor performance of these children for the FPT.

Interestingly, the LND group also had a history of recurrent OME. This finding is also consistent with the observation of higher rates of incidence of OME in children with listening difficulties in an earlier study (Dawes, Bishop, Sirimanna, & Bamiou, 2008). The results of the current study are, however, unable to explain any causal link between the histories of recurrent OME and the deficits observed in the LD group. It is difficult to explain why despite having a similar clinical symptom (listening difficulty in noise) and history of recurrent OME, only a subset of LND group (i.e. APD) also showed additional deficits in their frequency resolution and working memory skills. It is possible that the frequency resolution and working memory deficits observed in the APD group may be independent of their attention switching and inhibitory control ability. It is also possible that recurrent OME during early years of life may lead to variable deficits showing a common clinical symptom of listening difficulty in noise. Further research in needed to test this hypothesis.

Conclusion

The present study aimed to assess auditory attention switching, processing and memory skills in school-aged children with persistent listening difficulties in background noise. The results of this investigation indicate that children with listening difficulties in noise have attention switching and inhibitory control deficits. Additionally, a subgroup of these children (n=5) were diagnosed as having an APD and demonstrated additional deficits in their frequency resolution and working memory skills. Based on these results, it would be reasonable to suggest that the assessment of attention switching, working memory and frequency resolution should be included in the clinical test battery.

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Table 1- Details of the clinical tests used to identify the presence of an auditory processing disorder in Phase 1 of the study.

Measures	**Skills**	**Tests**
Peripheral Hearing	Hearing sensitivity	Pure tone audiometry
	Middle ear integrity	Immittance audiometry
Temporal Processing	Temporal resolution	Gap detection in noise test (Baker, et al., 2008)
	Temporal ordering	Pitch pattern test (Musiek, 2002)
Binaural processing	Binaural integration	Dichotic digits test (Musiek, 1983)
	Binaural separation	Binaural masking level difference test (Wilson, et al., 2003)
		LISN-S test (Cameron & Dillon, 2008)
Speech Perception in Noise	Speech recognition in presence of spatially separated noise.	LISN-S test (High cue SRT condition) (Dillon, et al., 2012)
Auditory Attention	Auditory sustained attention and vigilance	Auditory Continuous Performance Test (Riccio, et al., 1996)

Table 2- List and brief description of the procedure for the tasks used in Phase 3 of the study

Skill	Task	Procedure
Auditory sequential stream segregation	ABA_ paradigm (van Noorden, 1975)	Two pure tones (A and B) were presented in a sequence at a sufficiently high rate using a single interval-two alternative forced choice paradigm. The frequency separation between tones was varied until the listener could no longer perceive the sequence as a single stream to measure their temporal coherence boundary (Bregman, 1994)
Localization	Speech localization in presence of competing speech (Best, Carlile, Kopčo, & van Schaik, 2011; Kopčo, Best, & Carlile, 2010)	The target speech syllable was presented in one of the 7 possible locations in the horizontal plane against a background of a 2 competing talkers. The task of the participants was to point their nose to the perceived location of the target.
Temporal envelope processing	Modulation detection (Rocheron, et al., 2002)	Sinusoidal amplitude modulation detection task at a low (4 Hz) and high (128 Hz) modulation rate using an AXB paradigm. We varied the modulation index at a constant modulation frequency to determine the modulation detection thresholds.
Temporal fine structure processing	TFS1 & TFS-LF tests (Sęk & Moore, 2012)	The TFS1 and TFS_LF tests were used to examine temporal fine structure perception for high and low frequencies respectively. Both tasks involved the use of a 2 alternative forced choice paradigm.
Frequency discrimination	Brief tone frequency discrimination (Thompson, et al., 1999)	Frequency discrimination thresholds were examined for short duration (100 ms) pure tones at 100 and1000 Hz.
Auditory Memory	Forward and Backward digit span test (Lezak, Howieson, & Loring, 2004; Reynolds, 1997)	We aimed to assess short term/working memory capacity with this test. The task involved asking the participants to verbally repeat a set of numbers presented auditorily in either the same or reverse order that they are presented.

Table 3- The table shows the summary of results for the correlational analysis performed to determine the association between the working memory and auditory processing skills. Only the statistically significant ($p<0.05$) correlations have been depicted in the table.

Test 1	**Test 2**	**Correlation Coefficient**
Frequency pattern	**Backward Digit span**	
Right ear		r = 0.34, p = 0.04
Left ear		r = 0.36, p = 0.03
Frequency discrimination	**Backward Digit span**	
100 Hz		r = -0.48, p < 0.01
1000 Hz		r = -0.42, p = 0.01
Dichotic Digits Test	**Backward Digit span**	
Right ear		r = 0.41, p = 0.01
Left ear		r = 0.47, p < 0.01
Frequency pattern	**Frequency discrimination**	
Right ear	100 Hz	r = -0.61, p = 0.00
Left ear		r = -0.50, p = 0.00
Right ear	1000 Hz	r = -0.78, p = 0.00
Left ear		r = -0.70, p = 0.00

Table 4: The table shows the mean scores with standard errors for the test performed in Phase 3. There was a significant difference ($p<0.05$) between the 3 groups for the tests marked with an asterisk.

Tests	Control Group	LD group	APD group
Frequency discrimination*			
100 Hz	6.17 (0.65)	5.51 (0.62)	17.71 (3.3)
1000 Hz	5.76 Hz (1.05)	5.45 Hz (0.61)	41.16 Hz (9.43)
SAM detection			
4 Hz	-24.46 dB (0.51)	-22.89 dB (0.63)	-21.72 dB (1.88)
128 Hz	-21.05 dB (0.69)	-20.76 dB (0.44)	-18.79 dB (0.94)
TFS-LF	44.98 deg (4.92)	31.56 deg (2.58)	52.58 deg (10.4)
TFS1	29.05 Hz (5.18)	24.54 Hz (1.81)	37.34 Hz (6.33)
Localization			
LAE	12.95 Az (0.66)	16.08 Az (1.41)	16.92 Az (2.03)
PAE	12.73 Az (1.63)	8.94 Az (0.94)	16.55 Az (5.54)
Sequential stream segregation	69.54 Hz (8.03)	65.69 Hz (7.57)	58.57 Hz (11.65)
Digit Span			
Forward:	10.33 (0.62)	8.5 (0.49)	8.4 (0.74)
Backward*:	7.06 (0.40)	6.06 (0.23)	4.8 (0.66)

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Supplementary material

Auditory Stream Segregation

Stimulus preparation

We used the ABA_ paradigm as suggested by Van Noorden (1975) along with a constant-stimuli procedure. Each stimulus sequence comprised of two loudness equalized pure tones (using filters based on equal loudness contours) namely stimulus 'A' which was a 100 Hz pure tone and stimulus 'B' which consisted of 14 different frequency pure tones from 100-500 Hz. The tone duration was 100 ms with a 10 ms rise/fall time (raised cosine ramp). The loudness equalization ensured that the stream segregation task would be predominantly dependant of pitch based difference in the tones. There was a silence of 20 ms between stimulus 'A' and 'B' and 100 ms between the ABA triplets. As logarithmic rather than linear step sizes in frequency separation have been speculated to be suitable for stream segregation tasks (Albert Bregman, personal communication), the intermittent frequency steps for the variable tones were calculated by dividing the highest frequency to the lowest frequency in the desired range and then a 14th root of the resultant value was used to get the multiplier for the reference frequency through which the 14 frequency components were obtained. A total of 12 ABA sequences were stringed together to form each test sequence.

A total of 150 trials were presented in a random order (each test sequence presented 10 times) binaurally to each participant at 70 dB SPL. We used repetitive and long loop of sequences in order to facilitate the build-up of stream segregation and to avoid bias in the responses due to formation of memory traces of the initial or last part of the sequence[1].

Procedure

We assessed sequential stream segregation by presenting the participants with ABA_ sequences at a sufficiently high rate of presentation and varied the frequency separation between the A and B tones until they could no longer perceive the sequence as a single stream in order to measure their temporal coherence boundary[1-3].The presentation of the test sequences was done using a custom program using the Alvin2 software[4]. A practice trial was given to all subjects using the test sequences whose patterns were easily perceptible to demonstrate the two patterns (galloping or non-galloping). The practice trial continued until the participants demonstrated an acceptable level of accuracy for the recognition task. The participants were asked to listen for the pattern/rhythm of the test sequences and judge them being either in a galloping or a non-galloping pattern. The response was collected via a yes/no button press task. The stimulus presentation order was randomized.

Care was also taken to instruct the participants to base their judgements on the complete test sequence in order to allow for the build-up of segregation. Moreover, the test was designed to allow button press response only after each stimulus sequence ended. The children were reinforced using animation that appeared on the computer screen after each response, regardless of the type of response (yes or no), to keep them motivated for the task. As the cues for the separation of the two streams in this experiment may involve ambiguity in perceiving coherent or non-coherent streams, the participants would always be able hear two streams voluntarily, by directing attention to only one of the types of tones (A's or B's). We therefore asked the participants to attempt to listen for the galloping rhythm and to report "no" when they couldn't hear it. This procedure measures the "temporal coherence boundary" (compelling level of segregation even though the listener is biased against hearing it) rather than the "fission boundary" (segregation when the listener is trying to hear it).

The responses for each participant was collected and quantified in terms of the percentage 'Yes' (gallop) responses for each frequency combination and generated using a bootstrapping and maximum likelihood Gaussian line fit of data (gamma =0.031). The temporal coherence boundary (TCB) was estimated by taking the 50 % point from the psychometric curve. We also analysed the results using signal detection theory. The number of 'Yes' (gallop) responses given by the participants when the frequencies of A and B tones were the farthest apart (i.e. B-tone at 499 Hz) was used to estimate a 'false-alarm' rate. We measured the performance in terms of sensitivity (d') using these hit and false alarm rates. Hit or false alarm rate values of 0 or 1 were adjusted by 1/2n or 1-1/2n respectively where n is the number of trials at each epoch to compensate for extreme values (i.e. 0 and 1) in the calculation of d'. We also measured response bias (criterion) which is a measure of the participants' decision variable to respond to a target. A liberal criterion (negative value) would suggest a bias of the participant towards responding yes (i.e. gallop) regardless of the stimulus and a conservative criterion (positive value) would indicate a bias towards responding no(i.e. no gallop).

Localization

Stimulus preparation

The target speech syllable (/da/) spoken by a female speaker with Australian English as her first language was recorded in a sound treated room at a sampling rate of 44100 Hz, 16 bits resolution using a high quality audio recorder. The duration of the syllables were shortened to 150 ms using audio processing software (Adobe Audition 2.0). The relatively short duration of the target sound also ensured minimal role of head movements to aid in the source localization task[5]. A spectral analysis of the target stimuli indicated maximum spectral energy in the stimuli up to about 4000 Hz. The maskers were created using recorded sentences with heterogeneous context and content taken from standardized passages spoken either by the same female speaker or by another native English female speaker (to avoid giving pitch based cues for segregation). The presentation level of the target syllable was kept at 60 dB SPL and the signal to masker ratio was kept constant at approximately 0 dB. This signal to masker ratio was 5 dB above the mean threshold (70% correct identification) on a syllable identification task in presence of the same competing maskers that was administered to all the participants as part of another experiment to ensure adequate audibility and identification of the target syllable.

Procedure

The target speech syllable was presented in one of the 7 possible locations in an anechoic chamber against a background of a 2 competing talkers. The target and maskers were presented through loudspeakers in a triple walled sound attenuated anechoic chamber (working area 2.5 x 2.5 x 2.5 meters). The moving robotic arm and hoop speaker apparatus used by Carlile, Leong and Hyams (1997) was used for testing. A two way intercom system was kept in the testing chamber to facilitate communication between the participant, parents and the experimenter and to monitor any signs of discomfort or inconvenience to the participants during the testing session. The target syllable (/da/) was presented in each trial through the hoop loudspeaker along with the 2 competing talkers narrating stories from the rear 2 loudspeakers (kept at ±45 degrees Azimuth) and the participant's task was to point their nose to the perceived location of the target and press a response button. The target and maskers were presented using custom developed scripts through the Playrec[6] utility in Matlab 2009b and routed via an external USB driven computer sound interface (RME - Fireface 400) to Audience A3 (frequency response = 40-22000 Hz) and Tannoy V6 (frequency response - 87 Hz to 35000 Hz) loudspeakers respectively. The maskers were gated along with the target stimuli with an onset and offset time of 800 ms.

Participants stood on a platform at the centre of the testing chamber with their head aligned roughly in the centre of the platform. The target speech syllable was played via a loudspeaker and the location of the loudspeaker was varied using a computer controlled positioning system with a suspended double hoop design[7]. A tracking device that consisted of a head tracker (Intersense IC3) which was fitted on the head of each of the participants using an adjustable plastic frame constantly monitored their head position from a calibrated reference point in the centre to record the localization responses. We examined the localization for 7 different locations viz. 0, ±30, ±60, ±90 Azimuth in the horizontal plane. The responses were measured in terms spatial co-ordinates of the participants by nose pointing to the position of the target in a spherical coordinate system. The errors were defined as the difference between the actual target location and that indicated by the participants. We measured the lateral angle errors (LAE) as the root mean square (RMS) errors in horizontal plane (Left-Right) localizations, and the polar angle errors (PAE) were the RMS errors in vertical plane corresponding to those positions in the horizontal plane[8,9]. The polar angle errors were corrected for inflation due to the relative differences in the dimensions of the cone of confusion at different positions.

Brief Tone Frequency Discrimination

Stimulus preparation

Frequency discrimination was assessed for pure tones (100 and 1000 Hz) at an intensity level of 70 dB SPL using the AXB paradigm and a 1 up, 3 down transformed up-down staircase procedure (Levitt, 1971). The AXB paradigm was used based on its advantages such as reduced short term memory demand and resistance to bias over other designs such two or three alternative forced choice[10,11]. The stimulus intensity was calibrated using a Bruel and Kjaer artificial ear and type 1 sound level meter assembly using a linear frequency weighting scale. The stimulus duration was kept either brief (100 ms) or long (500 ms) with constant inter-stimulus interval of 300 ms and a 20 ms raised cosine rise/fall ramp. The initial frequency difference at the start of the test was intentionally kept large (i.e. 30 Hz and 100 Hz) in order to orient the participants to the task.

Procedure

The task was implemented in Matlab 2009b using Psychophysics Software Suite (Goldberg, Lvovsky and Banai, 2010) which is a child friendly interface designed to conduct psychophysical experiments and uses animations. Feedback was provided after each trial based on their responses to all the participants. This feedback acted as a positive reinforcement for the participants for their correct responses on each trial. The frequency difference between the fixed and reference frequencies (delta) changed adaptively based on a pre-defined set of rules. The delta for the reference frequency of 100 Hz initially changed in larger steps (5 Hz), progressing to intermediate steps (2 Hz) and later in small steps (1 Hz), whereas that for the reference frequency of 1000 Hz varied from large steps of 10 Hz to intermediate steps of 5 Hz and lastly smaller steps of 1 Hz in order to reach the threshold. The experiment continued until 10 reversals were obtained. The participants were instructed to listen to all the 3 tones that were presented in a trial and then determine which of the tones (1st or 3rd) was not identical to the reference tone (2nd). The participants responded by clicking the appropriate 'graphic' (animated picture of a mouse or dragon) on the computer screen. We also monitored each participant’s performance based on the variability of their track widths (standard deviations) in this task and repeated the task if there was an evidence of variable track width suggesting a possible attentional lapse[12,13]. The threshold was calculated from the staircase using the arithmetic mean of the last 5 reversals. This threshold would converge at the 77% point on the psychometric function.

Temporal Envelope processing

Based on the procedure from Rocheron et al[14], we used a sinusoidal amplitude modulation rate (SAM) detection task at a low (4 Hz) and high (128 Hz) modulation rate as a measure to examine temporal envelope processing. The stimuli was a sinusoidally amplitude modulated broad band noise (BBN) (0-20KHz) with a duration of 500 ms (20 ms rise/fall time) with a modulation frequency of 4 and 128 Hz respectively. The modulation depth of the BBN was varied to determine the detection threshold for amplitude modulation. The intensity of the unmodulated reference sound was normalized such that the overall power was the same for the reference and variable (modulated) sound. The task design (AXB paradigm; 1 up-3 down transformed staircase procedure) and implementation was similar to that of the frequency discrimination experiment.

Temporal Fine Structure processing

We examined high and low frequency temporal fine structure encoding at supra-threshold levels using the TFS1 and TFS-LF tests respectively[15-17]. We used the default stimulus settings and procedure as recommended by Sek and Moore (2012) for both the tests. The high frequency fine structure encoding was assessed mono-aurally using the TFS1 test and consisted of a 2 alternative forced choice (AFC) task to discriminate two complex tone based on the pitch cue as a result of a uniform phase shift of all the harmonics in one of the tones. The centre frequency (Fo) for the complex tones was 200 Hz and the frequency of the lowest component was 9Fo (1800 Hz). The test ear as well as the starting phase for both the stimuli was randomized and there were with 5 frequency components within the pass-band. The threshold was measured (in Hz) in terms of the minimum amount of phase shift required for successful discrimination. Low frequency fine structure encoding was assessed binaurally using the TFS-LF test and comprised of a 2AFC task to assess the listener’s sensitivity to inter-aural phase differences for 500 Hz tone bursts. The stimulus duration and ISI was kept at the default values of 0.4 and 0.2 seconds respectively. The threshold (geometric mean of last 6 reversals) was measured as the minimum phase difference in azimuths required for discrimination. Adequate practice was provided to all the participants before administering the actual tasks.

Auditory memory

We assessed auditory memory using the forward and backward digit span test[18]. This test has been widely used to assess auditory memory[19]. The forward digit span test involved presentation of a series of numbers and the participants were asked to verbally repeat the numbers in the same order in which they were presented whereas for the backward digit span test the participants were instructed to repeat the numbers verbally in the reverse order than what was presented. The test was pre-recorded using a female native Australian English speaker with an inter-stimulus interval of 1 second and was presented binaurally at 60 dB SPL through the PC using the windows media player. Care was taken during the recording of the test such that there was a falling voice inflection on the last digit presented on each trial. There was also a beep cue (1000 Hz; 300 ms tone) to signal the onset and offset of each trial in order to orient the listener's attention. The participants were instructed to verbally repeat the numbers in either the same or reverse order in which they were presented. The length of the sequence of numbers was continually increased until the participant could no longer correctly recall them on 2 successive trials.

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Overall Discussion

The main aim of this project was to evaluate school aged children (10-15 years) who presented with persistent listening difficulties especially in presence of background noise despite having clinically normal hearing sensitivity. We assessed them on a wide range of tasks in order to assess their auditory processing, attention and memory abilities. We then compared their performance with an age equivalent control group who had no reported listening difficulty or history of Otitis Media with Effusion (OME). The auditory processing skills were evaluated using some of the routinely used (Emanuel, 2002; Emanuel, Ficca, & Korczak, 2011) and recommended (American Speech and Hearing Association, 2005) clinical tests as well as on some additional tasks (Chapter 1). The additional tasks were selected with an aim to assess auditory stream segregation, spatial localization, frequency resolution and temporal processing skills including envelope and fine structure abilities.

In study 1 (Chapter 2) we assessed a group of adults (18-30 years; n=12) and children (10-15 years; n=15) with no reported listening difficulty on tasks to examine their auditory sequential stream segregation, spatial localization in noise, frequency resolution and temporal envelope processing ability. The main aim of this study was to assess the participants on these tasks which were designed by modifying various suitable tasks that have been used in previous studies (Best, Carlile, KopCo, & van Schaik, 2011; Noorden, 1975; Rocheron, Lorenzi, Füllgrabe, & Dumont, 2002; Thompson, Cranford, & Hoyer, 1999) and to acquire performance benchmarks. The results of this study showed no significant differences in performance between adults and children suggesting that the processes that were assessed through the tasks administered in this study, operated similarly in school aged children and adults.

In study 2 (Chapter 3), the aim was to evaluate auditory selective attention and attention switching ability in children with (n=12) and without (n=12) persistent listening difficulties in presence of background noise. We also evaluated their auditory processing abilities using a set of clinically recommended (American Speech and Hearing Association, 2005; American Academy of Audiology, 2010) tests as well as on a range of additional tasks that were designed in study 1. The recommended clinical test battery consisted of the Frequency Pattern (Musiek, 2002), Dichotic Digits (Musiek, 1983), Listening in Spatialized Noise (Cameron & Dillon, 2007), Masking Level Difference (Wilson, Moncrieff, Townsend, & Pillion, 2003) and Gaps in Noise (Musiek et al., 2005) tests. Additionally, we also examined their sustained auditory attention (Keith, 1994) and memory (Cowan et al., 2005) abilities. In this study (published in Nature's Scientific reports, 2013), we designed a novel test to assess auditory attention in two forms, namely selective attention and attention switching. The results of this study showed no significant differences in performance on the auditory processing and memory tests for the children with listening difficulties compared to the age equivalent Control group. The results showed that children with listening difficulties were notably ***slower*** to re-orient their auditory attention and had a higher false alarm rate compared to those in the Control group. These results were suggestive of poor attention switching and inhibitory control ability in the LD group.

In study 3 (Chapter 4), we expanded the previous study by including more children reporting listening difficulties in background noise (LD group; n=21). The study was split in three phases. In Phase 1, we examined their attention switching ability using the test designed in study 2. The results were consistent with those in study 2 and indicated that all children reporting listening in noise problems had poorer attention switching and inhibitory control ability in comparison to the Control group (n=15). In Phase 2, we tested the LD group on a set of recommended clinical tests in order to identify the presence of an auditory processing disorder (APD). The results revealed that only five children amongst those in the LD group exhibited poor performance (3 standard deviations below the age based norms) on the Frequency pattern test (FPT) and thus could be diagnosed with APD. Based on the results of this phase of testing, we further categorised the children within the LD group as those who could be diagnosed with APD (APD group; n=5) and the remaining who did not (LD group; n=16). Lastly, in Phase 3, we evaluated the LD and APD groups on additional set of tasks to assess their auditory processing skills and memory ability with the aim of determining any further differences between these 2 groups. The results indicated poor frequency discrimination and working memory skills in the APD group compared to the LD and Control groups. These findings were suggestive of frequency resolution and working memory deficits in the APD group.

Previous studies have found deficits in other auditory processing skills such as binaural integration (Musiek, Geurkink, & Kietel, 1982; Sharma, Purdy, & Kelly, 2009), temporal resolution (Balen et al., 2009; Phillips, Comeau, & Andrus, 2010), temporal sequencing (Sharma, et al., 2009), spatial stream segregation (Cameron & Dillon, 2008; Cameron, Dillon, & Newall, 2006) and binaural interaction (Sweetow & Reddell, 1978) in populations with reported listening difficulties. Moreover, the auditory processing deficits found in these populations are often considered to be heterogeneous in nature (Musiek, Geurkink, & Kietel, 1982;Sharma, et al., 2009; American Academy of Audiology, 2010). In the current research, however, we found frequency resolution to be the only auditory processing skill that separated the APD from Control and LD groups. It is hard to explain why we encountered such homogeneity of deficit in the APD group. Considering the limitation in sample size, it is possible that evaluating a much larger cohort of children may still exhibit heterogeneous deficits as suggested in the previous literature. The presence of listening difficulties is usually apparentto parents and teachers at a much younger age than 10 years. It is thus possible that evaluating a younger age group of children may have resulted in a wider range of auditory processing deficits.

Additionally, since we invited relatively older age group (10-15 years) of children who had persistent listening difficulties in background noise, it is possible that a majority of those who participated in this study may be the ones who could/had not been diagnosed with APD. None of the children had previously been assessed for attention switching. It is possible that serendipitously we have tapped into the population who have listening in noise problems typical of APD population but have attention switching deficit instead.

Interestingly, in contrast to the children in the Control group, all those who reported with listening difficulties in this study also had an associated history of recurrent OME. This finding is consistent with the observation of higher rates of incidence of OME in children with listening difficulties in an earlier study (Dawes, Bishop, Sirimanna, & Bamiou, 2008). Moreover, there were no significant differences in the number of episodes of OME between the LD and the APD groups. It is, however, not possible from the results of this study to demonstrate any evidence of a causality link between the histories of recurrent OME and observed deficits or the listening difficulties in background noise. Previous studies that have examined attention skills in children with histories of recurrent OME have shown mixed results (Roberts et al., 2004). While one subset of these studies has found poor attention skills in these populations (Klausen, 2000; Mody, Schwartz, Gravel, & Ruben, 1999), the others have not (Hooper, Ashley, Roberts, Zeisel, & Poe, 2006; Minter, Roberts, Hooper, Burchinal, & Zeisel, 2001; Roberts, Burchinal, & Clarke-Klein, 1995; Schilder, Snik, Straatman, & van den Broek, 1994).

Significance of research

All the children who reported with listening in noise difficulties in this research had attention switching and inhibitory control deficits. This deficit in attention switching for the children with listening difficulties in background noise, may affect their ability to rapidly switch their focus of attention from a target speaker to another in a noisy environment especially that involving multiple talkers (Astheimer & Sanders, 2009; Haykin & Chen, 2005; Koch, Lawo, Fels, & Vorländer, 2011; Shinn-Cunningham & Best, 2008). This delay in switching attention focus may then affect their information processing and listening ability and thus partly explains the difficulties reported by these children. Poor inhibitory control on the other hand, may lead to a greater distractibility of these children in listening environments that consist of multiple sources of distractors such as competing noise (Fillmore, Milich, & Lorch, 2009). Such increased distractibility may then subsequently affect their focus on the relevant source of auditory information. Furthermore, both, attention switching and inhibitory control have been suggested to predominantly involve top down processing control (Coull, Frith, Buchel, & Nobre, 2000; Coull, Vidal, Nazarian, & Macar, 2004; Dhamani, Leung, Carlile, & Sharma, 2013; Li, Huang, Constable, & Sinha, 2006). This may indicate a possible central information processing deficit in the children who reported with listening difficulties in background noise.

A subset of children who reported listening difficulty in presence of background noise were diagnosed to have APD based on the diagnostic criterion recommended by American Speech and Hearing Association (2005). This cohort further showed poor performance on the frequency discrimination task which remained consistently poorer than the Control group irrespective of inter-stimulus interval and stimulus duration modifications. This suggests a predominant spectral rather than a temporal processing deficit. Frequency resolution (as assessed by discrimination task) is an important skill which is considered to be crucial to separate the target sounds from other distractors based on the frequency differences between them (Moore, 1996, 2003). A deficit in this skill as observed in the current study for the APD group may contribute to their inability to listen in presence of background noise.

Auditory working memory skills have been suggested to assist in segregating the relevant information from the competing sounds by temporarily storing and actively processing the auditory information which helps in linking related information across time and form coherent representations while ignoring irrelevant distraction (Arlinger, Lunner, Lyxell, & Kathleen Pichora-Fuller, 2009; Conway, Cowan, & Bunting, 2001; Kraus, Strait, & Parbery-Clark, 2012; Pichora-Fuller, Schneider, & Daneman, 1995; Rudner, Lunner, Behrens, Sundewall Thorén, & Rönnberg, 2012; Snyder & Gregg, 2011). In the current research we found working memory deficits ***only*** in children with APD. This finding is consistent with the results of earlier studies that have shown poor auditory memory for children with APD (Maerlender, 2010; Maerlender, Wallis, & Isquith, 2004).

Summary

Overall, there are two main findings of the current research

1) Children with difficulties listening in noise despite having clinically normal hearing sensitivity had poor attention switching and inhibitory control
2) A subset of this population also had an APD as well as working memory deficits.

In summary, the results of this study indicate the importance of assessing attention switching, inhibitory control, and frequency resolution as well as memory skills for populations with listening difficulties and strongly suggest that tasks to assess these skills should be included in the clinical test battery used to assess such populations.

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Future Research Directions

1) Examine the abilities assessed in the current study with larger samples of children with listening difficulties in background noise

In the current study, we evaluated a modest sample size of children due to constraints such as testing time; participant and parental consent and participant follow up. It is possible that the potential performance differences on some tasksbetween the children with listening difficulties and the Control group may have been obscured by the limitations in sample size. Moreover, the relatively greater inter-subject variability in results on some tasks such as auditory sequential stream segregation, frequency discrimination and temporal fine structure perception for the participants in the APD group may suggest heterogeneity in their performance. Future studies are thus needed to examine the abilities assessed in the present study on larger cohorts of children with such listening difficulties.

2) Explore attention skills in these populations in the visual modality in order to know if the attention switching deficits are specific to the auditory modality in these children.

In the current study, we assessed attention switching ability for the children in the auditory modality and found that children who reported with listening difficulties in background noise showed deficits in attention switching. It is, however, possible that the attention switching deficits observed in these children may not be modality specific in nature. Further studies are required to examine attention switching ability in other modalities such as vision to determine if the deficit is modality specific.

3) Examine selective attention and attention switching abilities in the spectral and spatial domain for such populations.

In the current study we assessed the children for auditory selective attention and attention switching ability in the temporal domain based on the rationale that in noisy environments the relevant auditory information may often be overlapping with the distractors such as noise in spatial location. However, such overlap may also occur in the spectral as well as spatial domain. It is possible that the children with listening difficulties in background noise may also have similar attention switching deficits in spatial and/or spectral domain. Future research is required to examine these abilities in these two domains.

4) Studies are also required to further explore the possibility of a link between attention switching and inhibitory control ability

The results of the present study indicated that all the children who reported with listening difficulty in background noise had deficits in their attention switching and inhibitory control ability. Further research needs to determine if these are independent deficits or if there is a link or association between these two abilities.

5) Refine the task designed to assess selective attention and attention switching ability

In the current study, the task that was designed to assess selective attention and attention switching ability did not specifically allow us to compare the selective attention ability between the children with listening difficulties and the Control group. Further refinement of the task and analysis procedure can be undertaken in future research in order to determine a metric to calculate selective attention performance which may subsequently facilitate the comparison of selective attention ability between different groups. Moreover, the limitations in the number of trials at the unexpected in contrast to the expected epochs prompted us to pool the hit and false alarm rates across the participants within each group to compare the performance between groups. Further studies are required to explore the possibilities of achieving an optimal balance between the number of trials at the expected and unexpected epochs as well as increasing the overall number of trials for each condition ("early" and "late"). This may then improve the statistical power for analysing selective attention and attention switching ability for each participant individually which may be useful in future clinical applications of this task.

6) Transforming the selective attention and attention switching task to make it suitable for clinical use to assess children with listening difficulties

The current task was administered in an anechoic chamber in free-field. The task in its current format may, however, be difficult to administer in clinical scenarios. Future research is also required to look at possibilities of making this task more viable and easy to administer in clinical settings. The use of individualized or generic head related transfer functions (HRTF) to generate a virtual auditory space may facilitate the presentation of the stimulus and masker sounds through headphones which may then further enhance its clinical suitability. In order to make this task clinical usable we are planning further studies in the following directions:

1) To collect data for more participants especially for children with APD to confirm the findings of the present research

2) The next step would then be to collect HRTF data from a group of children to develop a sufficient database to recreate the task under headphones in virtual auditory space instead of free field

3) We are also planning to simplify and automate the analysis procedure to determine the temporal re-orientation time with the minimum number of trials possible to be time efficient.

4) The last step would then be to administer the new test under headphones to a group of children with and without listening difficulties in noise to test the validity and reliability of the test.

Appendices

Appendix I

Research information and consent form

Auditory stream segregation in children with auditory processing difficulties

You are invited to participate in a study of hearing and listening skills in children, and adults. This study will help us understand the difficulties faced by those with listening difficulties in their everyday environments especially in noisy environments and may also be useful in developing tests to assess the listening abilities and remediation/rehabilitation strategies for populations with listening (auditory processing) difficulties.

The study is being conducted byDr. Mridula Sharma (Lecturer, Dept. Of Linguistics, Macquarie University, Email: mridula.sharma@mq.edu.au, Ph: 9850 4863), Dr Robert Mannell, (Senior Lecturer, Dept of Linguistics, Email: robert.mannell@mq.edu.au, Ph: 9850 8771), Dr. Suzanne Purdy (Associate Professor, Dept. Of Speech Science, University of Auckland, Email: sc.purdy@auckland.ac.nz, Ph: 3737599 ext 82073), Dr. Simon Carlile (Associate Professor, Dept. of Physiology, University of Sydney, Email:simonc@physiol.usyd.edu.au, Ph: 61-2-93513205),Imran Dhamani (PhD. Student, Macquarie University, Email: imran.dhamani@students.mq.edu.au, Ph: 0468932582), PiaGlydenkaerne (PhD. Student, Macquarie University, Email:pia.gyldenkaerne@students.mq.edu.au) and Prof Benoit Jutras (Visiting Prof, School of Audiology and Speech Language Pathology,University of Montreal, Email: benoit.jutras@umontreal.ca).

This research is being conducted to meet the requirements of PhD. in Linguistics by Imran Dhamani under the supervision ofDr. Mridula Sharma, Dr Robert Mannell and Dr. Suzanne Purdy.

The current study requires participants aged between 18-30 years of age who either do or do not have concerns hearing in quiet and noisy situations. If you decide to participate you will be given a thorough hearing assessment and will receive a copy of the results and summary of the research result if requested. You will also be asked to complete a questionnaire regarding your medical history and academic achievements. The testing will be done in two sessions of 3 hours each. The testing sessions will take place at the Auditory Neuroscience Laboratory in the Department of Physiology (University of Sydney). A giftvoucher of $ 30/session will be given to the participants as a contribution towards their time spent for the research along with a $20 voucher for travel and parking expenses.

Your hearing will be assessed using the following procedures:

Pure tone audiometry

You will be required to respond to tones presented through earphones which will determine the softest sounds that can be heard (hearing sensitivity).

Immittance Audiometry

This measures energy flow through the middle ear (tympanometry) and the contraction of a muscle in the middle ear in response to loud sounds (acoustic reflex). This tests the middle and inner ear and the hearing pathways in the lower part of the brain.

Auditory processing Tests:

In this battery of listening tests you will be presented a few sounds via headphones and will be asked to listen and repeat or judge the pattern of sounds.

Auditory Stream Segregation, Selective attention and Localization test:

In the auditory stream segregation test a sequence of tones will be presented to you via headphones and you will be asked to judge the pattern and location of the sounds/tones. The selective attention and localization testing will be done in a quiet room with walls that can absorb sound (and thus do not allow the echo of the sound produced inside the chamber to be heard) which is called an anechoic chamber with an arrangement of multiple loudspeakers at different locations in the room. A low level laser beam will be used for a few seconds to mark your position correctly for the localization test. Laser-Safe goggles will be provided to you to wear during the initial marking phase of the localization test which takes no more than 5 minutes after which Laser will not be needed.There will be a set of speech sounds played through any one of the loudspeakers and some background speech through the other loudspeakers and your task will be to point/indicate to the location of the target speech sound.

There are no risks associated with this research. The loudness levels of the sounds will be carefully monitored. The testing will be immediately terminated if you have any discomfort or other related issues during the test procedure.

Any information or personal details obtained in the course of this study are confidential except as required by law. To protect your privacy, you will be assigned a code number and no material that could personally identify you will be used in any reports on this study. Only Dr Mridula Sharma, Dr. Robert Mannell, Dr. Suzanne Purdy, Dr. Simon Carlile, PiaGlydenkaerne (PhD. Student) , Imran Dhamani (PhD. Student) and Dr. Benoit Jutras would have access to the data files and these would be used in the de-identified form.

Participation in this study is entirely voluntary: you are not obliged to participate and if you decide to participate, you are free to withdraw at any time without having to give a reason and without consequence.Should you have any questions about the study, do not hesitate to contact the Principal Investigator (Dr Mridula Sharma, ph 02 9850 4863).

I, ___________________________________ haveread or have had read to meand understand the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this research, knowing that I can withdraw from further participation in the research at any time without consequence. I have been given a copy of this form to keep.

Participant's Name:

(Block letters)

Participant's Signature: Date:

Investigator's Name:

(Block letters)

Investigator's Signature: Date:

The ethical aspects of this study have been approved by the Macquarie University Human Research Ethics Committee. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Director, Research Ethics (telephone (02) 9850 7854; email ethics@mq.edu.au). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

(INVESTIGATOR'S [OR PARTICIPANT'S] COPY)

Research information and consent form

Auditory stream segregation in children with auditory processing difficulties

You are invited to participate in a study of hearing and listening skills in children, and adults. This study will help us understand the difficulties faced by those with listening difficulties in their everyday environments especially in noisy environments and may also be useful in developing tests to assess the listening abilities and remediation/rehabilitation strategies for populations with listening (auditory processing) difficulties.

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This research is being conducted to meet the requirements of PhD. in Linguistics by Imran Dhamani under the supervision ofDr. Mridula Sharma, Dr Robert Mannell and Dr. Suzanne Purdy.

The current study requires participants aged between 10-18 years of age who either do or do not have concerns hearing in quiet and noisy situations. If you decide to participate you will be given a thorough hearing assessment and will receive a copy of the results and summary of the research result if requested. You will also be asked to complete a questionnaire regarding your medical history and academic achievements. The testing will be done in two sessions of 3 hours each. The testing sessions will take place at the Auditory Neuroscience Laboratory in the Department of Physiology (University of Sydney). A giftvoucher of $ 30/session will be given to the participants as a contribution towards their time spent for the research along with a $20 voucher for travel and parking expenses.

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Any information or personal details obtained in the course of this study are confidential except as required by law. To protect your privacy, you will be assigned a code number and no material that could personally identify you will be used in any reports on this study. Only Dr Mridula Sharma, Dr.

Robert Mannell, Dr. Suzanne Purdy, Dr. Simon Carlile, PiaGlydenkaerne (PhD. Student) , Imran Dhamani (PhD. Student) and Dr. Benoit Jutras would have access to the data files and these would be used in the de-identified form.

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I, ___________________________________ haveread or have had read to meand understand the information above and any questions I have asked have been answered to my satisfaction. I agree to participate in this research, knowing that I can withdraw from further participation in the research at any time without consequence. I have been given a copy of this form to keep.

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(Block letters)

Participant's Signature: Date:

Investigator's Name:

(Block letters)

Investigator's Signature: Date:

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(INVESTIGATOR'S [OR PARTICIPANT'S] COPY)

ASSENT FORM

Study name: Auditory stream segregation in children with auditory processing difficulties.

Investigators: Dr. Mridula Sharma, Dr. Robert Mannell, Dr. Simon Carlile, Dr. Suzanne Purdy, Dr. Benoit Jutras, Imran Dhamani, PiaGyldenkaerne.

Purpose and benefits of the study:

We want to check your hearing and listening ability by giving you some sounds. This will help us learn more about children with listening difficulties and ways to help them. This is a science study.

Procedures:

If it’s okay with you then we will present various sounds in your ears using headphones or loudspeakers. You will have to either indicate if you can detect the sounds or describe the pattern or point to the location of sounds by saying yes/no or pressing a button. This test may take 2 sessions of three hours each to complete.

Risk, Stress and Discomfort:

In one of the tests you will be asked to wear colourful glasses and close your eyes for a very brief duration. This is done so that you should not look at the lasers used for marking the position of your head. You can let me know if you have any discomfort or problem during the test procedure. The test will be stopped immediately if you feel any discomfort during the same.

Other information:

We won't tell anyone you took part in this study. You don't have to take part in this study if you don't want to. No one will be mad at you. We will give you a copy of this paper to keep.

Signature of investigator Date

Participant's statement:

This research study has been explained to me. I agree to take part in this study. I have had a chance to ask questions. If I have more questions, I can ask the investigators.

____ _______________

Signature of participant Date

Copies to:

- Participant
- Investigator's file

Appendix II

QUESTIONNAIRE

Name of participant: ______________________________

DOB of the participant: ______________________________

Gender Female ☐ Male ☐

Handedness Right ☐ Left ☐ Ambidextrous ☐

____

____

Did your child receive ESL support at school? Yes ☐ No ☐

Address ______________________________

____

Phone ______________________________

Email ______________________________

Does your child have or ever had concerns about your hearing, listening or reading?

Yes ☐ No ☐

____

____

____

____

____

Does anybody in the immediate family have a hearing concern? Yes ☐ No ☐

If yes, how are they related to the child?

Have the school or work place colleagues raised any concerns about your child's hearing or listening? Yes ☐ No ☐

If yes, what are their concerns?

Does your child have any history of earache, infections or grommets? Yes ☐ No ☐

If yes, since when and how many episodes - please provide as much information as possible:

Does anybody in the family have reading difficulties? Yes ☐ No ☐

If yes, how are they related to the child?

Has your child repeated any school year? Yes ☐ No ☐

If yes, which year and could you provide more information:

Are there any other medical or health concerns?

Are there any other issues you have observed regarding your child's concentration, memory or attention?

Up to this point has your child received any assistance or therapy for any of your concerns?

Yes ☐ No ☐

If yes, what kind of assistance or therapy?

Please rate the child's ability based on your observation for the following:

Rating scale: 1= Very Good 2= Good 3= Average 4= Poor 5= Very Poor

Hearing ability: 1 2 3 4 5

Listening ability: 1 2 3 4 5

Reading ability: 1 2 3 4 5

Listening in noise: 1 2 3 4 5

Name

Signature

Date

Appendix III

In the current research we grouped the children from age 10 to 15 years into one single group based on the assumption that a majority of auditory processing abilities such as temporal resolution, binaural unmasking, frequency resolution, frequency discrimination and forward masking have been reported to be fully matured and adult-like by 10 years of age (Saffran, Werker and Werner, 2007). Additionally, the data for the results of the attention switching test for the normal children was compared within the same group. The data comparison was done between two subgroups viz. 10-12 years and 12-15 years. The results indicated no significant differences between the 2 groups for the hit and false alarm rates across the 5 epochs as well as for the predicted temporal re-orientation time. This finding further supports the grouping of children within 10-15 years of age.

Figure A: Pooled hit rates for the 5 epochs for the 2 age groups of normal children. The dashed lines represent the line of best fit for linear extrapolation of temporal re-orientation time

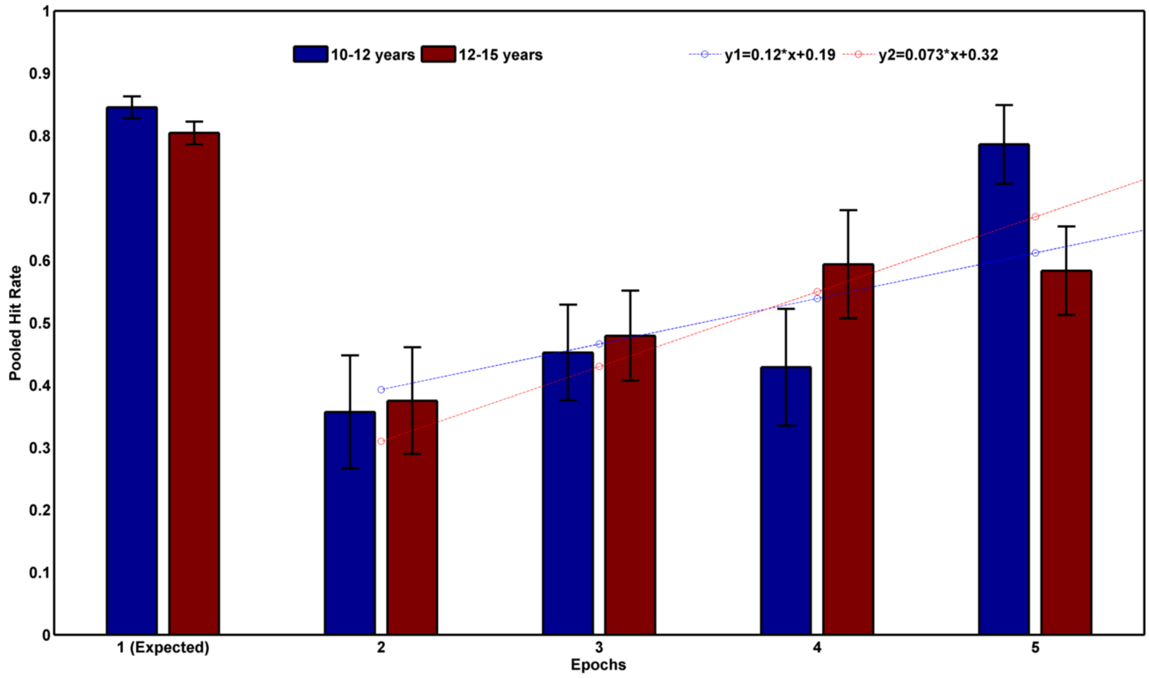
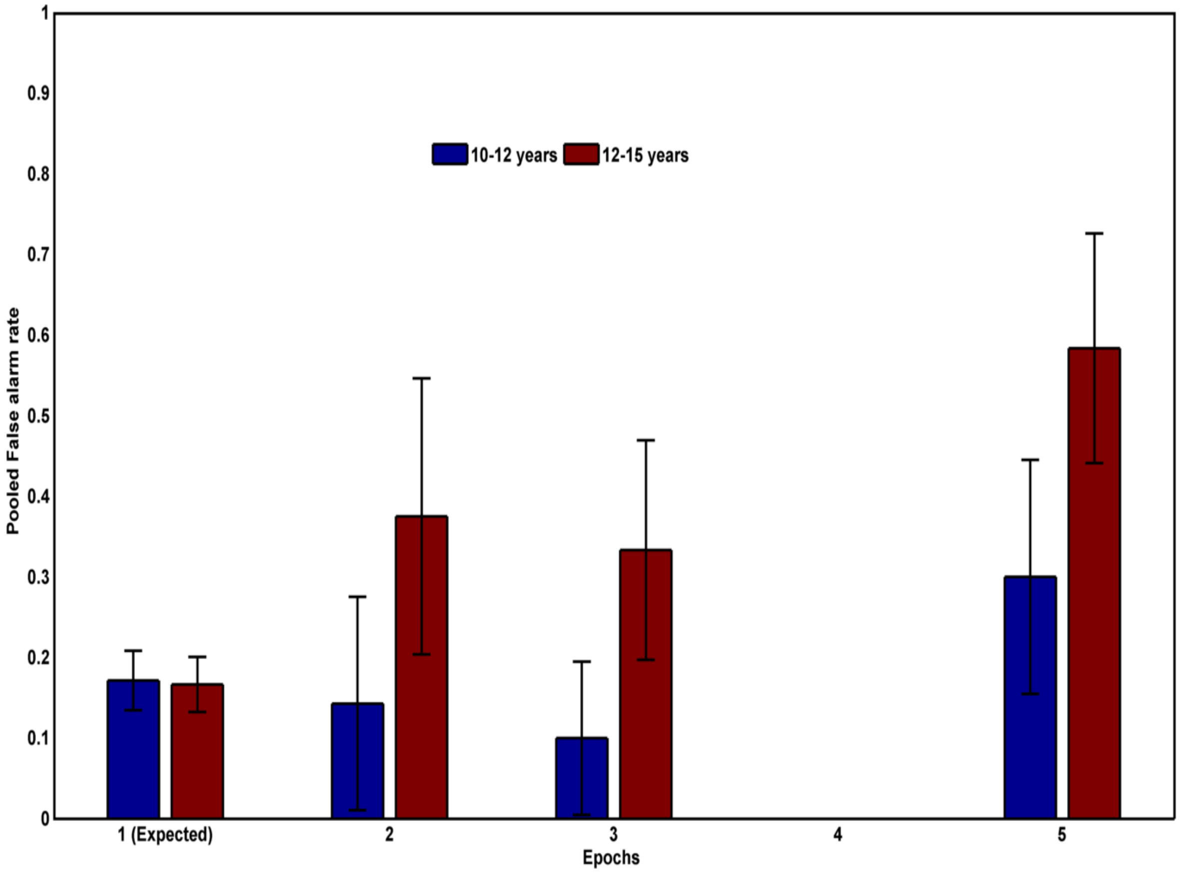


Figure B: Pooled false alarm rates for the 5 epochs for the 2 age groups of normal children. The dashed lines represent the line of best fit for linear extrapolation of temporal re-orientation time



SCIENTIFIC REPORTS

OPEN

Switch Attention to Listen

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SUBJECT AREAS:
CORTEX
ATTENTION
COGNITIVE CONTROL
DIAGNOSTIC MARKERS

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The aim of this research was to evaluate the ability to switch attention and selectively attend to relevant information in children (10–15 years) with persistent listening difficulties in noisy environments. A wide battery of clinical tests indicated that children with complaints of listening difficulties had otherwise normal hearing sensitivity and auditory processing skills. Here we show that these children are markedly slower to switch their attention compared to their age-matched peers. The results suggest poor attention switching, lack of response inhibition and/or poor listening effort consistent with a predominantly top-down (central) information processing deficit. A deficit in the ability to switch attention across talkers would provide the basis for this otherwise hidden listening disability, especially in noisy environments involving multiple talkers such as classrooms.

Listening and understanding a single talker in the presence of other talkers or distracters requires adequate hearing sensitivity, processing of the spectral (frequency and intensity) and temporal (time) cues, separating the information into coherent streams as well as selectively attending to the relevant talker and ignoring the distracters[1]. Selective auditory attention and re-orientation in a noisy environment is a basic yet complex behavior[2–4]. Most of our listening experiences in the environment are dynamic and the sources as well as information change constantly in time and space. Therefore the listener needs to orient attention when there is relevant information and rapidly re-orient attention from one stream of information to another as the situation demands[2].

There have also been suggestions that the deficits in auditory processing skills and speech perception in noise, which are most often observed in children who have a history of recurrent otitis media (middle ear infection) with effusion (OME)[5], are associated with poor attention abilities[6]. We have focused our research to study the attentional mechanisms in such a population in order to gain further insight into the underlying cause of the listening difficulties in background noise.

Auditory attention can involve both top-down and bottom-up processing based on the types and demands of a listening task[7–9]. A task which requires a voluntary selection of targets amongst distracters would involve top down (cognitive) control, whereas that requiring involuntary focus of attention due to factors such as salience will recruit bottom up (sensory) processing resources[10]. From a functional perspective, listening to speech in a noisy background requires a listener to remain alert and responsive to relevant cues (intrinsic and phasic alertness), orient attentional focus to important or salient signals (orienting) and selectively focus attention on the sounds of interest while ignoring the distracters (selective attention)[11,12]. In addition, there may also be a need to simultaneously focus attention on two or more signals (divided attention) and/or disengage and switch attentional focus between multiple sources of information based on relevance or salience (attention switching/re-orientation)[13,14].

Selective auditory attention in the time domain is especially important in situations where speech and noise sources overlap in space and where the listeners are required to constantly switch attentional focus in time[15]. A number of studies have demonstrated that tone detection in the presence of background masking noises improved significantly when the temporal interval of target occurrence was expected or cued[16–19]. An extension to this notion of temporal selective attention is the time required for the subjects to *re*-orient their attention after attending to the expected time window. This has been studied in vision where the temporal re-orientation time varied between 200–500 ms[20]. However to our knowledge, this has yet to be examined in audition.

In this study, we designed a task to examine the relative roles of top-down and bottom-up control of attention and the time taken to re-orient attention in the auditory domain. Based on a combination of the multi-probe signal method[21] and Posner's cueing paradigm[22], this method involved priming a target signal at a specific time interval in a stimulus sequence (temporal epoch) by cueing, followed by frequent presentations of the target at the cued epoch. This ensured the focus of attention on the expected epoch. To identify attention specific effects, in addition to presenting targets at the expected interval, stimuli were also presented infrequently at unexpected epochs. Importantly we also allowed for the presentation of catch trials to facilitate bias correction and sensitivity analysis. Here, we used a target identification task involving the discrimination and identification of a target syllable from a string of five syllables in the presence of a two-talker speech babble (see Figure 1). The duration of the five temporal windows (epochs) was based on the subject's individual reaction time via button press responses in a control experiment. This ensured a correlation between attention and reaction, while also providing a means to quantify the subject's response accuracy over time and allowed us to model the patterns of attentional re-orientation. Additionally, by changing the temporal position of the priming cue and the expected epoch between the first and last stimulus windows, we were able to gain insights into the subject's auditory selective attention abilities.

Performance benchmarks were collected from two control groups of subjects with normal hearing sensitivity and no reported listening difficulty (adults and children). We then applied this paradigm on a third (experimental) group of children who presented with persistent listening difficulties in noise. In particular, apart from parental and teacher concerns about their listening difficulties and a concomitant medical history of recurrent OME, this last group of children otherwise performed similar to the control (children) group when assessed using a wide range of clinical tests for hearing sensitivity and auditory processing. Apart from the standard test battery recommended by the American Academy of Audiology (2010)[23], they were also examined on additional tests (See Table 1) that ruled out deficits in peripheral hearing, auditory short-term memory, auditory sustained attention and auditory processing (See Table 2).

Previous studies, although using shorter observation time windows than the current experiment, have demonstrated a reduction in sensitivity to targets outside a certain time window around an expected epoch[16,18]. Detection of the targets occurring earlier than expected has been shown to involve involuntary shifts of attention requiring bottom-up processing resources; whereas the detection of targets later than expected involves voluntary disengagement and switch of attention from the expected temporal epoch requiring top-down processing resources[9,10]. Furthermore, we anticipate a gradual improvement in sensitivity over time at the unexpected epochs following the epoch when a target was expected but not presented[24]. We assessed the difference in sensitivity to identify a target for expected and unexpected targets presented at the first epoch as a measure of selective attention and the time taken to relatively recover the sensitivity for the unexpected targets as a measure of attention switching. All the participants were tested on 2 conditions, an "Early" condition in which the target syllable occurred frequently (60%) in Epoch 1 and a "Late" condition in which the target occurred frequently in last epoch (Epoch 5). That is, for the "Early" condition the target syllables occurred infrequently at the unexpected epochs (2–5) while the converse was true for the "Late" condition where target occurrence at epochs 1–4 was unexpected. The "Early" condition allowed us to examine the voluntary attention re-orientation mechanisms that are distinct from the involuntary attentional processes of the "Late" condition[25].

To our knowledge, this is the first investigation and demonstration of temporal attentional re-orientation in children. Most importantly, these results indicated a significantly longer attentional re-orientation time for children who reported with persistent listening difficulties and a history of recurrent OME, in contrast to an age matched control group.

Results

Adults and children with no listening difficulty. *Early condition.* We examined subjects with normal hearing and no reported listening difficulties (12 adults and 12 children). We observed several distinct patterns in hit rate and false alarm responses. Overall, the hit rates at the expected epoch were considerably higher than those at the unexpected epochs in children but not for adults (Figure 2, blue and green bars). For the children, the hit rates dropped substantially immediately after Epoch 1 (from 0.82 ± 0.01 to 0.39 ± 0.07) in the "Early" condition, then gradually improved consistent

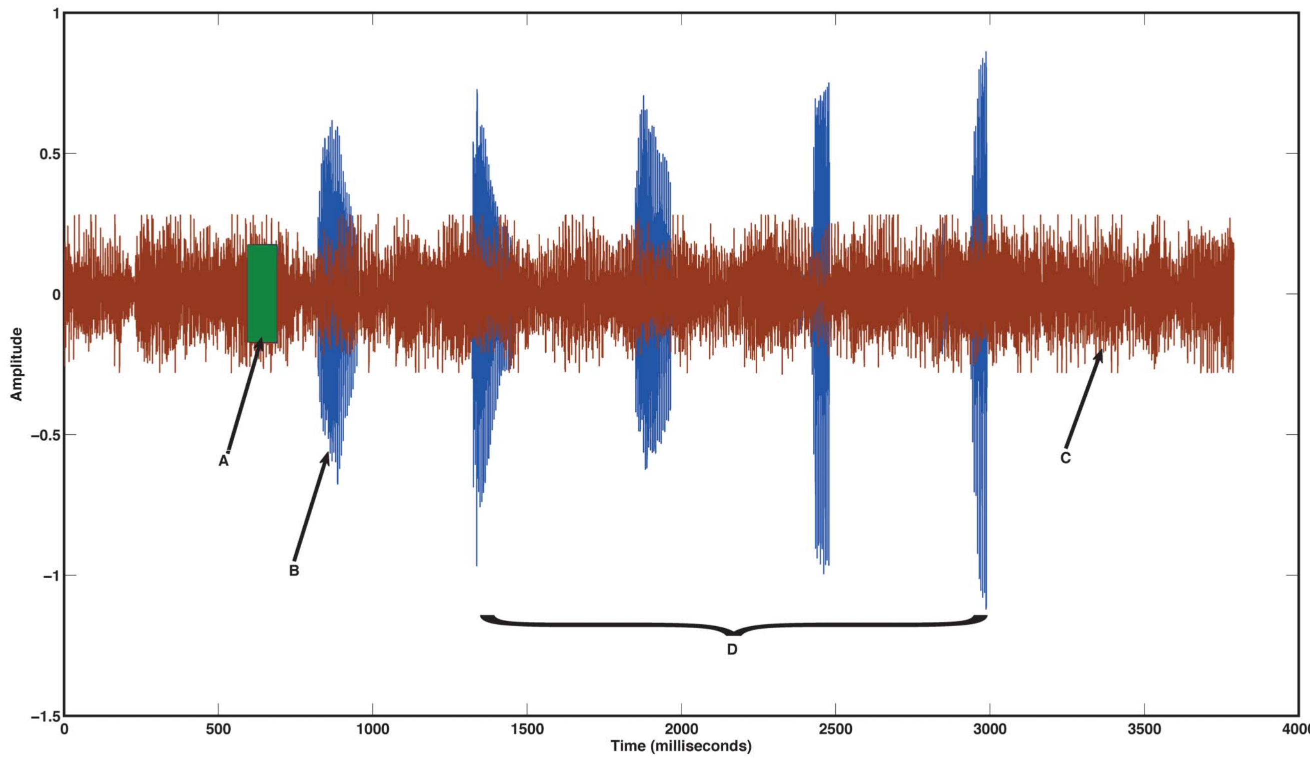

Figure 1 | A time domain view of the stimulus presented in a test trial within an experimental block ("Early" Condition) in which the target was presented frequently and cued at the first temporal epoch. (A) – Cue-Tone (2500 Hz); (B) – Target (da) validly cued and occurs in 60% of trials at this epoch; (C) – 2 Talker Babble (Female); (D) – Target (da) invalidly cued and occurs in 20% of trials at these epochs.

Table 1 | Details of assessment measures, skills and tests undertaken in the current study to investigate peripheral hearing, auditory processing skills as well as auditory memory and attention

Measures	Skills	Tests
Peripheral Hearing	Hearing sensitivity	Pure tone audiometry
	Middle ear integrity	Immittance audiometry
Spectral Processing	Frequency Discrimination	Brief tone frequency discrimination test[55]
Temporal Processing	Temporal resolution	Gap detection in noise test[56]
	Temporal ordering	Pitch pattern test[23]
	Temporal envelope processing	Sinusoidal amplitude modulation (SAM) detection threshold[57]
	Temporal fine structure processing	Low frequency fine structure - Inter aural phase sensitivity (TFS-LF)[58]
		High frequency fine structure - phase shifted harmonic discrimination (TFS1)[58]
Binaural Processing	Binaural integration	Dichotic digits test[23]
	Binaural separation	Binaural masking level difference test[23]
	Localization	Speech localization in presence of 2 talker babble[59]
Auditory Stream Segregation	Sequential stream segregation	ABA_ paradigm (temporal coherence boundary)[60]
	Spatial stream segregation	Listening in Spatialized noise test (LiSN-S)[46]
Speech Perception in Noise	Speech recognition in presence of Spatialized noise.	High Cue SRT condition of LISN-S test[46]
Auditory Memory	Short term and working memory	Forward and Backward Digit span test[41]
Auditory Attention	Sustained attention	Auditory Continous Performance Test[42]
	Selective attention and Attention switching	Test Developed in the current study

with a reorientation/re-preparation process[24] (Figure 2A, blue and green bars), reaching 0.69 ± 0.05 in Epoch 5. This did not occur for the adult subjects, where there was no notable drop in their hit rates after the expected epoch, maintaining a hit rate of 0.72 ± 0.06 at Epoch 2 (0.51 ± 0.01 seconds, see Methods). The considerable reduction in hit rate for the normal children after the expected epoch coupled with a relatively slow reorientation time meant that there remained a notable difference in hit rate between Epoch 1 and Epoch 5, the last temporal window. In order to compare the reorientation time between normal adults and children, we extrapolated the hit rates using a simple line of best fit ($y = 0.089^*x+0.22$, adjusted $R^2 = 0.81$) and projected that normal children will only regain sensitivity at 3.32 ± 0.08 seconds with a hit rate of 0.84 ± 0.18 (see Figure 2A). In the expected epoch (Epoch 1), there was no notable difference in hit rates for the normal adults and children, however, there was a considerably higher number of false alarms committed by the children (Figure 2B, blue and green): 0.17 ± 0.02 versus 0.06 ± 0.01 respectively - suggesting a reduction in sensitivity (see below for d′ analysis).

*Late condition***.** In the "Late" condition (Figure 3); the hit rates were substantially higher for the adults in all epochs with a consistently lower false alarm rate. While there was a notable difference in hit rates between adults and children in Epoch 5, both groups performed above the 75% threshold, with adults reaching 0.94 ± 0.00 and children 0.87 ± 0.01. In comparison between Early and Late conditions, the hit rates at the expected epoch showed a similar pattern. There was a higher hit rate for adults in the "Late" condition; however, a commensurate increase in false alarm rate was also observed, suggesting a similar level of sensitivity for target identification at the expected epoch for both groups of participants. That was not

Table 2 | Mean scores with standard errors for auditory processing, memory and attention tests. There was no significant difference between the 2 groups for any of the tests ($p > 0.05$). For the tests marked with an asterisk the individual scores for normal children were also within the previously published[42,43] age based normative data

Tests	Normal Children	Children with Listening Difficulty
Brief tone frequency discrimination (threshold in Hz)	100 Hz: 6.15 Hz (0.84)	100 Hz: 6.54 Hz (1.05)
	1000 Hz: 5.43 Hz (1.04)	1000 Hz:6.70 Hz (1.37)
Gap detection in noise (threshold in ms)	2.92 ms (0.27)	3 ms (0.30)
Pitch pattern* (Percentage correct score)	Right: 92.21% (2.14)	Right:91.93% (2.85)
	Left: 92.76% (1.91)	Left: 92.2% (1.85)
SAM detection (threshold in dB)	4 Hz: −23.79 dB (0.55)	4 Hz: −22.21 dB(0.78)
	128 Hz: −20.97 dB (0.71)	128 Hz: −19.59 dB (1.34)
TFS-LF[58] (Interaural phase difference threshold in degrees)	44.05 deg (5.05)	35.23 deg (3.04)
TFS1[58] (score in Hz)	24.5 Hz (4.43)	28.39 Hz (3.41)
Dichotic digits* (Percentage correct score)	Right: 98.49% (0.89)	Right:95.23% (1.31)
	Left: 94.81% (2.3)	Left: 93.24% (1.70)
Binaural masking level diffference* (difference in dB)	12 dB (1.2)	12.08 dB (0.80)
Localization (Root mean square lateral and polar angle errors (LAE and PAE) in Azimuth)	LAE:11.5 Az (0.9) PAE: 14.25 Az (0.72)	LAE: 14.58 Az (1.43) PAE: 13.08 Az (0.57)
Sequential stream segregation (temporal coherence boundary in Hz)	60.92 Hz (9.90)	80.90 Hz (9.69)
Spatial stream segregation* (spatial advantage raw score)	11.90 (0.70)	11.44 (0.56)
Speech Recognition in Noise* (Signal to masker ratio threshold in dB)	SRT: −15 dB (0.6)	SRT: −13.74 dB (0.78)
Digit Span* (Forward and backward digit span raw score)	Forward: 9.33 (0.54)	Forward: 8.5 (0.59)
	Backward: 7.08 (0.49)	Backward: 5.57 (0.25)
Auditory Continous Performance* (raw scores)	Inattention: 2.25 (0.65)	Inattention: 4.08 (1.08)
	Impulsivity: 1.08 (0.66)	Impulsivity: 1.5 (0.59)
	Vigilance: 0.66 (0.28)	Vigilance: 1 (0.30)

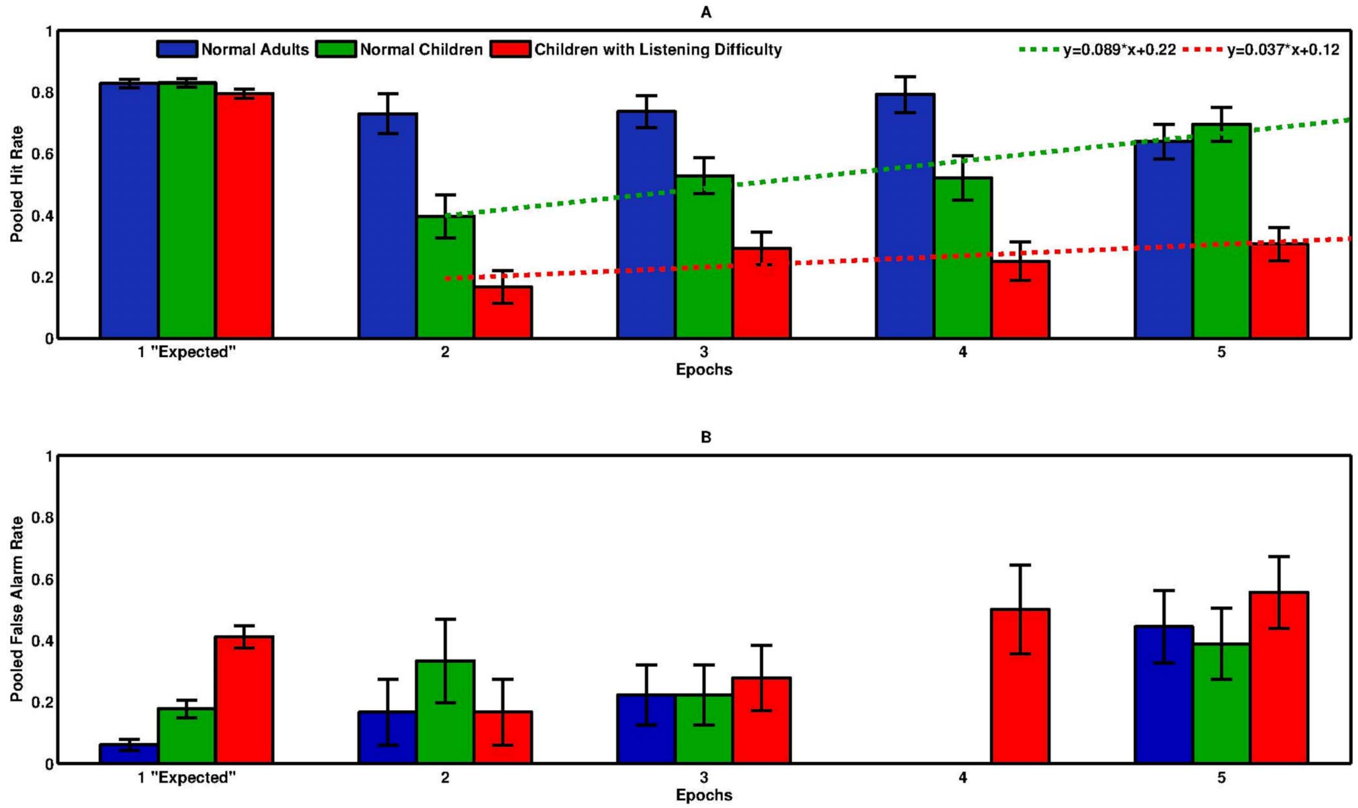

Figure 2 | 2A and 2B: Pooled hit and false alarm rates for target identification for the 3 groups in the "Early" Condition across the 5 temporal epochs. The blue bars represent the data for the adult participants with no listening difficulty, the green bars for the children with no listening difficulty and the red bars for children with listening difficulty. The green and red dashed line in figure 2A are the lines of best fit used to extrapolate the attention re-orientation time for children without and with listening difficulties respectively. Error bars represent standard errors of the mean.

true for children though, where a considerable increase in false alarm rate was observed in the Late condition (from 0.13 ± 0.02 to 0.46 ± 0.03), suggesting a lower level of sensitivity. Similar to the finding in the "Early" condition, there was no notable difference between the false alarm rates for the unexpected epochs within each of the two groups (See Figures 2B and 3B, blue and green bars).

Selective attention. The hit rate and false alarm results were summarized with a sensitivity (d′) analysis (See Method and Supplement 1 for further details). We compared the target identification sensitivity at the first temporal epoch when the target was expected at that epoch ("Early" condition) to when it was unexpected ("Late" condition) as a measure of temporal selective attention ability[24] and found a notably higher sensitivity for target identification at the first epoch in the "early" condition (Expected) compared to that at the first epoch in the "Late" condition (Unexpected) suggesting a marked effect of focusing attention selectively on the expected epoch for both groups of participants. Further we also compared the sensitivity for identifying the target at the expected epochs for both Early and Late conditions (Figure 4). In the Early condition, normal adults had a sensitivity of 2.49, 95% CI of [2.2 2.75] while normal children were considerably lower at 1.87, 95% CI of [1.62 2.11]. In the Late condition, normal adults had a sensitivity of 2.64, 95% CI of [2.35 2.91], with the normal children dropping in sensitivity to 1.23, 95% CI of [1.01 1.44]. In summary, sensitivity for the adult population did not vary between conditions and was consistently considerably higher than that of normal children. However, the converse was true for the normal children tested, where we observed a notable decrease in sensitivity between the Early and Late conditions.

Children with listening difficulties. *Early condition*. This group of subjects consisted of 12 children, age-matched ($p > 0.05$) against the children in the control group, who presented with persistent listening difficulties especially in a noisy environment (see Methods). Consistent with the results from the children in the control group and from previous research[16,18], the hit rates for target identification was considerably higher when the target syllable occurred at the expected epoch and poorer elsewhere for all the participants (See Figures 2A and 3A, red bars). A comparison between the children in the experimental and control group showed no notable difference in hit rates at Epoch 1. Substantially more false alarms were committed by children in the experimental group (0.41 ± 0.03 versus 0.17 ± 0.02 (normal children) and 0.06 ± 0.01 (normal adults)).

Similar to the responses in the control group of children, there was a substantial drop in pooled hit rate immediately after the expected epoch – from 0.79 ± 0.01 (Epoch 1) to 0.16 ± 0.05 (Epoch 2). Additionally, hit rates were considerably lower for all the unexpected epochs when compared with the control group and the normal adults, only reaching 0.30 ± 0.05 at Epoch 5; However, a trend of recovery can still be seen, albeit at a much slower rate (Figure 2A). Again, we extrapolated the hit rates from Epoch 2 to 5 and estimated that the experimental group would have recovered their sensitivity at 9.47 ± 0.25 seconds, reaching a hit rate of 0.78 ± 0.27; a notable increase in duration from the control group.

Late condition. In the Late condition the hit rate at the expected epoch was notably lower for the children in the experimental group. Interestingly, the false alarm rates in the expected epoch for the experimental group did not vary significantly when compared with the "Early" condition, maintaining at 0.47 ± 0.01, even though a substantial increase was observed for children in the control group.

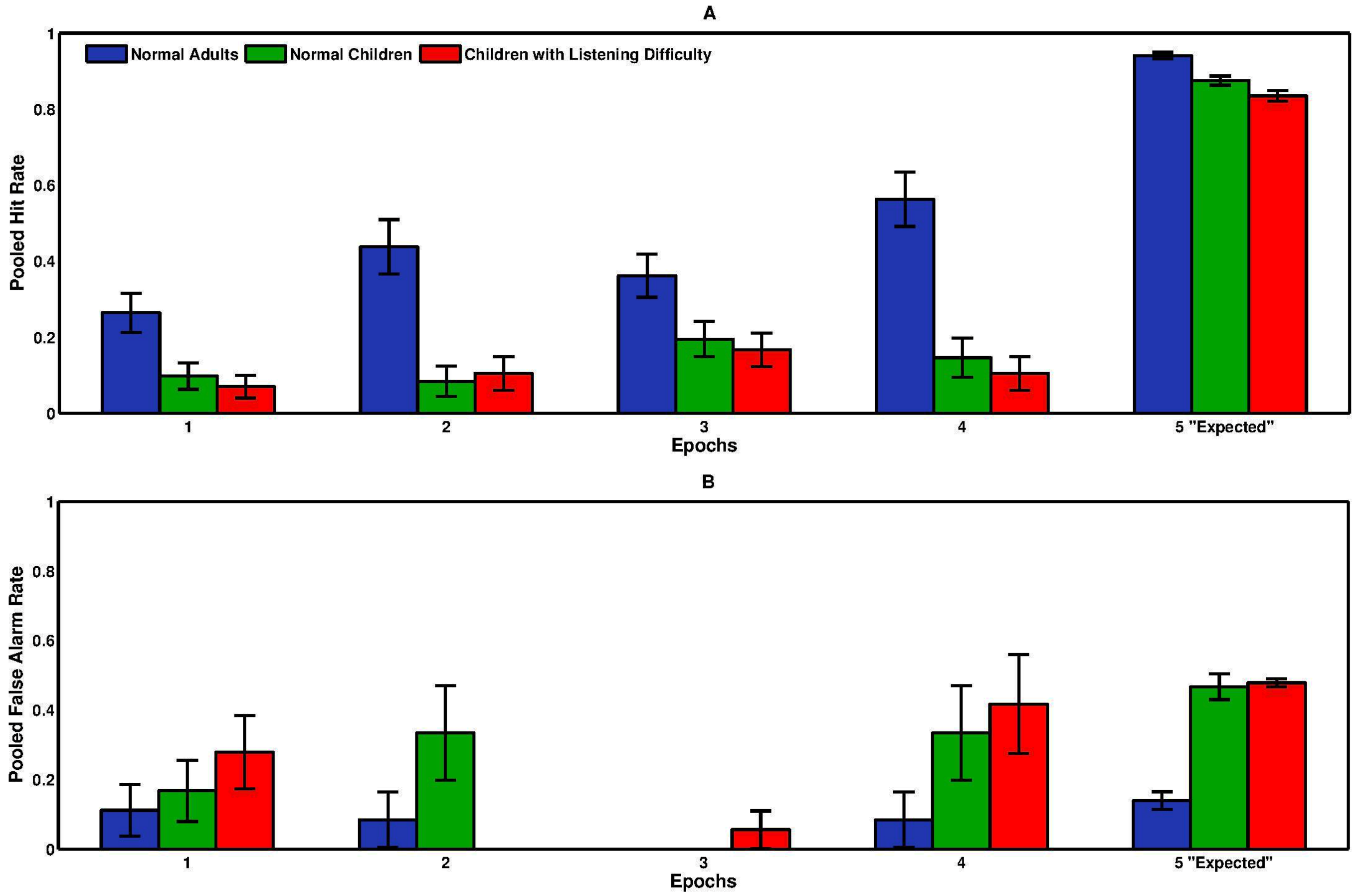

Figure 3 | 3A and 3B: Pooled hit and false alarm rates for target identification for the 3 groups in the "Late" Condition across the 5 temporal epochs. The blue bars represent the data for the adult participants with no listening difficulty, the green bars for the children with no listening difficulty and the red bars for children with listening difficulty. Error bars represent standard errors of the mean.

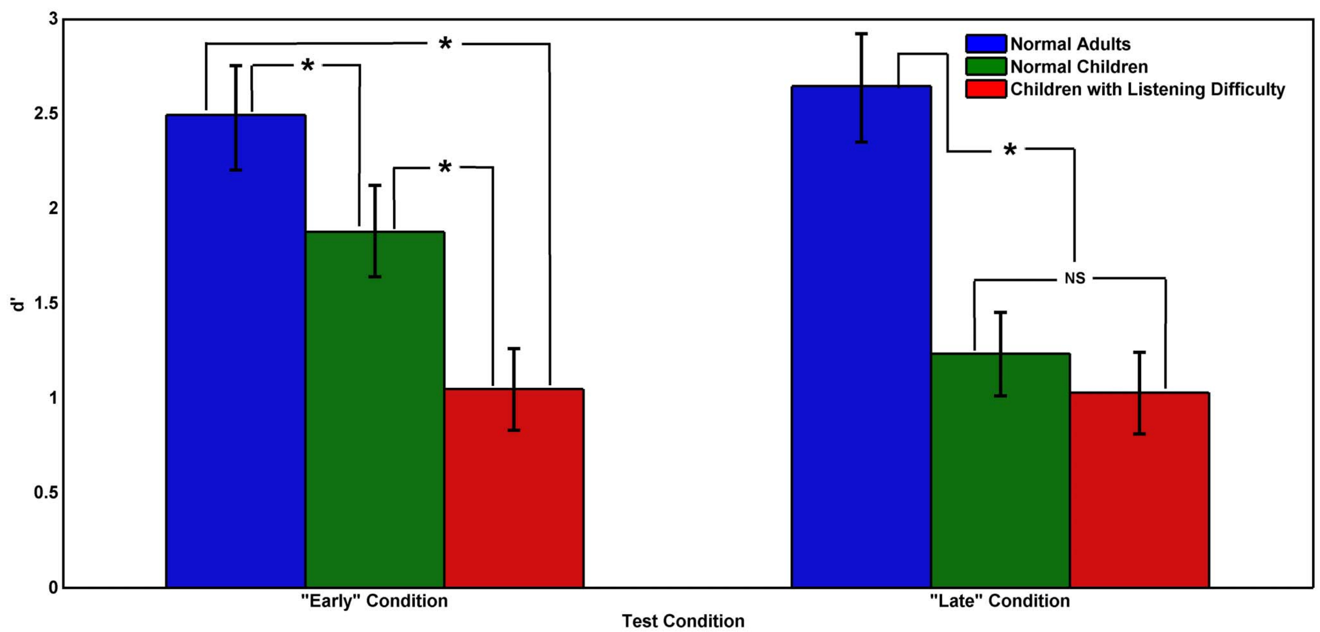

Figure 4 | Pooled sensitivity (d′) for target identification at the expected epochs for the 3 groups for "Early" and "Late" conditions. The blue bars represent the data for the adult participants with no listening difficulty, the green bars for the children with no listening difficulty and the red bars for children with listening difficulty. Error bars represent the 95% confidence intervals. * – Substantial Difference; NS – Non-substantial difference.

*Selective attention***.** Similar to the results obtained in the previous experiment, we observed considerably higher sensitivity for target identification at the expected epoch compared to the unexpected epoch for both groups of children suggesting that similar to the children in the control group, the children in the experimental group showed an advantage for identifying the target based on its expectancy. Further comparison of target identification sensitivity between the 2 groups at the expected epochs for both "Early" and "Late" conditions showed a notably higher sensitivity for the children in the control group in the Early condition but there was no substantial difference in sensitivity between the two groups in the "Late condition (See Figure 4).

Discussion

In these experiments, we used a modified probe-signal method to analyze the rate of recovery in attention and extrapolated the time course necessary for subjects to regain attentional focus. In addition to segmenting each trial into equal response windows (epochs) based on each individual's minimal response times, false alarms were also recorded to ensure the validity of the task and to calculate the sensitivity for target identification across the epochs. The catch trials used in the task also played an important role of reducing the attentional preparation of the listeners for targets presented at the unexpected epochs[24]. The role of the catch trials in context of this paradigm would be to generate a degree of uncertainty regarding the occurrence of target which may relax the participants' state of preparation for responding to the target especially at the unexpected temporal epochs[24]. Although the proportion of catch trials used in the current study was relatively small (20%), it has been shown previously that such dis-preparation due to the presence of catch trials is an 'all or none' process, such that even a small percentage of catch trials is sufficient for the effect to be observed[24]. By combining a rigid time response window with hit rates and false alarm measures we were able to derive bias-free sensitivity measures at the expected epochs.

We also found enhanced sensitivity for target identification at expected vs. unexpected epoch indicating an ability to attend selectively to the target at the expected time interval for all 3 groups of participants. From the present data we are unable to compare and contrast the magnitude or strength of selective attention abilities between these groups.

While other studies have also shown a reduction in sensitivity after the expected epoch, here we also quantified the recovery rate. Such recovery can be attributed to the process of "re-preparation" by which the listener develops a new state of preparation across the unexpected epochs, due to the absence of targets at the expected epoch[24]. Despite the temporary disruptions in re-preparation caused by the presence of catch trials, the participants gradually recover their sensitivity. This recovery would require a goal driven mental effort for the listeners[26] involving predominantly top down voluntary control of shift in attention across time[25] with possibly some involuntary bottom-up processing[10,24].

Interestingly, the results showed that our adult participants had an essentially flat distribution of hit rates across the five epochs in the "Early" condition. Given the similarities in hit rate, the results may suggest that adults reoriented faster than could be detected using a button press response paradigm. The duration of the epochs was tailored individually based on the response times derived from a set of control experiments (see Methods), which for adults was 360 $\pm$ 15.56 ms. These results suggest a relatively rapid attention switching time in the time domain for adults. This is consistent with earlier studies pertaining to the recovery of the "attentional blink" phenomenon in which the detectability of the second target in a dual target detection task was substantially reduced if it occurred within 200–500 ms from the first and improved thereafter[27]. This has been observed in audition as well as vision[20,28] and indicates that the listeners' attention is captured by the first target and thus unable to rapidly switch to the next. While this may provide a tentative explanation to the results from the adult population, "attentional blink" in the auditory modality has not been examined in children.

In contrast, the hit rates for normal children dropped significantly between Epoch 1 and Epoch 2 - before increasing slowly in Epoch 5. A linear extrapolation projected a reorientation time of 3.32 $\pm$ 0.08 seconds to attain parity with the expected epoch, which is significantly slower than adult behavior. To our knowledge, this is the first report that quantified the differences in attentional reorientation between adults and children and suggests that this process continues to mature into adulthood.

Most significantly, when we applied this testing methodology on a cohort of children who reported with persistent listening difficulties (Experimental group), their hit rates, false alarm rates and temporal re-orientation time were respectively lower and longer than that of the normal children and adults. A comparison of sensitivity in the expected epochs (Figure 4) clearly demonstrates this trend. Interestingly, there was a significant difference in d′ between the Control and Experimental cohorts only in the "Early" condition, with the d′ for the Control cohort reduced to the level of the Experimental subjects in the "Late" condition. The difference in hit rate responses between the cohorts could not account for such a drop in sensitivity. Rather, there was a highly significant difference in false alarm rates between the expected epochs for the children in the Control group, where a much smaller number of false alarms were committed in the "Early" condition. This suggests that the Experimental cohort were less able to inhibit their responses in the expected epoch of the "Early" condition, rather than representing a decrease in sensitivity of the Control group.

The substantially higher false alarm rate in the Experimental group at the expected epoch in the "Early" condition may be due to a combination of excessive facilitation effect due to a reflexive shift of attention at the expected epoch along with poor response inhibition[29]. Moreover, the total number of false alarms across the five epochs was significantly higher for these subjects, suggesting a general reduced ability to avoid responding in a catch trial. Previous work has shown that such intentional or voluntary inhibitory control processes are vital in regulating the allocation of attention[29,30]. A poor control of response inhibition as observed may also be related to poorer working memory capacity[31]. This inability to intentionally inhibit the allocation of attention to irrelevant stimuli may lead to increased distractibility of these children especially in noisy listening environments and may thus partly explain their difficulties in listening.

The results seen with the experimental group are consistent with the idea that there are differences in the ability to rapidly shift attention in the group of children with persistent listening difficulties compared to their age matched peers. This difference could involve a combination of top-down and bottom-up processing deficits. Listening in a noisy background or in a multi-talker environment, like a group discussion, not only requires efficient peripheral hearing, auditory processing and memory but also rapid switching of the focus of the listeners attention from one talker to another based on the changing relevance of information[32,33]. This requires the application of listening effort to attend to the expected as well as unexpected sources of information and the ability to inhibit responding to distracting stimuli. Deficits in any of these abilities may affect an individual's ability to listen effectively in a noisy or multi-talker situation. Previous brain imaging studies indicate the involvement of predominantly frontal and parietal cortical areas of the brain in attention switching, listening effort and response inhibition control which further suggests a more central or top down processing deficit in the experimental group tested in this study[8,34–36].

Previous work involving children with listening difficulties has reported variable performance on psychoacoustic tasks meant to measure their auditory processing abilities. This has also been

attributed to poor auditory attention and is the consistent with the findings reported here[37,38]. Interestingly, all the participants in our experimental group reported a history of recurrent otitis media. While the data does not speak directly to any definitive links with OME, it may be that due to the transient disruptions in hearing associated with recurrent OME[39,40] the experimental group may have learnt to allocate most of their cognitive resources to selectively focus attention on expected information and the remaining resources are insufficient for them to switch their attention to any unexpected stimulus. Future studies are needed to evaluate this hypothesis. Further research should also explore whether these attention switching
deficits are specific to the auditory modality or are modality independent general cognitive deficits.

This work has described an auditory attention switching deficit in a group of school-aged children with persistent listening difficulties in noisy environments. As the current set of standard clinical tests was unable to discriminate this group of listeners from normal controls, the test reported here may provide a good candidate test for children with listening difficulties. As attention switching requires predominantly top down control, the data is consistent with the suggestion that this deficit represents a more central pathology in contrast to a peripheral auditory processing deficit. An aspect of considerable interest will be the capacity of training or practice regimes to assist in overcoming this deficit. In a similar study, we are currently focusing on assessing children diagnosed with an auditory processing disorder to determine if it is part of the broader spectrum of listening difficulties and to gain insights into its underlying cause.

Method

Participants. We examined three groups of participants – 12 normal adults (mean age 21.09, SD 3.52), 12 normal children (control group) (mean age 12.5, SD 1.55) and 12 children with persistent listening difficulties (experimental group) (mean age 11.38, SD 1.48). All subjects spoke Australian English as their first language, had normal hearing sensitivity and did not present with any middle ear pathologies. We ruled out any auditory memory, sustained attention or processing deficits for all the participants based on a comprehensive clinical test battery[23,41] (See Table 1 and 2). The test scores for each of the normal children on the standardized clinical tests were within the previously published norms[42,43]. All the children in the experimental group presented with persistent listening difficulties that were based on parental, teacher and participant reports of concerns regarding their listening abilities especially in noisy environments.

Children with a history or formal diagnosis of attention deficit/hyperactivity disorder (ADHD) were excluded from the study. Furthermore, all children were tested on the auditory continuous performance task[44] and there was no significant difference (See Table 2) between the control and experimental group children. Earlier studies have reported the continuous performance task as a screening test for ADHD[45]. Interestingly, their medical history also revealed a history of recurrent (>2 episodes, Mean $= 2.91$, SD $= 0.51$) otitis media with effusion between the ages of 2–5 years that was absent in the control group. Both the control and experimental groups were age matched ($p > 0.05$). Informed consent was obtained from all the participants in accordance with procedures approved by the Human Research Ethics Committee at Macquarie University. For every child participant, care was taken to avoid participant fatigue and loss of motivation[46] by constant positive reinforcements and dividing the tests across multiple sessions within a span of 2 weeks.

The modified Multi-probe signal method. The multi-probe signal method examines the allocation of attentional resources by examining a subject's target detection sensitivity in expected and unexpected time windows. It focused the subject's attention to the expected epoch by 1) presenting an auditory priming cue and 2) repeated presentations of the target signal, at the primed epoch. Target signals were then presented at the unexpected temporal epochs. This allowed us to examine the subject's attention reorientation time by comparing the target detection sensitivity between the time windows. Here, we examined five temporal epochs with the following target presentation ratio: 60% in the expected epoch, 5% in the four unexpected epochs and 20% catch trials. All the participants were tested on two conditions, an "Early" condition in which Epoch 1 was the expected epoch, where the target syllable occurred frequently and a "Late" condition in which Epoch 5 was the expected. This allowed us to compare between voluntary endogenous attention re-orientation mechanisms ("Early") and involuntary exogenous process ("Late")[9,25].

The duration of the epochs was set based on the subject's response time (RT) derived from a series of training trials (see below), where

$$\text{Epoch duration} = RT_{mean} + RT_{STD}$$

This ensured a reasonably high level of test difficulty within the motor constraints of the participants. The mean inter-stimulus interval for each group of participants was: Adult: 360 $\pm$ 15.56 ms, Control group: 404.16 $\pm$ 13.84 ms, Experimental group: 410.83 $\pm$ 14.3 ms.

Stimuli and procedure. The experiments were performed in a darkened anechoic chamber. Stimuli consisted of five speech syllables from the list (/da/pa/ga/ka/ba) each 150 ms long spoken in a male voice, presented from a loud speaker (Audience A3) located 1 m directly in front of the subjects (0°Azimuth). Maskers in the form of female "babble speech" were presented from two speakers (Tannoy V6) placed 1 m in front at $\pm$45°Azimuth at a constant intensity level of 70 dB SPL. The target to masker ratio varied between subjects (by varying the intensity of the syllable train) to keep a 75–85% target detection threshold. Speech syllable stimuli were used to emulate a natural listening environment within the constraints of linguistic load. It has been shown in an earlier study that attention can be specifically allocated to a single syllable[47]. The stimulus duration was kept short to preserve a narrow listening window[18].

Each trial began and ended with 800 ms of masker followed the syllable train that was mixed pseudo-randomly, with/da/being the target. A priming cue (100 ms, 2.5 kHz tone) always preceded the expected epoch by 100 ms (see Figure 1). Previous research suggests that such cues may facilitate detection and help orient attention involuntarily even if the listener is unaware of its presence[22]. The cue frequency was chosen based on the premise that the key differences in the acoustics of the syllables used are in the 2nd and 3rd formant transitions and may enhance identification of target syllable at the cued epoch[48]. The duration between the cue and the onset of a syllable (stimulus onset asynchrony (SOA)) was maintained at 100 ms to avoid the phenomenon of inhibition of return at longer SOAs which is known to impair the speed and accuracy of target identification at the cued epoch[49,50]. Auditory stimulus was generated using Matlab (version 2009b, The MathWorks Inc., Natick, Massachusetts) on a PC connected to an external sound card (RME FireFace 400). The subject's task was to press the response button as quickly as possible when the target syllable/da/was detected. Subject's also received instantaneous visual feedback (a red or green LED light) for correct target and false alarm identifications. A head tracker (Intersense IC3) constantly monitored the subject's position to ensure they directly faced the front speaker and a TDT System 2 (Tucker Davis Technologies) recorded the button press responses. Button presses that occurred 50 ms prior to the occurrence of target in a trial were rejected from the analysis with an assumption that they were random guesses.

Each subject participated in two training and test blocks. Each training block consisted of 25 trials which had both cued and un-cued targets presented in a randomized order. They were initially presented at a target to masker ratio of -10 dB and subsequently varied in 1 dB steps to reach a hit rate threshold of 75–85% and $<$40% false alarm rate on catch trials[18]. Each test block examined the "Early" and "Late" conditions separately and was further divided into two split halves of 60 trials each of approximately 5 minutes in duration, short enough to avoid participant fatigue (See Appendix 2). The first 10 trials always had the syllable/da/presented at the expected epoch (priming trials) to focus the attention of the participant and were excluded from subsequent analysis. The remaining 50 trials were presented in a pseudo-random order that preserved position of the expected epoch (either "Early" or "Late").

Analysis. The results were analyzed using hit and false alarm rates of target identification at each epoch, as well as d′ analysis at the first epoch. The hit rate was the proportion of correct responses, while the false alarm rate was the proportion of responses (button presses) in catch trials. The false alarms were assigned to the epochs based on the subject's response time[51]. Since the number of trials across the five epochs was uneven, the proportion of catch trials allocated to each epoch was based on the distribution probability of the targets; i.e., 60% of false alarms would be committed in the expected epoch. A control study corroborated this assumption by showing that uniform target presentation rates lead to a uniform false alarm distribution (see Supplement 2). Subsequent analysis was performed on the pooled hit rate and false alarm rates by combining the results across participants in each group[18,52,53]. Sensitivity (d′) was calculated using the pooled hit and false alarm rates only at the first temporal epoch for both conditions in order to assess selective attention ability. The 95% CI for the sensitivity measures were calculated using Miller's approach[54] (see Figure 4). Also, hit or false alarm rate values of 0 or 1 were adjusted by 1/2n or 1-1/2n respectively where n is the number of trials at each epoch to compensate for extreme values (i.e. 0 and 1) in the calculation[52].

In order to predict the temporal reorientation time, we modeled the hit rate from the unexpected epochs with a line of best fit (linear least square interpolation) and extrapolated to the epoch at which the hit rate reached 1 standard error of the expected epoch (see Figure 4). An adjusted chi-square test was used to calculate the goodness of fit.

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Author Contributions

I.D. and M.S conceived the overall concept for the project. I.D., J.L. and S.C. designed the experiments. I.D. recruited the participants and collected the data. I.D. performed the analysis with inputs from J.L. and S.C. The manuscript was mainly prepared by I.D. and J.L. with input from S.C. and M.S. I.D. created the figures. All authors reviewed the manuscript.

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Switch Attention to Listen

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Supplementary Information

Supplement 1

Auditory Processing Assessment

The psychophysical test paradigm for assessing auditory stream segregation, frequency discrimination and amplitude modulation detection (See Table 1 for details) consisted of 10 trials at random intervals in which the stimulus difference was kept intentionally large to monitor attentional lapses. We also monitored each participant's performance based on the variability of their track widths (standard deviations) in the tests and repeated the tests if there was an evidence of attentional lapse or variable track width[1,2].

Additional Analysis

The data for hit and false alarm rates was pooled across participants within the same group based on the finding of similar response bias across participants within the same group. We assessed the data for normality using a 2 tailed Shapiro–Wilk test and found the data to be normally distributed. Although, the statistical test used to test the hypothesis did not allow us to get specific significance level values (p values), to our knowledge, there is only a limited scope of comparison of such data otherwise.

To the best of our knowledge, there is no literature suggesting an appropriate procedure for calculating d primes in the test paradigm that we have used in this study. The confidence intervals observed were much larger at the unexpected temporal epochs in contrast to the expected ones due to the fewer number of trials at those epochs an thus were not graphically represented. During the calculation of target identification sensitivity, we observed few negative d' values at the unexpected temporal epochs which were normalized to zero based on previous treatment of such data and the fact that the 95% confidence intervals for sensitivity on those epochs included zero suggesting a sampling error[3]. The presence of negative d′ values for target identification at the unexpected temporal epochs suggest that the false-alarm rate was greater than the hit rate at those epochs. If the participants had responded only on the basis of the expected epoch, it would have yielded chance (very low) unexpected interval d′ values. However, the observation of some negative d′ values at the unexpected epochs suggested that the participants responded on the basis of the full interval and shifted their response criterion consistent with target expectation.

In addition to comparing pooled hit and false alarm rates, we also compared the mean derived from individual participant's results and found similar results as obtained with pooled rates. We also measured response bias, which was calculated in terms of the criterion and is a measure of the participants' decision variable to respond to a target[4]. A liberal criterion (negative value) would suggest a bias of the participant toward responding yes, regardless of the stimulus and a conservative criterion (positive value) would indicate a bias towards responding no[3,4]. The analysis of the response criterion across the 5 epochs indicated shifts in response criterion ranging from a relatively lax criterion to a more conservative criterion, consistent with target expectancies for both the group of participants suggesting that they responded to the target on the basis of the full trial interval and not only on the basis of the expected epoch, whereby they chose a relatively neutral criterion at the expected epoch and became gradually more conservative in their responses till epoch 4. A gradual increase in the hit rates across the epochs may further indicate that the listeners may soon realize the in-appropriateness of this strategy and re-adopt a more cautious listening strategy towards the later epochs. Alternatively it is also possible that the listeners may not have a voluntary control of their selective listening window in time[5]. There was a sudden change in the response criterion observed at the last epoch in which the participants became more liberal in their response criterion perhaps due to an inability to sustain the listening efforts in the task for the entire listening interval. In contrast to the controls, the participants in the experimental group chose a stricter criterion (i.e. bias towards responding no) for responding to targets presented in the 2nd temporal epoch suggesting that they may have momentarily employed a listening strategy that required relatively less effort[5], thereby missing unexpected information especially in a noisy background. As the participants were clearly instructed to press the response button when they identified the target syllable regardless of when it occurs in a trial, the probability of the participants not responding to the target presented at the unexpected interval despite identifying it, would be minimal[5,6].

Supplement 2

Control experiments

As part of additional control experiments, we also analyzed the reliability (internal consistency) of the test, the effect of target occurrence probability on the distribution of false alarms at different epochs, the possibility of interfering (forward masking) effects of the cue on target identification and the effect of serial position of the target on identification.

Split-half reliability (Internal consistency)

In order to assess the reliability of the test we assessed both the test blocks in two split halves of 60 trials each in a randomized order for all the participants (i.e. adult, control and experimental groups). We measured the split-half reliability by correlating (re-adjusted using the spearman-brown formula) the hit rates between the two halves due to constraints of testing time and found the test to be highly reliable ($r>0.8$).

False Alarm Distribution

This experiment was conducted on a small group of children (10-15 years; 8 controls and 8 experimental) in order to measure the distribution of false alarms on each temporal epoch when the target was equally probable to occur (20%) at each of the epochs. This was done to facilitate the allocation of catch trials for test blocks in which the target was unequally distributed at the various epochs. We compared the false alarm rate across the 5 epochs in such a control block in which the target was cued but occurred with equal probability at each of the epochs. No notable differences ($p>0.05$) were found across the epochs and between the two groups suggesting approximately equal distribution of false alarms. This suggests that the distribution of false alarms at the epochs would vary as a function of probability of target occurrence at that epoch.

Forward masking interference of the cue

We tested this by comparing the hit rates for 2 control blocks administered on 8 control and 8 experimental group participants. The target had equal probability of occurrence at each epoch for both the blocks. In the first block the target was cued whereas in the second block it was not. We observed a noticeable improvement in hit rates across the five epochs in the cued block compared to the un-cued block which rules out the possibility of the tonal cue reducing the hit rates for target identification, possibly due to a forward masking effect.

Reaction Time advantage and Serial position effect

We administered 5 test blocks in a random order on a smaller subgroup of 6 adult participants (18-30 years; Mean age=21.2; SD=2.68) in which the target was cued and frequently presented (60% trials) at each of the 5 epochs (Similar in structure to the test blocks used in "Early" and "Late" conditions in the main experiment). These test blocks were administered to study the effect of serial position of target on hit rates. As we had compared blocks in which the target was expected at the first and last serial position in experiment 2 with an aim to assess selective attention, a possibility of a bias in hit rates at those extreme positions compared to the middle ones due to limitation in short term memory capacity must be ruled out (primacy and recency effect). The results indicated no substantial difference in hit rates at each of the epochs when it was expected ($p>0.05$). This finding rules out the possibility of either an inherent reaction time advantage or the contribution of the serial position effect at a specific epoch due to short term memory capacity limitations[7]. In part, this was also facilitated by our experimental design using a go/no-go button press response to a rapidly presented auditory stimulus.

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