DIAGNOSIS OF
AUDITORY PROCESSING DISORDER
IN CHILDREN
USING AN
ADAPTIVE FILTERED SPEECH TEST

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"Better than a thousand days of diligent study is one day with a great teacher."

(Japanese proverb)

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Abstract

Auditory Processing Disorder (APD) is an auditory-specific perceptual deficit in the processing of auditory stimuli that occurs in spite of normal peripheral hearing thresholds and normal intellectual capacity American Speech-Language-Hearing Association (ASHA, 2005). The diagnostic process of APD typically involves a test battery consisting of sub-tests designed to examine the integrity of various auditory processes of the central auditory nervous system (CANS). One category of these sub-tests is the low-pass filtered speech test (FST), whereby a speech signal is distorted by using filtering to modify its frequency content. One limitation of the various versions of the FST currently available is that they are administered using a constant level of low-pass filtering (e.g. a fixed 1 kHz corner frequency) which makes them prone to ceiling and floor effects (Farrer & Keith, 1981). As a consequence, the efficacy and accuracy of these tests is significantly compromised (Martin & Clark, 1977). The purpose of the present study was to counter these effects by utilising the University of Canterbury Adaptive Filtered Speech Test (UCAST) which uses a computer-based adaptive procedure intended to improve the efficiency and sensitivity of the test over its constant-level counterparts.

A comprehensive APD test battery was carried out on 18 children aged 7-13 suspected of APD and on an aged-matched control group of 10 children. Fifteen of the APD suspected children were diagnosed with APD based on their performance on a traditional APD test battery, comprising the Compressed and Reverberated Words Test (CRWT), the Double Digits test (DDT), the Frequency Pattern test (FPT) and the Random Gap Detection test (RGDT). In addition, the UCAST was administered to examine whether the low-pass filter limit at which children score 62.5% of words correct i) differed significantly between children who either passed or failed the APD test battery; ii) correlated with their score on the traditional APD battery (TAPDB); and iii) correlated with their score on a commercially available low-pass filtered speech test, the Filtered Words Subtest of SCAN-C (Keith, 2000b).

Results demonstrated a significant difference between the UCAST low-pass filter limit at which APD and control children scored 62.5% words correct (two-way repeated measures ANOVA, $p < 0.01$). Significant correlations were found between the UCAST and three of the four tests used in the TAPD - the DDT, the RGDT and the FPT (Pearson Correlation coefficient, $p < 0.01$). No correlation was found between the UCAST and the CRWT or

between the UCAST and the SCAN-C (FW) test ($p > 0.05$). These findings provide evidence that an adaptive filtered speech test may discriminate between children with and without APD with greater sensitivity and specificity than its constant-level counterparts.

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List of Abbreviations

Terms

4AFC	Four-alternative forced choice
APD	Auditory processing disorder
ASHA	American-Speech-Language-Hearing Association
CANS	Central auditory nervous system
CAP	Central auditory processing
CG	Control Group
CNS	Central nervous system
CRWT	Compressed and Reverberated Words Test
CVC	Consonant vowel consonant
DDT	Dichotic Digits Test
EG	Experimental group
FPT	Frequency Pattern Test
LPF	Low-pass filter
LPFST	Low-pass filtered speech test
MLRST	Monaural low-redundancy speech tests
NU-CHIPS	Northwestern University Children's Perception of Speech test
OME	Otitis media with effusion
RGDT	Random Gap Detection Test
SCAN-C	Screening test for auditory processing disorder in children
SCAN-C (FW)	Screening test for auditory processing disorder in children, filtered words subtest.
SEM	Standard error of the mean
SNR	Signal-to-noise ratio
UCAST	University of Canterbury Adaptive Speech Test

Units

dB A	A-weighted sound pressure level in decibels
dB HL	Hearing level in decibels
dB SL	Sensation level in decibels
Hz	Hertz
ms	milliseconds

1 INTRODUCTION

The educational and social impact of communication difficulties, including listening difficulties, on children, their families and whānau is significant (Clegg, Hollis, Mawhood, & Rutter, 2005; Johnson, Bleitchman, & Brownlie, 2009). Auditory processing disorder (APD) is a processing dysfunction characterised by severe listening difficulties, despite normal peripheral hearing sensitivity. In estimates from the United States, approximately 3-5% of school aged children have APD (Chermak, Hall, & Musiek, 1997). No prevalence data for Aotearoa, New Zealand exists, although it may be expected that similar proportions of children are affected by listening difficulties in this country.

APD is a heterogeneous disorder, incorporating impairments of various aspects of auditory processing, including temporal, spectral and binaural hearing, as well as the ordering and grouping of sounds (Bellis, 2003; Moore, 2006).Children affected by APD display severe listening difficulties, particularly when listening to speech in the presence of background or competing noise. Academic deficits such as reading difficulties, remembering instructions and staying focussed while listening are common problems (Bellis, 2003; Chermak, et al., 1997; Musiek, Geurkink, & Keitel, 1982; Sharma & Purdy, 2009).

APD frequently co-exists with other language and learning disorders such as attention deficit hyperactivity disorder (ADHD), dyslexia and specific language delay (Moore, Halliday, & Amitay, 2009; Sharma & Purdy, 2009) and this overlap complicates the diagnosis of APD (Baran & Musiek, 1999). Whether APD is causative or symptomatic of other neurological or sensory disorders, or whether co-existing difficulties result from a common underlying cause, is currently unclear (Moore et al. 2009). What is clear is that children with APD are not currently receiving clear, scientifically based testing or management (Moore, et al., 2009).

No gold standard test for APD has as yet been formulated (Medwetsky, 2002). Therefore, the diagnostic process of APD typically involves a test battery consisting of sub-tests presumed to examine the integrity of various auditory processes of the central auditory nervous system (CANS). The underlying assumption is that the auditory pathways can be assessed by tests which challenge the different functions of the auditory system. One category of these sub-tests is the various versions of the low-pass filtered speech test (LPFST), which are routinely used internationally as part of a standard APD test battery. In

LPFSTs, a monaural, low-redundancy speech sample is distorted by using filtering to modify its frequency content.

One limitation of the LPFSTs is that they are carried out using a constant level of low-pass filtering (e.g. a fixed 1 kHz corner frequency) which makes them prone to ceiling and floor effects (Farrer & Keith, 1981). As a consequence, the efficacy and accuracy of these tests is significantly compromised (Martin & Clark, 1977). A further limitation of the LPFSTs is that scoring is based on the verbal response of the participant which requires additional processing skills, making it difficult to discern a given child's particular skill deficits.

The purpose of the proposed study was to counter these effects by utilising the University of Canterbury Adaptive Filtered Speech Test (UCAST). The UCAST is a computer-based adaptive procedure. It was designed to improve the efficiency and sensitivity of the test over its constant-level counterparts (O'Beirne, 2009).

A comprehensive APD test battery was carried out on a number of children who were suspected of having auditory processing deficits and on an aged-matched control group of normally-hearing children without any auditory processing or learning difficulties. In addition, the UCAST was administered to examine whether the low-pass filter limit at which the children score 62.5% of words correct is correlated with: i) their performance on the traditional APD battery (TAPDB), and ii) their score on a commercially available low-pass filtered speech test, the Filtered Word Subtest of SCAN-C (FW)(Keith, 2000b).

There is a clear need for an overhaul of the current APD test battery, and this study represents an important step in that direction.

2 LITERATURE REVIEW

2.1 Central Auditory Processing

Central auditory processing (CAP) is a primary function of the auditory structures of the central nervous system (CNS), known as the central auditory nervous system (CANS). The auditory pathways perform complex tasks of processing and manipulation necessary for interpretation of the acoustic information transduced by the peripheral auditory system (Moore, 2006; Musiek, et al., 1982). As sensory information travels within the CANS, auditory processing occurs not only in a serial order but also in a parallel manner resulting in a highly efficient and redundant system (Demanez & Demanez, 2003). The American Speech- Hearing-Association (ASHA, 2005) defines CAP as the “perceptual processing of auditory information in the CNS and the neurobiologic activity that underlines that processing…” (page 2). Simply stated, CAP is “what we do with what we hear”(Katz, Stecker, & Henderson, 1992).

However, the processing of auditory information is complex and does not occur in isolation from other brain processes such as attention, memory and language as displayed in Figure 1 (British Society of Audiology, 2007; McFarland & Cacace, 2009). While some of the complex mechanisms involved in the processing of verbal and non-verbal signals are specifically dedicated to the processing of acoustic signals, others are not necessarily unique to the processing of auditory information, e.g. attentional processes and long-term language representations (Baran & Musiek, 1999).

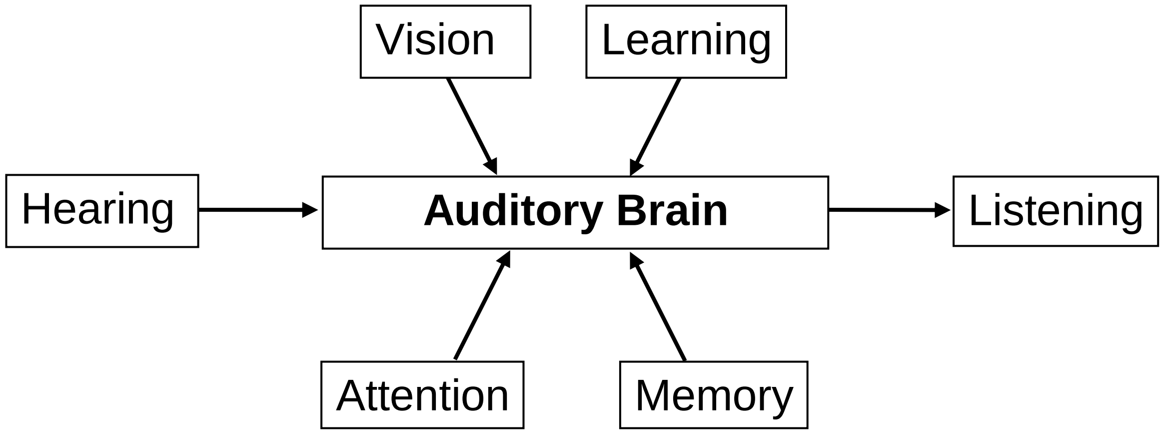

Figure 1. Simplified graphical representation of the interaction between different brain processes and auditory function (British Society of Audiology, 2007).

While research over the past 50 years has provided a better understanding of the neuro-anatomical and neuro-physiological processes underlying CAP, the complexity and interaction with linguistic and cognitive processing is an area of ongoing multi-disciplinary research (Richard, 2007). Much debate exists amongst researchers regarding the interaction between ‘bottom-up’ (sensory encoding) and ‘top-down’ (cognitive, language and other higher-order functions) processes, particularly in isolating purely auditory mechanisms from other brain processes (Bellis, 2003; Duchan & Katz, 1983; Katz & Tillery, 2005; McFarland & Cacace, 1995; Musiek, Bellis, & Chermak, 2005). In relation to the auditory system, bottom-up processing refers to encoding and processing guided by the acoustic input itself, whereas top-down processing is guided by higher level mental processes such as attention, language, cognition and executive function (Duchan & Katz, 1983; Friel-Patti, 1999). The interaction of both bottom-up and top-down processing skills are believed to guide pattern identification and interpretation (Bellis, 2003; Moore, 2007). Yet the relative contribution of bottom-up and top-down processes is influenced by the listening environment. Degraded signals such as those used in FSTs put increased demands on top-down processing skills as the sensory data becomes more and more unreliable and ambiguous (Chermak, et al., 1997).

2.2 Auditory Processing Disorder

The concept of APD was first described in the 1950s by Helmer Myklebust (1954) and a group of Italian researchers (Bocca, Calearo, & Cassinari, 1954). Since then there has been much confusion and controversy regarding a clear definition of what constitutes APD. There are controversial views amongst researchers of how APD can be clearly differentiated from other disorders that display similar symptoms, such as language or attention disorders (J. Jerger, 1998; Musiek, et al., 1982; Sharma & Purdy, 2009). Moreover, the actual existence of APD was questioned by Rees (1973) who claimed that APD was merely a language disorder that becomes apparent with auditory stimulation. In an effort to clarify issues surrounding APD, numerous committees and task forces have convened over the years to formulate guidelines on the definition, diagnosis and treatment of APD (ASHA, 2005; British Society of Audiology, 2007; Colorado Department of Education, 2008; J. Jerger & Musiek, 2000; Nickisch, et al., 2007).

Growing consensus in the literature holds that APD can be conceptualized as an auditory-specific perceptual deficit in the processing of auditory stimuli that occurs in spite of normal peripheral hearing thresholds, and is not due to higher order language, cognitive, or related factors (ASHA, 2005; British Society of Audiology, 2007; Moore, 2006). It is a heterogeneous disorder resulting in presenting symptoms and severity which differ significantly across individuals (Baran & Musiek, 1999; Bellis, 2003; Medwetsky, 2002; Moore, 2006). The following deficits in auditory processing can be observed: sound localization and lateralization; auditory discrimination; auditory pattern recognition; temporal aspects of audition, including temporal resolution, temporal masking, temporal integration and temporal ordering; auditory performance with competing acoustic signal; and auditory performance with degraded acoustic signal.

Children with suspected APD typically present with learning and listening difficulties affecting their academic and social development. While the expression of symptoms vary, common complaints include significant listening difficulties in background noise, inconsistent responses to auditory stimuli and difficulty with sound localization (Bellis, 2003; Chermak, et al., 1997; Musiek, et al., 1982).

Presenting symptoms of APD can be similar to those associated with disorders that inhibit learning, such as dyslexia, or more global processing deficits (Baran & Musiek, 1999). In many cases, APD co-exists with other learning deficits (Sharma & Purdy, 2009). Rarely, causes for the disorder in children include demonstrable neurological disorders or neuromorphological abnormalities. More commonly, the cause is unknown, but presumed to reflect neurological or genetic factors, maturational delay or a combination of various factors (Bellis, 2003; Chermak, et al., 1997; Musiek, et al., 1982).

One common cause for APD that is more readily identified is a significant past history of otitis media with effusion (OME). (Moore, 2007; Moore, Hartley, & Hogan, 2003) demonstrated that chronic OME - a common childhood problem throughout the world, but particularly among indigenous populations, including New Zealand Māori (Giles & O'Brien, 1989), can be associated with APD. Chronic OME results in disruptions in the temporal aspects of sound transmission to the two sides of the brain, leading to abnormal development of binaural hearing processes, such as speech discrimination in competing background noise (Hartley & Moore, 2003). Fortunately, most children with APD subsequent to OME appear to recover by late childhood (Moore, et al., 2003). Animal studies support the notion that given sufficient recovery time, restoration of consistent auditory input does result in the establishment of good binaural hearing. However, this recovery can take several years (Hartley & Moore, 2003). Thus, just as the consequences of chronic OME can outlive the actual disease itself by years, the consequences of APD may have significant long-term effects on a child’s learning and language development. A clear link between APD and language acquisition has not been established, but only by improving our ability to identify children who have difficulties with challenging listening tasks can we develop an understanding of the interplay between auditory processing and language development.

Due to the heterogeneous nature of APD coupled with the complexity of the CAP no gold standard test for APD exists (Medwetsky, 2002; Musiek, et al., 2005). Instead, a test battery approach is used for the assessment of APD in clinics worldwide. Over the past two decades a plethora of diagnostic APD tests have become commercially available consisting of sub-tests designed to examine the function of the various auditory processes (Bellis, 2003; Keith, 2000b; Musiek, et al., 1982). A typical APD test battery comprises the following sub-tests which are designed to tap into the following four different auditory processes:

- *Temporal processing tests*: to assess the ability of the auditory system to process time-related cues in an acoustic signal.
- *Dichotic speech tests*: to assess the ability of the auditory system to binaurally integrate and/or separate simultaneously presented speech stimuli.
- *Binaural interaction*: to assess binaural processes that underlie the timing, lateralization, and localisation of acoustic stimuli.
- *Monaural low-redundancy speech tests*: to assess the ability of the auditory system to analyse speech with reduced intelligibility (ASHA, 2005; Baran & Musiek, 1999; Bellis, 2003) . In view of the fact that the purpose of the current study is to examine the performance of the UCAST as an adaptive monaural low-redundancy speech test for the diagnosis of APD in children, the following section will focus on monaural low-redundancy speech tests, in particular, low-pass filtered speech tests.

2.3 Monaural Low-Redundancy Speech Tests (MLRSTs)

MLRSTs are one of the earliest types of tests used in assessment of the CANS (Bocca, et al., 1954; Bocca, Calearo, Cassinari, & Migliavacca, 1955). Several studies have demonstrated that MLRTs evaluate the part of the CANS that is presumed to be functionally responsible for listening in noise and comprehension of degraded speech and non-speech signals (Domitz & Schow, 2000; Schow & Chermak, 1999). MLRSTs are administered monaurally using stimuli that have been degraded electro-acoustically or digitally in the frequency/spectral, temporal or intensity domain. MLRSTs can be classified as speech-in-noise tests, speech-in competition tests, time-compressed speech tests and low-pass filtered speech tests (Krishnamurti, 2007).

2.3.1 Intrinsic and extrinsic redundancy

The rationale that the integrity of the central auditory pathways can be assessed by presenting a degraded signal to an individual is based on the construct of ‘intrinsic and extrinsic redundancy’ as facilitators of auditory processing. Extrinsic redundancy is a characteristic of the speech signal itself and is the result of multiple and overlapping acoustic and linguistic cues inherent to speech and language. Acoustic cues are, for example, frequency, intensity and temporal aspects of the signal; whereas linguistic cues include phonemic, prosodic, syntactic and semantic cues (Gelfand, 2001; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). Intrinsic redundancy is built into the neural richness of the auditory system where multiple and parallel pathways concurrently and sequentially transmit information across the CANS (Krishnamurti, 2007). Successful speech recognition is ideally facilitated by both intrinsic redundancy and extrinsic redundancy. However, an individual with an intact auditory system can process and understand a degraded speech signal; whereas that ability is often compromised for those with auditory processing deficits believed to reflect a reduction in intrinsic redundancy (Bellis, 1996).

Figure 2 shows the interaction between intrinsic and extrinsic redundancy for speech recognition. Normal speech recognition is achieved when a listener with normal intrinsic redundancy of the CANS listens to clear speech containing normal extrinsic redundancy (panel 1). Even when the redundancy of the speech signal is reduced normal speech recognition can be expected for a listener with normal intrinsic redundancy of the CANS (panel 2).

The ability to understand a degraded speech signal is presumed to reflect a listener's auditory closure abilities. (Baran & Musiek, 1999; Bellis, 2003; Keith, 2000a). Auditory closure refers to a listener's ability to 'fill in the gaps' when part of a signal is missing or partially unintelligible. In many 'real life' listening situations the target signal is degraded by background noise, reverberant conditions or inferior speech delivery. If a listener has reduced intrinsic redundancy due to CANS dysfunction, they are able to achieve normal speech recognition provided the speech signal itself is clear (panel 3). However, a degraded speech signal compounded with reduced intrinsic redundancy results in significantly reduced speech recognition (Krishnamurti, 2007).

1	Normal extrinsic redundancy (clear speech)	+	Normal intrinsic Redundancy (normal CANS)	=	Normal speech recognition
2	Reduced extrinsic redundancy (degraded speech)	+	Normal intrinsic Redundancy (normal CANS)	=	Normal speech recognition
3	Normal extrinsic redundancy (clear speech)	+	Reduced intrinsic redundancy (CANS dysfunction)	=	Normal speech recognition
4	Reduced extrinsic redundancy (degraded speech)	+	Reduced intrinsic redundancy (CANS dysfunction)	=	Reduced speech recognition

Figure 2. Interaction between intrinsic and extrinsic redundancy. Adapted from Krishnamurti (2007).

In addition to the extrinsic redundancy of the speech signal and the intrinsic redundancy of the CANS, auditory closure is further facilitated by factors such as a knowledge of the conversation of topic, familiarity with the vocabulary and knowledge of the syntax and grammar of the language (Bellis, 1996). Therefore auditory processing deficits have a particularly significant impact on children whose linguistic and general knowledge base is still developing (Moore, 2007). Children are consequently affected by auditory processing deficits in two ways: i) they are less able to compensate by drawing on extrinsic factors compared to an adult, and ii) the progress of acquiring this linguistic and general knowledge is jeopardized, thereby compounding the problem (Mlot, Buss, & Hall, 2010).

2.3.2 Impact of types of stimuli and degree of redundancy

The various types of MLRSTs share the underlying principle of challenging the CANS by presenting a degraded speech signal to assess auditory function. Yet it is the degree of redundancy and the type of stimuli used which has significant implications upon test outcomes. In a study conducted by Beasley and colleagues (1972) normal listeners showed essentially normal performance for recognition of monosyllabic NU-6 words when lower time compression (30-60%) was applied. However, when a greater portion of temporal segments were removed (70% time compression) the listeners' performance broke down.

The effect of the type of stimuli used on speech intelligibility test performance was demonstrated by Miller and colleagues (1951). Normal hearing listeners were presented with words in sentences, digits 0 to 9, and nonsense syllables. Digits (a small, closed stimulus set with minimal linguistic loading) reached 100% intelligibility at signal-to-noise ratios (SNR) of -10 dB, whereas listeners required a SNR of 18 dB to achieve the same performance level for words in sentences. In contrast, listeners achieved a maximum of 79% intelligibility for low-redundancy nonsense syllables at the highest SNR of 18 dB.

The impact of filtering in low-pass filtered speech tests is described in detail below.

2.4 Low-Pass Filtered Speech Tests

Low-pass filtered speech tests (LPFSTs) are a type of MLRST whereby a speech sample is degraded by using a low-pass filter to modify its frequency content (Bellis, 1996). The spectrum of speech encompasses frequencies from approximately 100 Hz to 8000 Hz (Noordhoek, Houtgast, & Festen, 1999). Intelligibility of speech is optimal when the entire speech spectrum is audible. However, a typical listener is able to recognise speech even when parts of the speech spectrum are missing (Bellis, 2003; Moore, 2006).

In LPFSTs, high frequency information is removed thereby affecting consonant recognition a crucial proponent of speech understanding (Bornstein, Wilson, & Cambron, 1994). Therefore, the lower the cut-off frequency (i.e. the point where the low-pass filter is implemented) the more difficult the task becomes for the listener (Rintelmann, 1985). The impact of filtering on speech recognition scores is demonstrated in Figure 2, showing mean identification scores of French vowel–consonant–vowel (VCV) stimuli across listeners obtained as a function of cut-off frequency (Ardoint & Lorenzi, 2010).

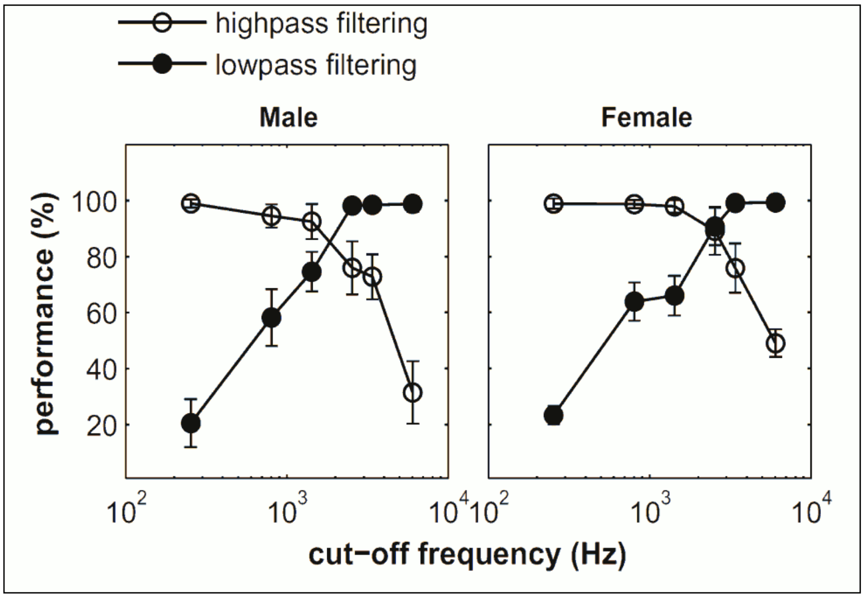

Figure 3. Mean identification scores of French vowel–consonant–vowel (VCV) stimuli across listeners obtained as a function of cut-off frequency, for male (left panels) and female (right panels) speakers. Filled and open circles correspond to the low-pass- and high-pass-filtering conditions, respectively. The cut-off frequencies were 254, 803, 1429, 2542, 3390, or 6030 Hz. Chance level corresponded to 6.25% correct. Error bars represent ± one standard deviation about the mean across listeners. Figure adapted from Ardoint (2010).

2.4.1 History of Low-pass Filtered Speech Tests

The origin of the LPFST can be traced back to the 1950s. Bocca and colleagues were the first to administer low-pass filtered speech testing on patients with temporal lobe lesions after peripheral auditory testing proved insensitive to the auditory difficulties these patients exhibited (Bocca, et al., 1954; Bocca, et al., 1955). In the presence of normal peripheral auditory function the tonal, high fidelity stimuli used (extrinsic redundancy) coupled with the extraordinary processing ability of the CANS (intrinsic redundancy) failed to diagnose higher auditory processing deficits. It was hypothesized that it might be necessary to combine redundancy of both the acoustic signal and the auditory system in order to develop a test method sensitive enough to challenge the CANS and thereby identify possible lesions. The LPFST was designed to ‘stretch’ the auditory system by assessing auditory closure or the ability to fill in the missing components (e.g. phonemes, syllables, words) (Bellis, 1996; Moore, 2006). Based on this rational, a low-pass filter was applied to the speech test signal thereby reducing its redundancy. Bocca et al. (1958) found that with cut-off frequencies above 500 Hz the majority of patients tested obtained poorer speech discrimination scores than the control group. Over the past three decades numerous studies have supported the suitability of LPFSTs in the diagnosis of cortical lesions (Calearo &

Antonelli, 1963; Hodgson, 1967; J. Jerger, 1960, 1964; Lynn & Gilroy, 1977; Musiek, 1994).

In the 1970s low-pass FSTs were applied in the assessment of children suspected with auditory processing deficits in the absence of any pathological insult to the CANS (Willeford, 1977). Researchers utilised their knowledge of CANS lesions and theorized that the same principles apply to auditory processing deficits observed in affected children using the same test approach (Dempsey, 1977; Keith, 1999; Martin & Clark, 1977).

A considerable amount of literature has since been published on the utility of low-pass FSTs for the diagnosis of APD in children (Bornstein, et al., 1994; Dempsey, 1983; Farrer & Keith, 1981; Keith, 2000a). The objective of these studies was to determine the appropriate cut-off frequency which enables separation of children with auditory processing difficulties from typically developing (TD) children (Willeford, 1977). However, there is considerable variability across studies regarding the speech material used involving: i) the presentation modality (pictures versus words), ii) the subject-response method (open versus closed-set) and iii) the scoring system (phonemic analysis versus correct or incorrect). For example, one subtest of the Flowers-Costello Test of Central Auditory Abilities (CAA) includes low-pass filtered speech with a cut-off frequency of 960 Hz, using pictures as the response modality. A second test battery, published by Willeford (1977) includes a filtered speech subtest of Michigan Consonant-Nucleus-Consonant Word Lists which are low-pass filtered at 500 Hz (Willeford, 1977).

Farrer and Keith (1981) applied various filter settings to two groups of children, one with auditory learning difficulties and the other with normal auditory processing ability. Their results indicated that a clear separation of the two groups was obtained with a filtered speech test condition of 1000 Hz; whereas a significant overlap between the groups was observed at 750 Hz and 500 Hz of low-pass filtering.

A widely used LPFST that uses a constant stimuli fixed at a corner frequency of 1 kHz is the Filtered Words sub-test of the SCAN-C (Keith, 2000b). The SCAN-C test performance in terms of test validity and reliability has been extensively researched (Amos & Humes, 1998; Anfinson, Hallberg, De Maio, & Drake, 2005; Chermak & Musiek, 1977; Domitz & Schow, 2000; Marriage, King, Briggs, & Lutmann, 2001). Numerous studies have presented findings that gave rise to concerns regarding the suitability of the SCAN-C as a screening or diagnostic tool for APD. Anfinson et al., (2005) studied a group of 20 children diagnosed with APD and a control group of 20 children without APD and found no difference between the SCAN scores of either group. Amos and Humes (1998) sought to determine the reliability of SCAN scores among 47 primary school children. A retest of the same children six to seven weeks after the initial test showed that approximately 80% of the children in the study demonstrated a higher composite SCAN score during the retest.

2.4.2 Constant versus adaptive stimuli

An obvious limitation of the various versions of the LPTSTs available to date is that they are carried out using a constant level of low-pass filtering (e.g. a fixed 1 kHz or 500 Hz corner frequency) which makes them prone to ceiling and floor effects (Farrer & Keith, 1981; Mitchell & Jolley, 2004). As a consequence, the sensitivity and specificity of these tests is significantly compromised, as a review of the literature has illustrated (Dempsey, 1977; Farrer & Keith, 1981; Martin & Clark, 1977). In other words, if the cut-off frequency is set too low then even children with normal auditory processing abilities will fail; whereas children with APD will pass if the cut-off frequency is set too high.

2.4.3 Adaptive filtered words tests

One method to overcome the ceiling and floor effects caused by utilizing constant-level stimuli is to apply an adaptive procedure. Contrary to the constant level method the presentation level of a test item is determined by the subject's previous response (Leek, 2001). As a result, the degree of difficulty is adjusted to the subject's ability, thereby eliciting a threshold at which the subject scores correctly at a given percentage of the number of trials presented. Unlike constant-level procedures adaptive methods can neither be too easy or too hard for a participant. The benefits of adaptive procedures in psychometric testing, have been extensively studied (Levitt, 1971; Levitt & Rabiner, 1967; Mackie & Dermody, 1986; Zera, 2004). The potential advantages over constant-level methods include greater flexibility, improved efficiency, high precision and reliability. Applying an adaptive-level method to low-pass FSTs implies that in the absence of a fixed filter level, ceiling and floor effects are avoided, as no limit is imposed by the dependent variable (Mitchell & Jolley, 2004).

The utility of adaptive stimuli has the further advantage of generating a more differentiated result than achievable with constant-level methods. Instead of examining a child's performance at a set filter level, the adaptive level method provides information on the degree of redundancy in the speech signal that is required by the subject to respond correctly (Leek, 2001). Adaptive procedures are also efficient as presentation levels quickly approach the subject's threshold avoiding fatigue and loss of attention and motivation (Zera, 2004).

2.4.4 University of Canterbury Adaptive Filtered Speech Test (UCAST)

The UCAST is a software programme that was developed by Dr Greg O'Beirne using National Instruments LabVIEW 8.20 (McGaffin, 2007; O'Beirne, 2009). In a previous study conducted by McGaffin (2007), the UCAST, then referred to as the University of Canterbury Monosyllabic Adaptive Filtered Speech Test (UC MAST), was pilot tested on adults and children with normal auditory processing skills. The study purpose was to establish the most efficient and accurate parameter configuration for subsequent studies. Sincock (2008) compared the clinical application of the UCAST to conventional methods of speech audiometry. This study clearly documented the superiority of the UCAST in view of accuracy, efficiency and reliably.

The absence of a gold standard for the assessment of APD has significant implications in relation to the sensitivity and specificity of the various sub-tests that are administered and used to analyse a listener's performance. Sensitivity refers to the degree of probability that a participant with a given disorder will have a positive test result; whereas specificity refers to the degree of probability that a participant without that disorder will have a negative test result (Portney & Watkins, 2000). Both are measures of test validity; consequently, the absolute validity of a test can only be established when a gold standard exists that has 100% sensitivity and specificity for comparison. The absence of a gold standard for APD assessment implies that the validity of any APD test must be viewed in relation to the performance of other tests that intend to examine the same auditory function.

To the author's knowledge the UCAST is the first adaptive speech test utilized in the diagnosis of APD in children. The following goals have been formulated.

2.5 Statement of the Problem

2.5.1 Goal of the study

The primary goal of this study was to evaluate the hypothesis that a computerized adaptive form of a filtered speech test can serve as a functional tool for distinguishing children with APD from children without the disorder. The present study aimed to find a positive correlation between the required acoustic bandwidth and other accepted measures of auditory processing ability.

A review of the literature revealed conflicting views on the effectiveness of the low-pass filtered speech test as a tool for the diagnosis of APD. However, inconsistent research methods and a great deal of variation concerning the appropriate level of the low-pass filter used in such tests are responsible for much of the confusion. Floor and ceiling effects inherent in constant-level procedures, such as fixed level low-pass filtered speech tests, limit the effectiveness of the test in its ability to distinguish between children with and without APD.

The use of an adaptive procedure may prove to be an excellent solution to the ceiling and floor effects that have plagued the filtered speech test thus far, as it is free of the restrictive assumptions that create such factors.

2.5.2 Research questions and hypotheses

This study aims to answer three specific research questions:

1. Is there a difference in performance on an adaptive computerised version of a low-pass filtered speech test (the UCAST) between normal control children and children who fail an APD test battery?
2. Does performance on the UCAST correlate with performance on other tests of central auditory processing?
3. Does the UCAST discriminate between those children in the present study with and without APD with greater specificity and sensitivity than a constant stimuli low-pass filtered speech test (the filtered words subtest of the SCAN-C)?

Based on the literature the hypotheses for this study are:

1. Performance on the UCAST, an adaptive computerised- version of a low-pass filtered speech test, will be significantly different in those children who fail an APD test battery compared to normal control children with no evidence of APD.
2. Performance on the UCAST will correlate significantly with performance on other tests of central auditory processing: the RGDT, the FPT, the DDT, and the CRWT.
3. The UCAST will discriminate between children in the present study with and without APD with greater specificity and sensitivity than the filtered words subtest of the SCAN-C

3 METHODS

Ethical approval for the present study was obtained from University of Canterbury Human Ethics Committee, reference HEC 2009/84 as shown in Appendix I.

3.1 Participants

3.1.1 Experimental Group (EG): Children with suspected APD

A group of eighteen (18) children with suspected APD were recruited from the waiting list for APD assessment at Speech and Hearing Clinic at the University of Canterbury, or through referrals from the Seabrook McKenzie Centre for Specific Learning Difficulties and from the Ministry of Education, Group Special Education (GSE). Both institutions provide services for children with learning disorders including dyslexia and dyspraxia. The gender distribution of the EG children was 78% (n=14) male and 22% (n= 4) female. The mean age for the EG participants was 9.27 ± 1.48 years (i.e. an average of 9 years 4 months).

3.1.2 Control Group (CG): Children without auditory processing difficulties

A control group of ten (10) children without known auditory processing or learning difficulties were recruited via members of the extended university community. The Control Group participants were matched to the EG participants by age and gender as closely as possible. The gender distribution of the CG children was 90% (n=9) male and 10% (n= 1) female. The mean age of the CG participants was 9.37 ± 1.09 years (i.e. an average of 9 years 4 months).

Inclusion criteria

All participants met the following inclusion criteria: (i) aged 7 – 13 years; (ii) used English as their first language; (iii) no peripheral hearing loss, i.e. a pure-tone average of ≤ 20 dB HL (500 Hz, 2000 Hz and 4000 Hz); and (iv) no known fluctuating hearing loss.

The following criteria were used to exclude any potential participant from participating in either group:

- Poor eyesight to the degree that the participant would not be able to clearly see the UCAST screen display;

- Poor fine motor skills to the degree that the participant would not be able to operate the response button or would not be able to discriminately point to/touch the UCAST computer screen;
- Presence of any behavioural or cognitive disorders to the degree that the participant would not be able to complete the required tasks.

None of the participating children in either group had any known brain lesions.

All invited families received an information pack containing detailed information sheets for the parents and the child outlining the purpose and procedure of the project. Parent and child consent forms and a parent questionnaire were also sent prior to the appointment as shown in Appendix I – V.

Parents and children were given the opportunity to address any queries with the examiners before completion of the consent forms. Consent was obtained prior to the commencement of the assessment session, which took place over a single 2 1/2 - 3 hour appointment at the Speech and Hearing Clinic at the University of Canterbury, Christchurch, New Zealand.

All participating children received a NZ$10 gift voucher to acknowledge their participation in the research project. Parents of participants also received a NZ$10 petrol voucher to assist with travel expenses to the research location.

3.1.3 Case history and parent questionnaire

A detailed and comprehensive case history is crucial to the interpretation of APD test results. Since APD is a heterogeneous disorder that often co-exists with conditions that can significantly confound test interpretation, information on the participant’s personal and family medical history, and psychological and behavioural factors - including communication, listening and auditory skills - should be gathered from a comprehensive case history (Baran, 2007; Bellis, 2003; Lasky & Katz, 1983).

During each case history, the completed parent questionnaire was used as a guideline for interviewing the parents. The parent questionnaire was adapted from McGaffin (2007) and is shown in Appendix VI. The comprehensive questionnaire is divided into three sections: Developmental history, Otologic history and Listening and Understanding behaviours.

3.1.4 Teacher questionnaire

Teacher questionnaires were sent to teachers of those participants who were diagnosed with APD. The questionnaire, shown in Appendix VII, contained questions about the student's listening, learning and behaviour at school. This questionnaire is based on the Children's Auditory Processing Performance Scale 'CHAPPS'(Smoski, Brunt, & Tannahill, 1998) and is used at the University of Canterbury Speech and Hearing Clinic. The teacher questionnaire forms an integral part of the overall assessment process as it provides the clinician with details of the student's specific learning and listening difficulties in the classroom setting.

3.2 Peripheral audiometric assessment

Peripheral audiometric assessment was carried out on all participants to determine their peripheral hearing status. While it is documented that APD may co-exist with peripheral hearing loss, an individual's performance on most tests of auditory processing is affected by hearing loss (Baran, 2007; Chermak & Musiek, 1997). Therefore normal peripheral hearing was used as an inclusion criterion in the current study. Furthermore, normative data available for the APD tests utilized in this study apply only to individuals with normal peripheral hearing (Kelly, 2007).

3.2.1 Equipment

All audiometric testing took place in a double-walled, sound-treated room at the University of Canterbury Speech and Hearing Clinic, Christchurch, New Zealand. A GSI-61 audiometer (Grason-Stadler Corp., USA) connected to an Onkyo DX-C390 Compact Disc changer was used to administer pure-tone and speech audiometry. A GSI TympStar – Middle Ear Analyzer was used for tympanometry and acoustic reflex recording. Distortion product otoacoustic emissions were measured with a Scout® Sport (Bio-logic® System Group) connected to a Madsen-Capella unit.

All items of equipment were calibrated within the previous 12 months by an authorized calibration service.

3.2.2 Administration of peripheral auditory assessment

In order to minimise the impact of fatigue and flagging attention on the results of APD testing, the peripheral test battery was structured in the following manner: Part 1 included those tests for which the outcome was critical for subsequent APD testing, namely otoscopy (to confirm appropriateness of the use of insert ear phones); tympanometry, pure-tone and speech audiometry (to establish hearing threshold levels). These tests were performed at the beginning of the session. Part 2 included tests which did not require attention or active participation, namely ipsi- and contra-lateral acoustic reflex testing and DPOAEs. Those tests were performed at the end of the session following completion of all six APD tests. All procedures were carried out following standard audiological protocols (New Zealand Audiological Society, 2008).

Details regarding each component of the test battery are as follows:

3.2.2.1 Immittance audiometry

Following otoscopy, each participant's tympanograms and ipsilateral and contralateral acoustic reflexes at 500, 1000, 2000 and 4000 Hz were recorded bilaterally using standard clinical procedures (New Zealand Audiological Society (NZAS), 2007).

3.2.2.2 Pure-tone and speech audiometry

A standard threshold seeking technique was used to determine participants' thresholds of hearing - down to a minimum screening presentation level of 10 dB HL - at 500, 1000, 2000 and 4000 Hz, using inserts or supra-aural headphones. A minimum presentation level of 10 dB HL was used in order to lessen the amount of time spent establishing a pure tone audiogram, thereby minimising participant fatigue and loss of interest. Speech perception was tested monaurally by presenting a New Zealand recording of Meaningful Consonant-Vowel-Consonant (CVC) word lists to each ear individually (Boothroyd & Nittrouer, 1988). Only CVC word lists that were not utilized for the Compressed and Reverberated Words test included in the APD test battery were used in standard speech audiometry testing (see Section 3.6.1 on page 34).

3.2.2.3 Distortion product otoacoustic emissions (DPOAE)

DPOAEs for each participant were obtained at 1500 Hz to 6000 Hz. In accordance with standard clinical procedures used at the University of Canterbury Speech and Hearing Clinic, DPOAEs were deemed present at each frequency band if the signal-to-noise ratio was $\geq$ 6 dB and the absolute response amplitude of the emission was $\geq$ -10 dB SPL (Hall, 2000).

3.2.2.4 Peripheral testing pass criteria

A participant was considered to have passed their peripheral hearing screening assessment if their pure tone average (average of 500, 1000, 2000 and 4000 Hz) was $\leq$ 20 dB HL, and DPOAEs were present at the frequencies tested.

3.3 Assessment of Central Auditory Processing

All participants who passed the peripheral auditory assessment outlined above subsequently underwent APD assessment consisting of the UCAST, the four sub-tests of the TAPD and the SCAN-C (FW) as outlined in Chapter 1.

APD assessment is a lengthy process. Fatigue, loss of attention and loss of motivation can have a detrimental effect upon an individual's test performance, thereby contaminating the findings. To reduce the overall testing time for each participant as much as possible, assessment sessions were conducted by two clinicians: the principle researcher and the supervisor.

While the supervisor obtained the participant's case history and interviewed the parents, the principle researcher explained the assessment procedure to the participant in an adjacent room. Parents and participants were encouraged to ask questions at any time. To minimise fatigue, the participants were given breaks throughout the session either when requested or at a recommendation made by the attending parent or either of the two attending clinicians. During these breaks the participants were given the opportunity to step outside the examination room for fresh air, a snack and/or a drink provided by the examiners or brought along by the parent.

Each participant was given a 'Track Sheet' that was ticked off by the participant after the completion of each task. The purpose of the track sheet was to provide the participant with a sense of achievement and to illustrate the progress they were making as they proceeded through the testing session. The Track Sheet is shown in Appendix VIII.

In order to minimize test-order bias, the Knuth implementation of the Fisher-Yates shuffling algorithm was used to randomise the order of the six APD tests applied in this study (Knuth, 1998). The test order of ears was also randomised for each test by a coin toss.

3.4 University of Canterbury Adaptive Filtered Speech Test (UCAST)

The following section provides an overview of the test material, procedure and parameters that were chosen for the implementation of the UCAST employed in this study.

3.4.1 Design

As stated in chapter 1, the UCAST is a software programme that was developed by Greg O'Beirne using National Instruments LabVIEW 8.20 (O'Beirne, 2009). LabVIEW (National Instruments, 2009) is a graphical development environment for signal acquisition, measurement analysis, and data presentation. The algorithms of the program control the presentation of the stimuli in the adaptive speech tests and the program records the acquisition data (including number of trials, low-pass filter corner frequency, responses, confidence intervals, provisional and final threshold estimates) to tab-delimited text files.

Through the analysis of participant data generated by the UCAST software, the low-pass corner frequency threshold at which a participant correctly identifies a predetermined percentage correct is computed and can be used to calculate a psychometric function (Kaernbach, 1991).

As described in Chapter 1 the UCAST was administered to determine any difference between the control and experimental groups in the LPF cut-off frequency where a score of 62.5% correct is achieved on a psychometric function for a four-alternative forced choice test (4AFC) (Kaernbach, 1991; Sincock, 2008).

The UCAST protocol and parameter settings selected for the current study were based on the findings by McGaffin (2007) and Sincock (2008) and were further modified as detailed below. The main procedural modifications included using: i) a weighted up/down staircase procedure (Kaernbach, 1991); ii) a filter function that was less steep than previously utilized (to minimize phase distortion); and iii) the utilization of pictures instead of written words as a test response mode. A detailed description is presented below.

3.4.2 Test material

The selection of speech stimuli for this study was based on the preceding work by McGaffin (2007) on the development and implementation of the UCAST for the identification of APD . McGaffin based the choice of appropriate word lists as speech stimuli on the following criteria, as suggested by Jerger and Jerger (1983);

- Four-alternative, forced choice closed-response format (4AFC);
- Appropriate vocabulary for young children;
- Words with a monosyllabic structure

- Acoustic speech stimuli presented in familiar accent;

The monosyllabic word lists from the Northwestern University Children's Perception of Speech Test (NU-CHIPS) Book A and B, developed by (Elliott & Katz, 1979) were therefore chosen as the test material for the UCAST (as shown in Figure 4) for the following reasons:

3.4.2.1 Four-alternative, forced choice closed-response format

Previous research findings have shown that forced choice closed-response formats are more suitable for testing infants and children than open-set formats due to the limited vocabulary base of infants and young children (Meyer & Pisoni, 1999; Olsen & Matkin, 1979). Closed-response formats incorporating four choices rather than two have shown to reduce the effects of chance responding and decrease variability while increasing accuracy of the threshold estimate (Schlauch & Rose, 1990). For this study, therefore, a four-alternative, forced choice closed-response format (4AFC) was chosen to establish the participant's threshold level.

The NU-Chips test, originally designed as a 4AFC picture-pointing task, consists of 65 words arranged in response plates depicting four pictures each – one being the target word and the others acting as foils in a randomized order.

3.4.2.2 Appropriate vocabulary for young children

The purpose of this study was to assess auditory processing ability, not vocabulary, and it was therefore critical to minimize vocabulary knowledge as a confounding variable by selecting word lists that are familiar to the young listener (Brandy, 2002) as shown in Figure 4. In their development of the NU-CHIPS test, Elliott and Katz (1979) documented that the items that were included are in the recognition vocabulary of normal children older than 2.5 years of age (Elliott, Clifton, & Servi, 1983; Elliott & Katz, 1979).

The fact that the NU-CHIPS test employs pictures rather than words removes the bias of literacy as a confounding variable, which is crucial in the assessment of auditory processing skills as many children seen clinically for APD assessment have literacy difficulties (Sharma & Purdy, 2009). As the NU-CHIPS test was designed in the USA, pictures were examined in view of their familiarity to New Zealand children. In general the investigators felt the pictures were sufficiently recognisable and unambiguous but in one case a slight modification was made. The American flag was removed from the picture for 'school' as schools in New Zealand do not typically display the national flag.

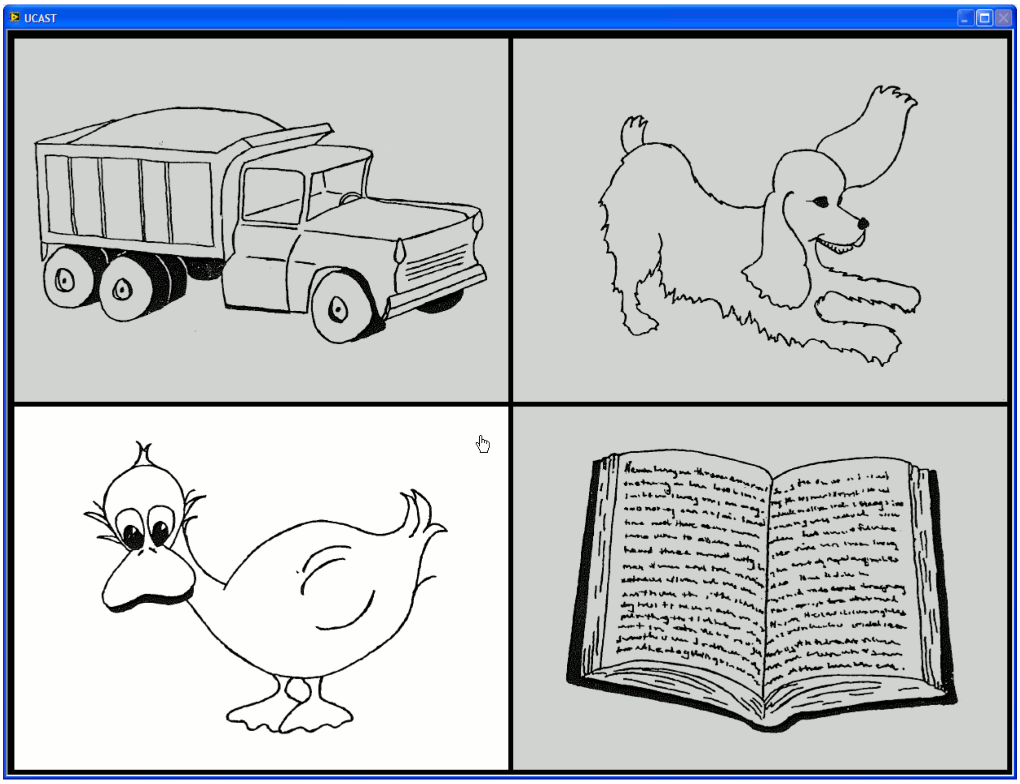

Figure 4. A sample of the UCAST touch screen display showing a NU-CHIPS test response plate. The selected item, here the duck, is highlighted.

3.4.2.3 Words with a monosyllabic structure

It is well documented that speech is an appropriate stimulus for paediatric audiological assessment because of its high level of interest and a complex spectrum (Gravel & Hood, 1999). Wright (1987) argued that any speech test should consist of words that are consistent in terms of their structure and similar in their level of intelligibility to a person of average ability. Monosyllabic word lists are widely employed in speech audiometry (Boothroyd, 1968; Olsen & Matkin, 1979; Wright, 1987).The initial and final consonants in the consonant-vowel-consonant (CVC) structure of monosyllabic words are phonetically balanced, i.e. they appear in accordance with their frequency of use in these positions in everyday language. In addition, studies have shown that monosyllabic words are more effective stimuli for challenging the CANS than spondees (Brandy, 2002).

3.4.2.4 Acoustic speech stimuli presented in a familiar accent

In order to measure a participant's speech recognition ability as accurately as possible the acoustic speech stimuli should be in an accent that is familiar to the participant (Wright, 1987). While a recording of the speech stimuli in a New Zealand accent would be optimal for the purpose of the present study, a recording of the NU-CHIPS test items spoken by a native speaker of New Zealand English is currently unavailable. Therefore, an Australian recording was selected ('Speech Recognition Materials' CD 1 by National Acoustic Laboratories (NAL)), because of the greater similarity of Australian English to New Zealand English when compared to the American recording (Gordon, 1991; Trudgill, Gordon, Lewis, & Maclagan, 2000).

3.4.3 **Weighted up-down staircase procedure**

The protocol used for this study was a simple weighted up-down staircase procedure (WUDR) based on Kaernbach (1991). Unlike the simple up-down procedure suggested by Mackie and Dermody (1986) and employed in the study by McGaffin (2007), the WUDR applies different sized steps for increases and decreases in stimuli presentation level as outlined below. The advantage of the WUDR method is that it can converge to any desired point on a psychometric function (Kaernbach, 1991). It is therefore suitable for this study because it enables convergence at the threshold level of 62.5% for an adaptive forced choice procedure with four-alternatives. This is based on chance performance being 25% and perfect performance being 100%; with 62.5% being halfway between these two extremes (Kaernbach, 2001). The accuracy and repeatability of weighted staircase procedures has been examined (García-Pérez & Alcalà-Quintana, 2005). The researchers found the overall performance in terms of accuracy and repeatability slightly superior to comparable procedures.

Based on the Kaernbach (1991) equation that defines the equilibrium conditions for convergence on a point using the weighted staircase rule, Sincock (2008) formulated the following equation for the calculation of a 62.5% correct threshold level ($X_{62.5}$):

$$S_{down}\, p = S_{up}\,(1-p) \qquad [1]$$

Where S_{down} is the downwards step, S_{up} is the upwards step and p is the point of convergence. Using the above equation [1], the size of the upwards step (S_{up}) and the size of the downwards step (S_{down}) for convergence on the 62.5% correct level ($X_{62.5}$) can be calculated. The generic rule for this situation would read: decrease the intensity 0.6 steps after each correct response and increase the intensity by 1 step after each incorrect response (Kaernbach, 1991; Sincock, 2008).

In the present study, steps of low-pass filter (LPF) cut-off frequency were used rather than steps in intensity, so the rule would read: decrease the LPF cut-off frequency by 0.6 steps after each correct response, and increase the LPF cut-off frequency by 1 step after each incorrect response. An increase or decrease in LPF cut-off frequency is referred to as a *reversal*.

3.4.4 **UCAST parameters**

The following is an overview of the UCAST parameters and settings for the current study:

3.4.4.1 Starting LPF frequency

The starting LPF frequency determines the amount of spectral information contained in the first word presented to each participant. It should to be set at a supra-threshold level which allows the conditioning of the participant to the task, yet is low enough to maximise the efficiency of the test. McGaffin (2007) concluded that of the three starting LPF values examined (500 Hz; 1000 Hz; 1500 Hz), 1000 Hz proved to be the level where almost all participants identified the stimuli correctly. McGaffin's findings were supported by previous studies. For example, Farrer and Keith (1981) determined that a LPF cut-off frequency of 1000 Hz was the most optimal setting for separating children with APD from normal hearing children. A starting frequency of 1000 Hz using a 6^{th} order Butterworth filter was used as the initial level at which the stimuli was presented.

3.4.4.2 Step size

Step size refers to the amount by which the LPF- level of the stimulus was varied after each response. Two different step size variations, referred to as *initial* and *working* increments / decrements were employed. This study's implementations of the WUDR procedure with larger initial step sizes followed that of Sincock (2008) and McGaffin (2007), with the transition between the initial and working step phase programmed to occur after five reversals (see Section 3.4.5 below).

The rationale for applying different step sizes was to improve both the accuracy and efficiency of the adaptive filtered speech test. The larger initial step sizes in the beginning of the test provide an approximate estimate of threshold, so that each participant's true threshold can be approached more rapidly, while the smaller working step sizes more precisely establish the target threshold. The initial increment/decrement step sizes were set at the larger values of 20.8333% and 12.5% than the working increment/decrement step sizes (8.333% and 5%). After a set number of reversals, namely five, the step size changed from these initial increment and decrement step sizes to the working step sizes. A UCAST sample track is displayed in Figure 5**.**

3.4.5 **Practice reversals and real reversals**

Each test consisted of a total of 25 reversals; five 'practice' reversals within the initial phase, as described above, and 20 'real' reversals within the working phase, to obtain each participant's threshold target score of 62.5% correct. Five (rather than fewer) practice reversals were used as McGaffin (2007) concluded in his study that the threshold tracking procedure became more reliable when the practice reversals were increased from two to five.

During the working phase of the UCAST, the reversals (referred to as 'real' reversals) were included in the generation of the UCAST threshold. This was obtained by calculating the average of the midpoints between each reversal.

By excluding the practice reversals from this calculation, the overall accuracy of the test was increased due to the difference in step sizes between practice and real reversals. Based on the protocols implemented by Kaernbach (2001), Mackie and Dermody (1986) and McGaffin (2007) the number of real reversals was set at 20.

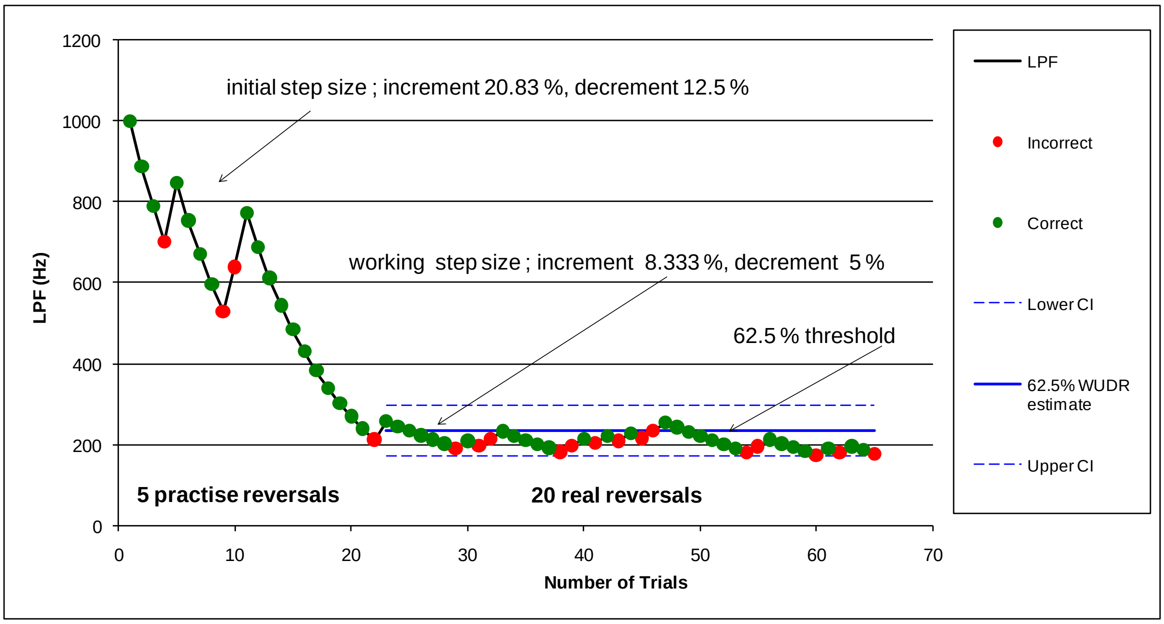

Figure 5. Example of a UCAST adaptive track from a Control Group participant. The measured WUDR threshold at 62.5% correct yielded a mean score of 234.19 Hz.

3.4.6 Summary of UCAST parameter default settings

Table 1 provides an overview of the UCAST default settings applied in this study.

Table 1. Summary of UCAST parameters and settings.

UCAST parameter	Setting
Test material	Northwestern University Children's Perception of Speech Test (NU-CHIPS) Book A and B
Acoustic speech stimuli	Australian recording of the NU-CHIPS test "Speech Recognition Materials" CD 1
Procedure	Weighted up-down staircase procedure
Response format	Four-alternative-forced choice close-response format (4AFC)
Threshold level	62.5%
Practice reversals	
• Number of reversals	5
• Step Sizes: increment/decrement	20.83% / 12.5%
Real reversals	
• Number of reversals	20
• Step Sizes: increment/decrement	8.333% / 5%
Termination criteria	25 reversals
Starting LPF frequency	1000 Hz
Presentation	Binaural practice run, followed by monaural presentations in randomized order
Filter setting	6^{th} order Butterworth filter
Presentation level	60 dB A
Time interval between presentations	1000 ms

3.4.7 Binaural practice run

McGaffin (2007) reported that scores on the UCAST during the pilot study improved as experience with processing low-pass filtered speech increased, indicating a significant learning effect. To counter these effects during test sessions, a binaural practice run (terminating after 1 practice and 12 real reversals) was incorporated in the McGaffin study to familiarise participants with the task, and the number of practice reversals was increased from three to five. Despite these protocol changes, the participants in that study still showed a significant improvement in performance between the first and second trials. Based on McGaffin's findings (2007), the protocol of the present study aimed at further minimising the learning effect by included a full binaural practice run and a randomisation of test ear order.

3.5 UCAST Test Procedure

3.5.1 Equipment

All testing took place in a sound treated booth at the University of Canterbury Speech and Hearing Clinic. The UCAST was run on a Hewlett-Packard laptop and the speech stimuli were presented via Sennheiser HD 215 supra-aural headphones driven by an InSync Buddy USB 6G sound-card attached to the laptop computer. An external ELO ET1715L 17" touch screen monitor (Tyco Electronics Corp., USA), connected to the hp laptop was used to visually present the closed-set stimulus words to the participants as shown in Figure 6.

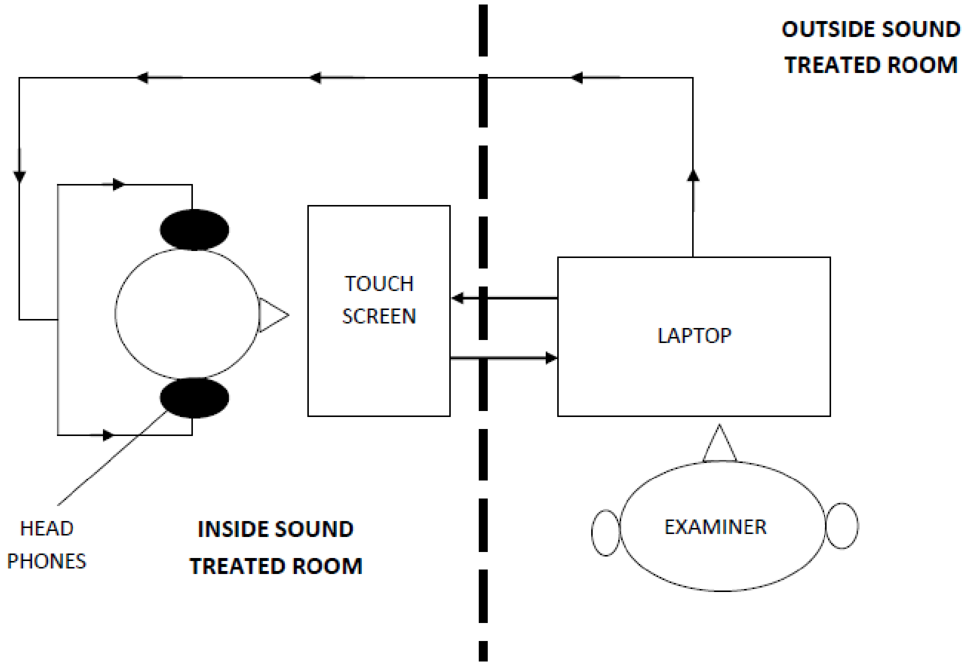

Figure 6. Schematic representation of the test set-up for the UCAST.

3.5.2 UCAST settings

For the administration of the UCAST in this study the parameters were preset by the developer as summarized in Table 1 and displayed in Figure 8 in the UCAST set-up window (O'Beirne, 2009). Prior to running each test, the ‘test ear’ was selected (left, right or binaural). As discussed above, a full binaural practice run preceded monaural presentation to minimise the impact of a learning effect on final threshold determination. Left and right were subsequently selected in a randomised order.

Five options were available to access the NU-CHIPS test items and could be individually selected. These included each of the four NU-CHIPS word lists (Book A, List 1 and 2; Book B, List 1 and 2) and a further option to select a combination of all 200 test items. This setting was utilised for the practice run for all participants as it reduced the chance of repeated presentation of the same test item to a participant.

To further decrease the impact of a learning effect on the UCAST test results, the presentation order and the screen position for each set of test items were randomised.

The participant's first name, surname and date of birth were entered into the provided spaces of the 'Client details' window displayed in Figure 8. This information was saved and stored together with the test results as a tab-delimited text file for data analysis.

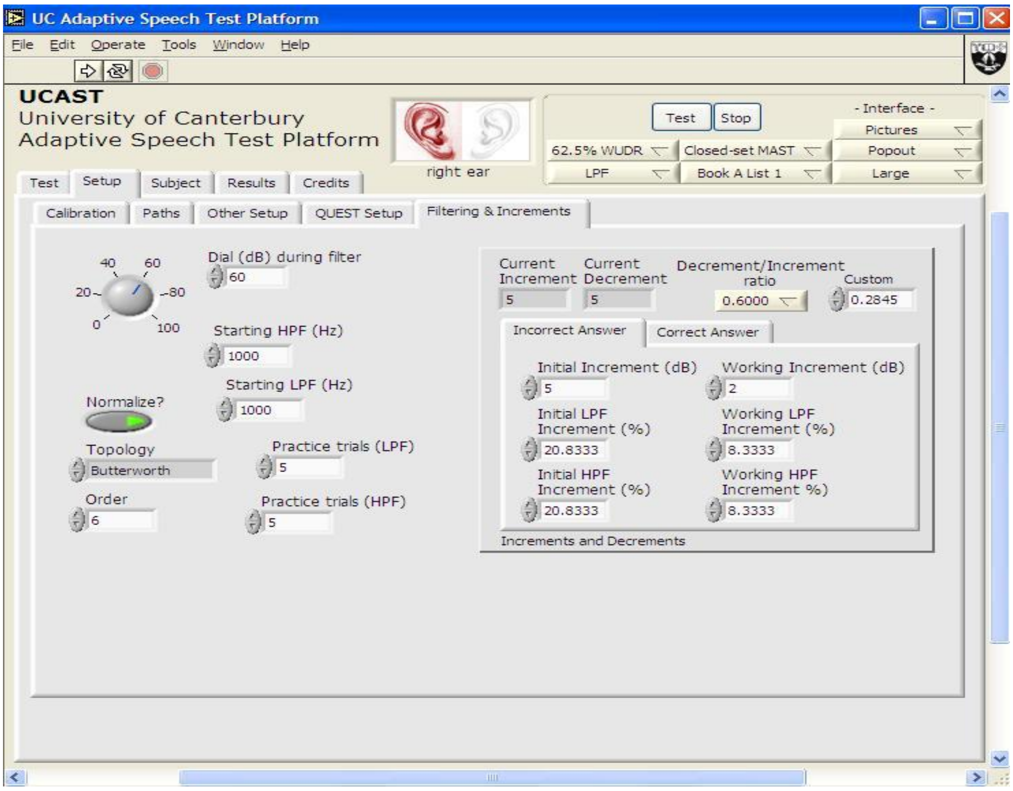

Figure 7. A screenshot of the UCAST filtering and increment interface.

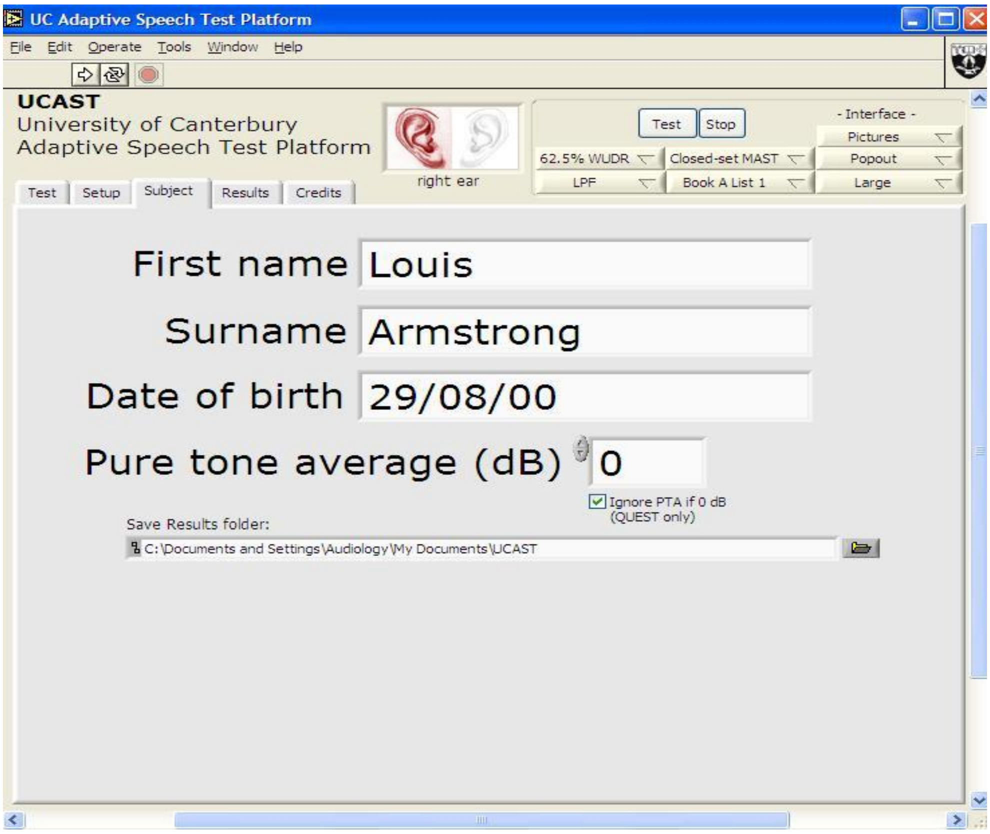

Figure 8. This screenshot displays the set-up UCAST window. The participant's first name, surname and date of birth were entered.

3.5.3 **Calibration**

A sound level normalization process was included in the construct of the UCAST, as low-pass filtering causes energy to be attenuated from the output signal causing a perceived loudness difference between the stimuli presentations as a function of LPF cut-off frequency. The Sennheiser HD215 headphones were driven by an InSync Buddy USB 6G sound card attached to a laptop computer. The headphones were placed on a Brüel & Kjær Type 4128 Head and Torso Simulator (HATS) connected to a Brüel & Kjær 7539 5/1-ch. Input/Output Controller Module. The 1-second average A-weighted sound level of each syllable sample was measured using the Brüel & Kjær PULSE 11.1 noise and vibration analysis platform. The average presentation level from the PC headphones was 60 dB A ± 2.7 dB as shown in Figure 9. For all corner frequencies above 300 Hz, the mean presentation level was 60.1 dB ± 2.7 dB when the sound level normalisation process was applied. There was a slight level increase of about 2.8 dB around 1 kHz, with a mean presentation level of 62.9 ± 2.0 dB for corner frequencies between 600 and 1200 Hz (Figure 9). The average ambient sound level in the test environment was less than 40 dB A.

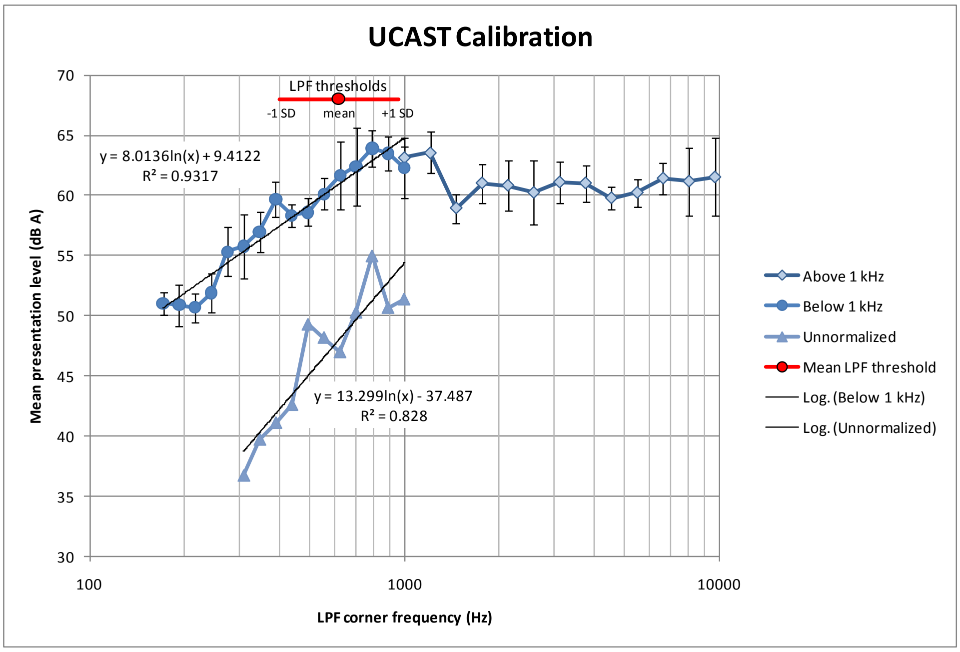

Figure 9. Result of UCAST calibration procedure showing mean presentation level as a function of the LPF corner frequency. Mean and ± 2 SD low-pass filter (LPF) thresholds for all participants are indicated by the solid and broken line at the top of the graph.

3.5.4 Administration of the UCAST

Each participant was seated facing the touch screen monitor at an appropriate distance that allowed for effortless viewing of the items displayed and within arm-length of the touch screen area. The following instructions were given to each participant: *"Look at the screen. There are four pictures. Can you tell me what they are? (Child points to each picture and says the corresponding word.) Now you will hear a man say a word like 'hat' or 'house' and I would like you to touch the picture on the screen that matches the word you hear."*

After the examiner was confident that the participant had understood the task, the headphones were then placed over the participant's ears.

The delivery mode for the stimuli was selected by toggling through the left, right and binaural modes of the 'Client Detail' set-up screen and the examiner started the test run by selecting the "Test" button. The set-up screen is displayed in Figure 8.

As each word was presented acoustically, four images were presented visually on a computer display – of which one image matched the acoustically presented word. As previously outlined, the task for the participant was to select one of the four images displayed, by using the touching the screen. No carrier phrase was presented. After each response the low-pass frequency was adjusted as determined by the adaptive algorithm until 25 reversals were completed and the 62.5% target of the participant's word recognition threshold on the psychometric function was obtained. The program used an automatic scoring system based on whole word correct.

The progression of each test run was traced and displayed on the UCAST screen visible only to the examiner on the lap top computer screen as shown in Figure 10. This screen traces the participant's response presented as a function of the number words and the LPF corner frequency. For each presentation the screen displays the target word and the foils and indicates the participant's selection. Decreases and increases in LPF settings are computed and listed and the final LPF setting is displayed as a mean score. The progression of the confidence interval (CI) was also recorded and displayed.

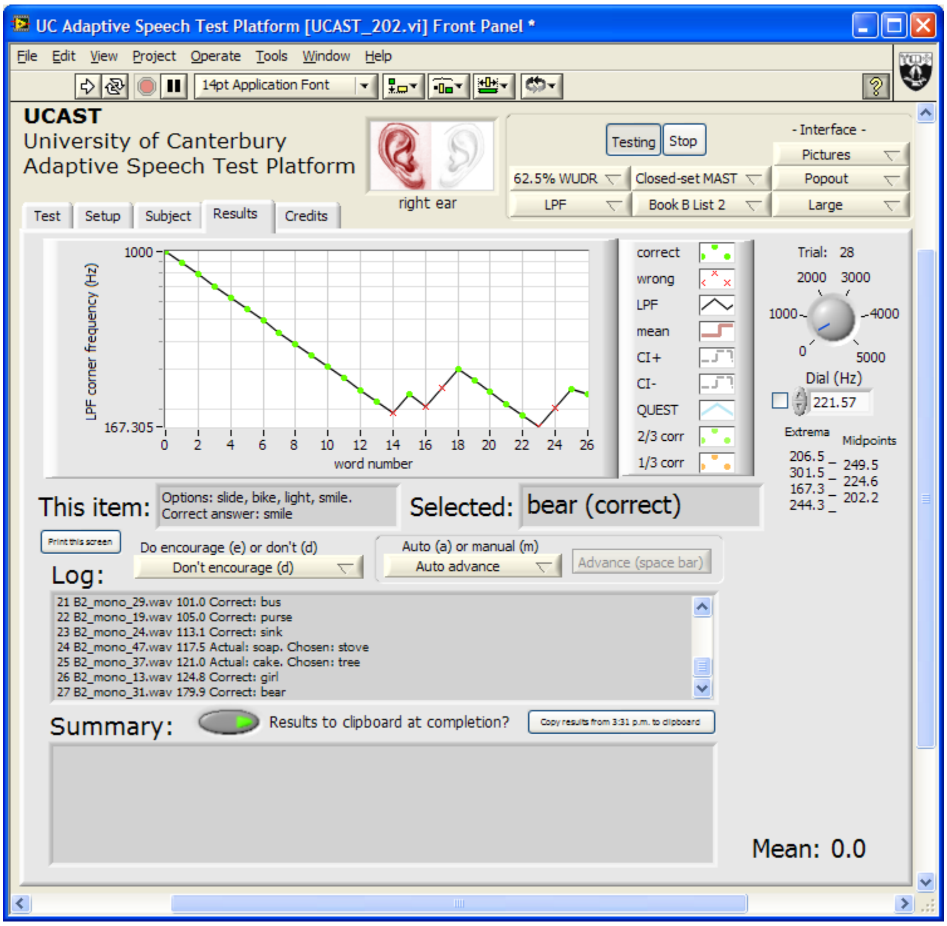

Figure 10. UCAST progress screen visible to examiner only during administration of the UCAST.

As the examiner monitored each participant's progress the "Encourage" function incorporated in the UCAST software (see Figure 11) was manually selected after a random number of trials to provide instant positive feedback to the participant.

Figure 11. Example of UCAST encouragement image.

3.6 Traditional APD Test Battery

3.6.1 Material

A traditional APD test battery (TAPD) was compiled from commercially available APD tests which are currently administered to assess auditory processing function in children at the Speech and Hearing Clinic at the University of Canterbury, New Zealand. The TAPD test battery consisted of four tests presumed to assess a broad range of auditory processes necessary for normal auditory function (ASHA, 2005). These were: Auditory closure: Compressed and Reverberated AB Words (CRW); Binaural integration: Dichotic Digits Test (DDT); Temporal acuity: Random Gap Detection Test (RGDT); and Temporal discrimination: Frequency Pattern Sequence Test (FPT). For all of the above tests New Zealand norms are available for children aged 7.0 to 12.11 years (Kelly, 2007).

3.6.1.1 Auditory Closure: Compressed and reverberated AB Words (CRW)

Compressed and reverberated AB words (CRW) is an example of a monaural low-redundancy speech test consisting of speech stimuli originally developed by Arthur Boothroyd (1968), the AB Word Lists. They are arranged in 12 lists of ten consonant - vowel - consonant words. The words are phonetically balanced, covering a wide frequency of occurrence in the English language. For the CRW, the acoustical characteristics of the words used in this test have been modified by applying 65% time-compression and 0.3 s reverberation and were recorded with a New Zealand speaker. The test items are presented to each ear separately and the listener is asked to repeat the words that have been presented. Responses are scored based on the number of phonemes repeated correctly. A percent correct score is derived for each ear and these are compared to age-appropriate norms (Kelly, 2007).

3.6.1.2 Binaural integration: Dichotic Digits Test (DDT)

The DDT is a central auditory test of binaural integration skills that assesses the listener's ability to process different information presented to each ear simultaneously (Broadbent, 1954; Kimura, 1961; Musiek, 1983; Musiek, 2006). For the DDT the listener is asked to listen to four numbers presented to both ears simultaneously at comfortable listening levels, usually at 50 dB SL. The test items consist of digits one through to nine, except number seven (which has two syllables). In each test item two numbers are presented sequentially to one ear, while at the same time two numbers are presented sequentially to the other ear. For example, the number '5' is presented to the right ear at the same time as the number '1' is presented to the left ear. Then the numbers '9' and '6' are presented simultaneously to the right and the left ear respectively. The participant is asked to repeat all four numbers heard in any order and a percent correct score is determined for each ear and compared to age-appropriate norms.

3.6.1.3 Temporal Acuity: Random Gap Detection Test (RGDT)

The RGDT is a revision of the Auditory Fusion Test-Revised (AFT-R) and is designed to test temporal resolution (McCroskey & Keith, 1996), described as the ability of the auditory system to respond to rapid changes in the envelope of a sound over time (Plack & Viemeister, 1993). It has been suggested that temporal resolution deficits are responsible for poor speech understanding in noise and reverberant listening conditions (Roberts & Lister, 2004). The RGDT determines the smallest time interval between two closely approximated stimuli that can be detected for different test frequencies (500, 1000, 2000, 4000 Hz). The interval is referred to as the gap detection threshold and is measured in milliseconds (ms).

3.6.1.4 Temporal Discrimination: Frequency Pattern Sequence Test (FPT)

The FPT is used to test the listeners' ability to discriminate frequency patterns. The stimuli consist of 880 Hz (low) and 1122 Hz (high) tones that are 150 ms in duration with an inter-stimulus of 300 ms (Musiek, 1994). Each ear is tested separately. The stimuli are presented as sets of three tone bursts; each consisting of two of one frequency and one of the other (e.g. high – high – low). The listener is instructed to repeat the pattern heard. Twenty sets are presented to each ear and responses are scored as percent correct.

3.6.1.5 Equipment

A GSI-61 audiometer (Grason-Stadler Corp., USA) connected to an Onkyo DX-C390 Compact Disc Changer was used to administer pure-tone and speech audiometry. For stimulus presentation either E-A-RTone® 3A insert ear phones or TDH-50P supra-aural headphones were connected to the audiometer. The test set-up is shown in Figure 12.

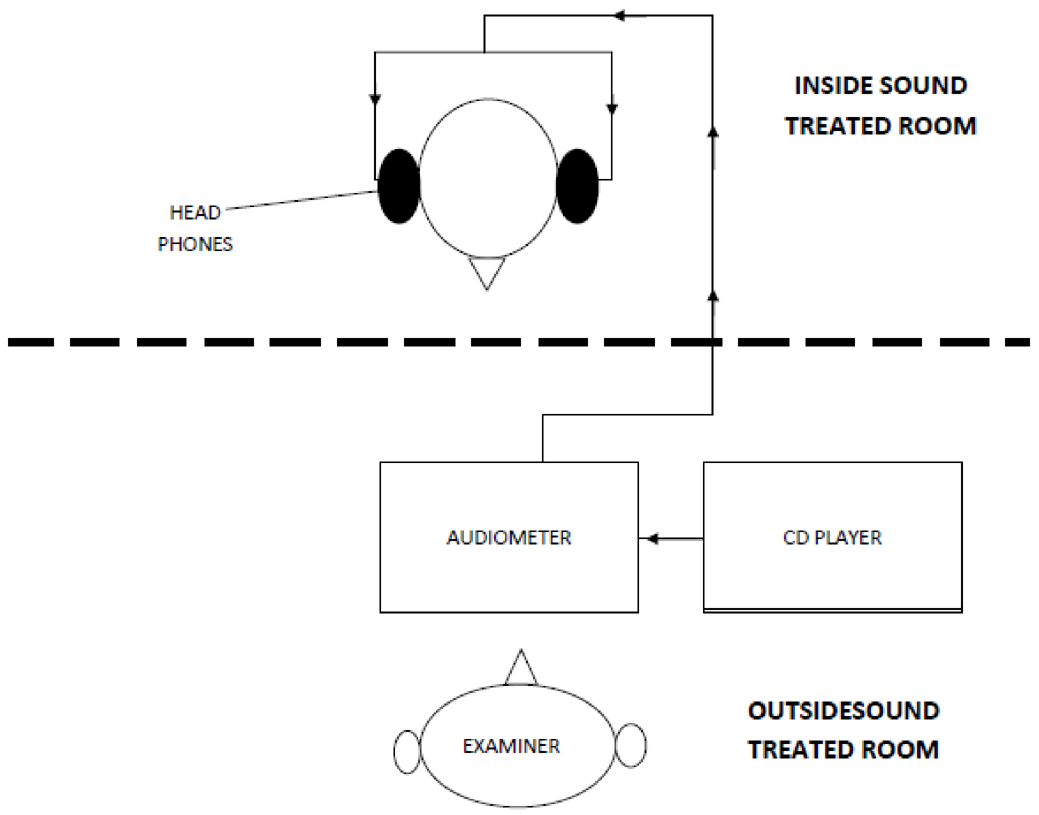

Figure 12. Schematic representation of the set-up of equipment utilized for the traditional APD test battery and the SCAN-C (FW).

3.6.2 **Calibration**

Prior to testing the output of both channels of the audiometer was calibrated by playing the calibration track of a 1000 Hz tone included on each of the compact discs (CDs) used.

3.6.3 **Administration of the traditional auditory processing test battery (TAPDB)**

As stated above, the order of all APD tests, including the UCAST was randomised in order to eliminate effects of test order on performance. All sub-tests were performed in accordance with standard clinical recommendations (ASHA, 2005). For all tests the participants were seated in a sound treated room. The stimuli were presented via head phones or insert ear phones at 50 dB SL. The participants were given clear instructions before each subtest which were repeated if required. Each new task was preceded by a practice run to ensure that the participant was thoroughly familiar with the task. Parents were present at all times and participants were given breaks at frequent intervals to avoid fatigue.

3.6.3.1 Monaural low-redundancy: Compressed and Reverberated AB Words (CRW)

Lists two to five of the AB Word Lists, each consisting of 10 words, were presented monaurally. These were preceded by List 1 for practice. The examiner paused the CD player when the participant required more time to respond than the pre-recorded gap on the CD allowed. The following instruction was given: *"You are going to hear a man talking really fast and he will say something like "say 'cat'" and you just have to repeat the word back to me. If you are not sure, just have a guess."* Responses were recorded on a response sheet and the number of phonemes repeated correctly was computed as a percentage correct score for each ear.

3.6.3.2 Binaural integration: Dichotic Digits Test (DDT)

The two channels of the audiometer required for the DDT were calibrated separately. Twenty single pairs were presented for practice followed by 20 double pairs for scoring. The participant was given the following instructions: *"You are going to hear a man's voice. He will say two numbers at the same time. One number you will hear in your left ear and the other in your right ear. All you need to do is to repeat the numbers back to me. It can be any number between 1 and 9. You can say them back to me in any order."*

After the practice run the following instruction were given: *"Now you are going to hear two numbers in each ear and again it can be any number between 1 and 9, and you just have to repeat the numbers back to me. You can repeat back the numbers in any order."* Participants were given ample time to respond and the CD was paused if necessary.

Responses were scored for the double pair digit test by dividing the total number of correct responses by two for each ear yielding a percentage correct score.

3.6.3.3 Temporal acuity: Random Gap Detection Test (RGDT)

For the RDGT short tonal stimuli of 7 ms duration were presented with inter-stimuli intervals of 0, 2, 5, 10, 15, 20, 25, 30 and 40 ms at frequencies of 500, 1000, 2000, and 4000 Hz. For the practice run a 500 Hz tonal stimulus was used with an inter-stimuli interval that increased sequentially. Stimulus pairs were separated by a 4.5 second interval to give the child time to respond. The recording was paused when the participant required more time to respond. The following instructions were given: *"For this task you are going to hear one beep or two beeps and you just have to tell me if you can hear one beep or two beeps. Two beeps will sound like an echo – they are really close together, so if it sounds like an echo it is probably two beeps."*

Scores were recorded as gap detection thresholds for each frequency tested, i.e. 500, 1000, 2000, and 4000 Hz and a composite gap detection threshold was computed as the average across the four test frequencies for each ear.

3.6.3.4 Temporal discrimination: Frequency Pattern Sequence Test (FPT)

The FPT was presented at 50 dB SL relative to the participant's threshold at 1000 Hz. The FPT is made up of a series of three tone burst patterns consisting of two pitch frequencies, 1122 Hz (HIGH) and 880 Hz (LOW). The test comprised 44patterns, the first four patterns were practice items presented binaurally followed by 20 test patterns presented to each ear. The participants were given the following instructions: *"This time you are going to hear three beeps, some are high pitched and some are low pitched and you just have to tell me if it's a high pitch or a low pitch. Do you know the difference between a high pitched sound and a low pitched sound?"* (Examiner demonstrated 1000 Hz and 750 Hz beeps). The participant had to respond by verbalizing the patterns, for example high – high – low, to be scored correctly. Hummed or hand signal responses were not considered a valid response. Reversals were recorded by scored as incorrect responses. Responses were scored as percent correct for each ear.

3.7 **SCAN-C Subtest 1: Filtered Words**

3.7.1.1 Material

The SCAN-C Filtered Words test (SCAN-C (FW)) is one of four sub-tests constituting the SCAN-C screening test for APD in children developed by Keith (2000a). Like the CRW it is a low-redundancy speech test that is a measure of auditory closure ability (Keith, 2000b). It comprises two 20- consonant-vowel-consonant word lists which are low-pass filtered at 1000 Hz with a roll-off filter of 32 dB / octave.

3.7.1.2 Equipment

For the administration of the SCAN-C (FW) the same equipment as for the TAPDB was utilized (see Figure 12 on page 36). Prior to administration of the SCAN-C, the CD was calibrated.

3.7.1.3 Administration of the SCAN-C

Test order was randomised and the following instructions were given: *"You are going to hear a man talking in a really muffled voice. He has an American accent. He will say something like 'say 'dog' and you just have to repeat back the word back to me. If you are not sure, just have a guess. Before you hear the first word that you are asked to repeat you will hear some instructions and an example will also be given".*

Raw scores were recorded for each ear separately based on whole word correct. Raw scores were then converted to an age-equivalent standard score using the SCAN-C instruction manual. These were then converted to a normative classification of 'normal', 'borderline' or 'abnormal' according to the SCAN-C instructions.

3.8 **Statistical Analysis**

All data were entered and analysed using Microsoft Office Excel 2007 and SigmaPlot for Windows version 11.0. (Systat Software Inc). Where appropriate, differences between groups or measures were evaluated using a Student's t-test (two-tailed) on the raw data. Positive interaction was determined by a two-way repeated measures analysis of variance (ANOVA). A significance level of $p = < 0.05$ was selected and used to evaluate the statistical outcome of the various measures. All results are given as mean +/- standard error of the mean (SEM).

Pearson Product Moment Correlation coefficients (r values) were used to measure the test performance of the UCAST against the sub-tests of the TAPD and SCAN-C.

4 RESULTS

4.1 Peripheral Auditory Assessment

Pure-tone audiometry (500, 1000, 2000 and 4000 Hz) yielded average hearing levels of ≤ 20 dB HL for all participants. Speech audiometry revealed normal speech recognition thresholds (SRTs) (≥ 93% at 35 dB HL) for all participants. The majority of participants had 'type A' tympanograms bilaterally. Two participants (S19, S20) had high volume 'type B' tympanograms bilaterally, indicative of patent ventilation tubes. Seven participants had either bilateral or unilateral 'type C' tympanograms which did not significantly impact on their hearing. The relatively high incidence of 'type C' tympanograms may reflect the season, as the testing phase of this study was carried out during the winter months.

The majority of participants had ipsilateral and contralateral acoustic reflexes at 500, 1000, 2000 and 4000 Hz; however not all test frequencies could be tested in all participants due to fatigue or intolerance of the test stimuli intensity. One participant (S17) had absent ipsilateral and contralateral acoustic reflexes across all test frequencies. However, subsequent auditory brainstem response (ABR) testing revealed normal responses (data not shown).

Distortion product otoacoustic emissions (DPOAE) for all participants, tested across frequencies 1.5 kHz to 6 kHz, yielded an average test result of a signal-to-noise ratio of > 5 dB and an absolute amplitude of the emission of > -10 dB SPL.

4.2 Traditional APD Test Battery

Individual traditional APD test battery (TAPD) test results for all EG and CG participants are shown in Table 2. The test results of the four sub-tests that comprised the TAPD were interpreted in accordance with ASHA (2005) guidelines. These guidelines specify that a diagnosis of APD should be made when the test performance on at least two APD sub-tests is two standard deviations below the age mean, or if the score on one subtest is at least three standard deviations below the age mean. In the latter case retesting is recommended before a diagnosis of APD can be confirmed. However, due to the limited time frame for data collection in the present study, retesting of subjects was not possible.

Normative data for behavioural tests of auditory processing for New Zealand school children aged seven to 12 years, published by Kelly (2007) was used in interpretation of the test results of all TAPD sub-tests as detailed below.

Auditory Closure: Compressed and Reverberated Words Test (CRWT)

CRWT mean scores for CG and APD Group participants are displayed in Figure 13. Participants' responses were scored based on the number of phonemes repeated correctly and a percent correct score was derived for each ear. CRWT scores obtained monaurally for all CG and EG participants (S01 – S28, except S25 [see below]) were at least two standard deviations above the mean for each age group thus all CG and EG participants passed this test, and the CRWT did not, therefore, discriminate between CG and EG participants. The CRWT was not administered to S25 who presented with disarticulation issues, making it very difficult for the examiners to score his verbal responses accurately.

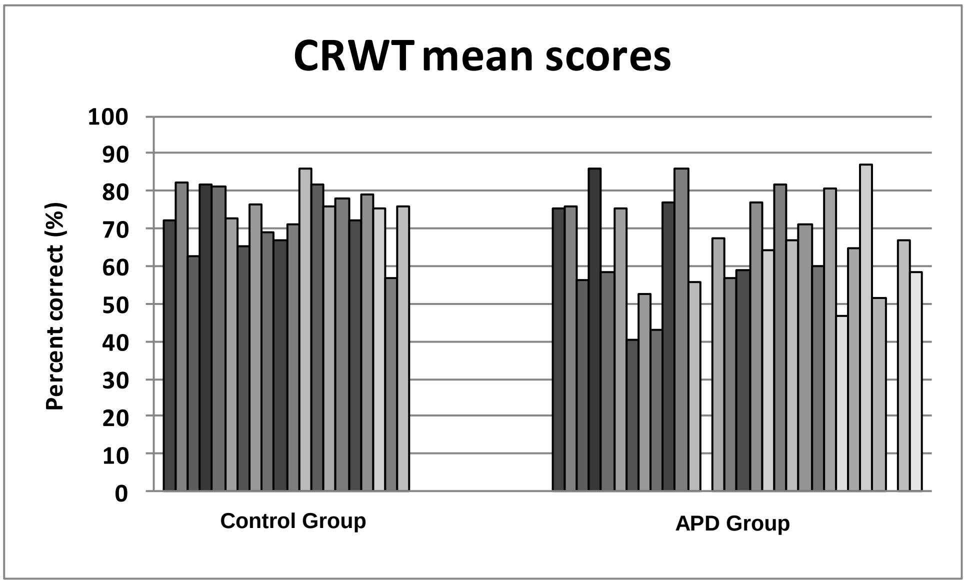

Figure 13. Mean percentage correct scores (left and right ears) for the CRWT for each participant in the study. CRWT mean scores show a large overlap between CG and APD Group participants.

Temporal Acuity: Random Gap Detection Test (RGDT)

Gap detection thresholds were expressed in milliseconds. Five (n=5) EG participants (S22, S23, S25, S27, S28) were given arbitrary scores of 40 ms (see Table 2.) This figure, the largest inter-stimulus interval used in the RGDT, was allocated to these participants for the purposes of data analysis. However, it should be noted that these participants were not able to discriminate two tones at this inter-stimulus interval, and their true gap detection threshold may have been much higher.

Of the total of 18 EG participants nine (n=9) failed and nine (n=9) passed the RGDT. All CG participants scored at least two standard deviations above the mean for their age and therefore passed the RGDT.

4.2.1.1 Binaural integration: Dichotic Digits Test (DDT)

Results were expressed in percentage correct per ear. Of the total of 18 EG participants 10 failed the DDT. Two participants (n=2) failed in both ears, four (n=4) in the left ear and four (n=4) in the right, all by at least two standard deviations below the mean for their age. All CG participants scored at least two standard deviations above the mean for their age and therefore passed the DDT. Six (n=6; 60%) CG participants and nine (n=9; 60%) APD Group participants had a higher DDT percentage correct score in the right than in the left ear. This observed difference in performance between the ears is commonly associated with the right ear advantage (REA) (Musiek & Chermak, 2007). Seven (n=7; 70%) CG participants and seven (n=7; 47%) APD Group participants showed a higher (i.e. worse) UCAST score in the right ear than in the left ear.

4.2.1.2 Temporal Discrimination: Frequency Pattern Sequence Test (FPT)

FPT test results are expressed in percentage correct for each ear. Twelve (n=12) EG participants failed the FPT; eight (n=8) failed in both ears and three (n=3) failed in the right ear only. All CG participants scored at least two standard deviations above the age mean and therefore passed the FPT.

Summary of TAPD Results

Based on the TAPD test outcome, a total of 16 of the 18 EG participants failed the TAPD of which 10 participants (S19 – S28) failed on at least two sub-tests by at least two standard deviations below the age mean, and 6 (n=6) participants (S13 – S 18) failed on one TAPD sub-test by at least three standard deviations below the age mean. These 16 EG participants were therefore considered, for the purposes of this study, as APD subjects and henceforth are referred to as the APD Group. Two (n=2) EG participants (S12 and S16) passed all sub-tests of the TAPD and therefore, were excluded from this study (i.e. these subjects were not considered CG subjects, nor were they included in the EG – they were removed from statistical comparisons altogether).

Participant S29 presented with ADHD related attention deficit issues that lead to unreliable test results. Therefore, this data was excluded from statistical analysis. However, this participant's case is presented in Section 5.4 on page 73, to illustrate the difficulties of isolating auditory processing deficits from ADHD related symptoms.

Table 2. Individual TAPD test results for all participants.

Subject	Gender	Age (yrs)	CRWT R (%)	CRWT L (%)	RGDT R (ms)	RGDT L (ms)	DDT R (%)	DDT L (%)	FPT R (%)	FPT L (%)
				Control Group						
S01	M	10.11	72	71	3.5	6.25	97.5	95	100	100
S02	M	11.3	82.5	86	7.5	7.5	97.5	87.5	100	100
S03	M	8.11	62.5	82	8.75	8.75	95	95	95	95
S04	M	8.5	81.5	76	9.25	4.25	97.5	87.5	70	85
S05	M	10.7	81	78	2.75	4.25	100	100	100	100
S06	M	8.3	73	72	10	7.5	97.5	95	100	95
S07	M	10.1	65.5	79	12.1	10	87.5	82.5	100	100
S08	M	8.6	76.5	75.5	5.5	2.75	95	95	90	70
S09	F	9.4	69	57	2.75	2.75	95	97.5	80	65
S10	M	9.1	67	76	7.5	6	97.5	95	100	95
				Experimental Group – failed TAPD test battery						
S13	F	9.1	75.5	59	11.25	5.5	97.5	**70**	80	75
S14	M	12.11	76	77	7.5	8.75	90	**47.5**	85	80
S15	M	7.11	56.5	64	5.5	12.5	80	85	**25**	45
S16	F	9.2	86	81.5	7	2	95	90	**40**	70
S17	M	10.6	58.5	67	8.75	6.25	**67.5**	90	70	85
S18	M	8.4	75.5	71	**37.5**	**40**	87.5	80	55	55
S19	M	8.11	40.5	60	**27.5**	**36.5**	80	87.5	**15**	**5**
S20	M	1 1.11	52.5	80.5	**35**	**32.5**	**82.5**	92.5	**20**	**20**
S21	F	10.8	43	46.5	6.75	9.25	90	**45**	**55**	**65**
S22	M	7.11	77	65	**40**	**40**	**65**	**42.5**	**0**	**0**
S23	M	9.3	86	87	**28.75**	**40**	95	**52.5**	**40**	**20**
S24	M	11.11	56	51.5	**15**	**14.25**	**68**	**82**	**25**	**30**
S25	M	8.4	**CNT**	**CNT**	**40**	**40**	72.5	**55**	**15**	**35**
S26	M	8.9	67.5	67	15	2	**70**	82.5	**5**	45
S27	M	7.11	57	58.5	**40**	**40**	87.5	85	**25**	**25**
S28*	M	9	51	43	**40**	**40**	**37.5**	87.5	**0**	**0**
				Experimental Group – passed TAPD test battery						
S11	F	10.1	82.5	68	7.25	10	95.5	92.5	80	70
S12	M	10.11	53.5	51.5	10	8.75	97.5	87.5	65	85

Note. *= Excluded from further data analysis due to unreliable TAPD test results. CRWT= Compressed Reverberated Words Test; RGDT= Random Gap Detection Test; DDT= Dichotic Digits Test; FPT= Frequency Pattern Test; L= left; R= right; CNT= could not test (see text). Values in bold indicate performance below the norm by at least by 2 SD.

4.3 Results of the UCAST

The UCAST software did a running calculation of i) the mean of the midpoints between the reversals, and ii) the 99% confidence interval (CI), and displayed these graphically on the results tab.

4.3.1 Individual UCAST mean scores

An overview of individual mean UCAST scores for, the binaural practice run and the monaural presentations is shown in Table 3 indicating the cut-off frequency at which the participants scored 62.5% correct on a psychometric function, referred to henceforth as the 'UCAST Score'. For the CG the mean UCAST Score for the right ear was 403.12 Hz (± 38.68), ranging from 234.19 Hz to 588.91 Hz, and for the left ear 425.54 Hz (± 42.91), ranging from 191.82 Hz to 568.90 Hz.

The APD Group participants yielded a mean UCAST Score of 772.15 Hz (± 82.95), ranging from 381.89 Hz to 1568.50 Hz for the right ear and 790.06 Hz (± 95.05), ranging from 427.03 Hz to 1778.34 Hz.

Table 3. Individual mean UCAST scores for the practice run (PR), right (RE) and left (LE) ears for each participant in the APD Group and Control Group.

APD Group				Control Group			
Subject	**PR**	**RE**	**LE**	**Subject**	**PR**	**RE**	**LE**
S13	620.37	682.23	631.31	**S01**	274.93	234.19	331.93
S14	1000.15	606.14	477.5	**S02**	521.94	564.83	568.9
S15	614.08	381.89	468.3	**S03**	418.49	401	346.96
S16	424.91	649.88	575.78	**S04**	719.39	523.96	537.43
S17	890.06	823.98	939.53	**S05**	785.98	281.66	488.2
S18	542.35	1568.5	1778.34	**S06**	459.05	406.65	499.65
S19	1118.19	1148.75	1057.16	**S07**	373.17	588.91	191.82
S20	1188.26	1036.05	994.61	**S08**	342.94	345.28	521.59
S21	549.11	481.65	470.15	**S09**	630.02	393.96	527.83
S22	761.27	915.88	970.05	**S10**	531.96	290.74	241.13
S23	767.29	479.09	764.82				
S24	645.24	610.49	443.96				
S25	1083.77	1071.14	1136.51				
S26	480.53	567.16	427.03				
S27	790.84	559.47	715.82				
Mean	765.09	772.15	790.06		505.79	403.12	425.54
SD	243.18	321.26	368.11		165.91	122.31	135.71
SEM	62.79	82.95	95.05		52.46	38.68	42.91
Quartile 1	581.60	563.32	473.83		384.50	304.38	335.69
Min	424.91	381.89	427.03		274.93	234.19	191.82
Median	761.27	649.88	715.82		490.50	397.48	493.93
Max	1188.26	1568.50	1778.34		785.98	588.91	568.90
Quartile 3	945.11	975.97	982.33		605.51	494.63	526.27
n		**15**				**10**	

The mean UCAST scores for the right and left ears for Control Group (CG) and APD Group are displayed graphically in Figure 14. Standard error bars are shown. A two way repeated measures ANOVA (one factor repetition) using Sigma Plot 11.01 revealed a significant group effect [F (1,23) = 10.983, *p* = 0.003] between EG and CG. No ear effect was found (F (1,23) = 0.429, *p* = 0.429] and there was no statistically significant interaction between EG and CG group scores and left and right ear scores (p = 0.942).

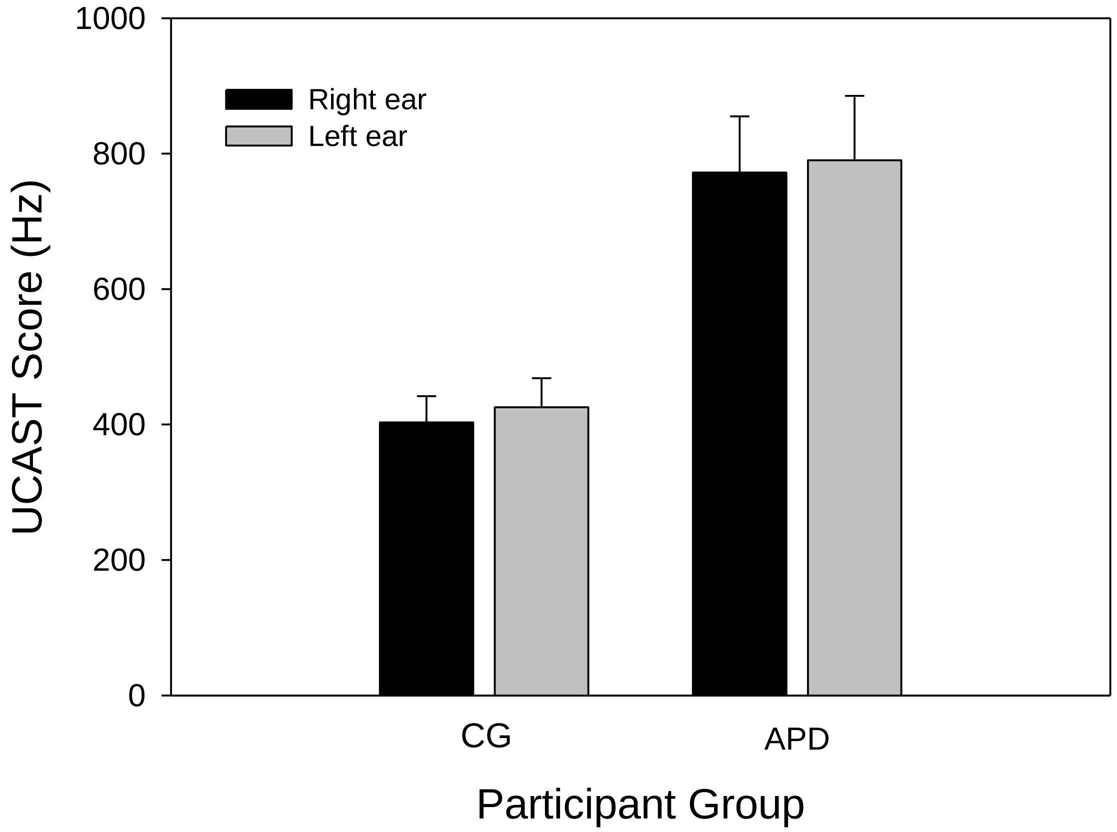

Figure 14. Shown are the mean UCAST scores (LPF cut-off frequencies) for the right and left ears for (CG) and APD group. Standard error bars are shown.

Figure 15 illustrates the spread of the data by displaying the mean UCAST Score for each ear for each participant in the CG and APD Group.

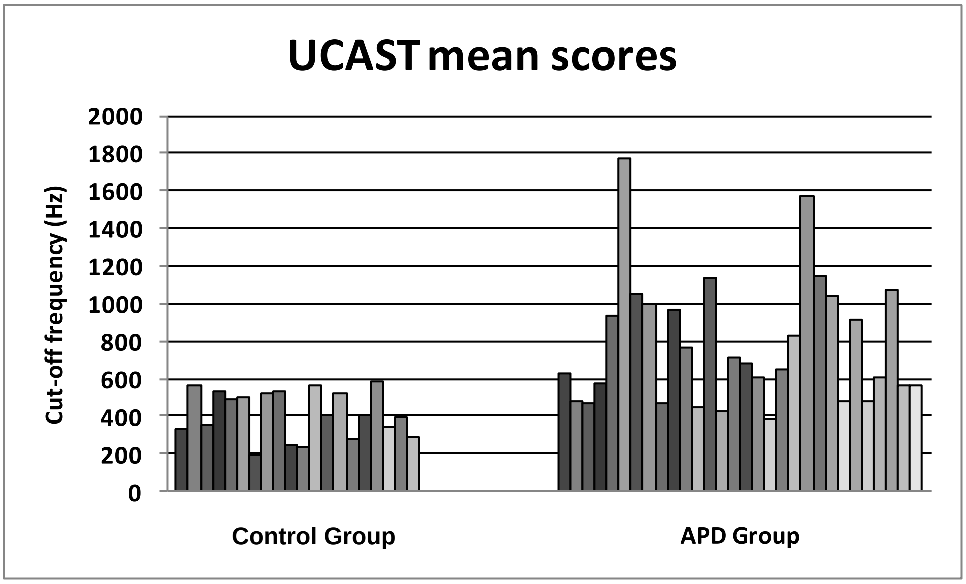

Figure 15. Individual mean UCAST scores for Control Group (CG) and APD Group participants.

4.3.2 Learning effect

A full binaural practice run preceded the monaural test mode in order to minimize the learning effect that was observed in McGaffin's study (2007). The results of the practice run are presented in Table 3 on page 46.

Of the 10 CG participants five (n=5) participants (S03, S04, S05, S09 and S10) had higher (i.e. worse) UCAST scores on the practice run showing an improvement in performance on monaural presentation compared to practice run mean scores. Four (n=4) participants (S01, S02, S06 and S07) scored better in one ear and worse in the other compared to the UCAST practice run mean score result. One (n=1) participant (S08) scored better on the binaural practice run than on either of the monaural presentations. The mean score for the practice run for all CG participants (505.79 ± 52.46) was higher (i.e. worse) than for either the left (425.54 ± 42.91) or right (403.12 ± 38.68) monaural presentation conditions, indicating that overall, there was a slight improvement in performance on monaural presentation compared to practice run mean scores. This difference, however, when mean (right and left) monaural presentation scores were compared to the binaural practice scores, was not statistically significant ($p < 0.05$, paired t-test). Of the 15 APD Group participants seven (n=7) participants (S14, S15, S20, S21, S23, S24 and S27) had higher (i.e. worse) UCAST scores on the practice run showing an improvement in performance on monaural presentation compared to practice run mean scores. Four (n=4) participants (S17, S19, S25 and S26) scored better in one ear and worse in the other compared to the UCAST practice run mean score result. Four (n=4) participant (S13, S16, S18, S22) scored better on the binaural practice run than on either of the monaural presentations. The mean score for the practice run for all APD participants (765.09 ± 62.79) was actually slightly lower than for either the left (790.06 ± 95.05) or right (772.15 ± 82.95) monaural presentation conditions, indicating that overall, this group tended not to show any learning effect over time, and that in some cases at least, a better score was achieved with binaural presentation compared to monaural. Again, however, this difference (when mean (right and left) monaural presentation scores were compared to the binaural practice scores), was not statistically significant ($p < 0.05$, paired t-test).

4.3.3 Sensitivity and specificity of the UCAST

The sensitivity and specificity of the UCAST as a clinical test of APD cannot be determined from the present study with its small sample size. However, within the context of the present study, a 'working pass criterion' was set at 2 SD above the mean UCAST Score for the CG participants, in line with the pass criteria (or cut-off scores) used in clinical interpreting of APD test results. (ASHA, 2005; Kelly, 2007). This working pass criterion was calculated to be 667 Hz (Table 4). Since there was no ear effect this value was calculated from the combined scores from right and left ears. All CG participants scored below this cut-off criterion; whereas the majority of APD participants scored above this criterion.

Table 4. UCAST mean and standard deviation for the Control Group results.

UCAST	Hz
Sum	8286.62
Mean	414.33
SD	126.26
2SD	252.52
Mean - 2 SD	**666.85**

4.4 Scan-C Filtered Words Test

SCAN-C (FW) raw scores and standard scores for all participants are displayed in Table 5. All participants from all groups were classified as ‘normal’ on the SCAN-C (FW), apart from S25 who was classified as ‘borderline’. It was not possible to obtain a standard score for participant S13 who was 12.11 years at the time of testing, due to SCAN-C norms being unavailable for this age.

Figure 16 illustrates the SCAN-C (FW) raw scores for left and right ears individually in a column graph. There was a variation in test performance between the groups although there was a significant area of overlap; however, the SCAN-C (FW) standard scores did not discriminate between the two groups as all participants passed apart from one ‘borderline’ classification as described above. The SCAN-C (FW) therefore did not identify any participant as being at risk of auditory processing disorder.

Table 5. Individual results for the Scan-C (FW) test.

Subject	Age	Raw score R ear	Raw score L ear	Raw score Total R and L	SCAN-C (FW) Standard Score	Normative classification
			Control Group			
S01	10.11	19	19	38	13	normal
S02	11.3	19	19	38	13	normal
S03	8.11	19	19	38	14	normal
S04	8.5	19	16	35	12	normal
S05	10.7	20	19	39	14	normal
S06	8.3	18	18	36	13	normal
S07	10.1	17	16	33	9	normal
S08	8.6	19	19	38	14	normal
S09	9.4	16	16	32	8	normal
S10	9.1	20	18	38	13	normal
			APD Group			
S13	12.11	20	18	38	unavailable	unavailable
S14	7.11	19	16	35	13	normal
S15	9.2	17	19	36	12	normal
S17	8.4	18	15	33	11	normal
S18	10.11	17	20	37	12	normal
S19	8.11	17	17	34	12	normal
S20	11.11	17	18	35	11	normal
S21	10.8	15	17	32	8	normal
S22	7.11	14	15	29	8	normal
S23	9.3	16	15	31	8	normal
S24	11.11	17	14	31	7	normal
S25	8.4	12	13	25	5	**borderline**
S26	8.9	19	17	36	13	normal
S27	7.11	17	16	33	11	normal

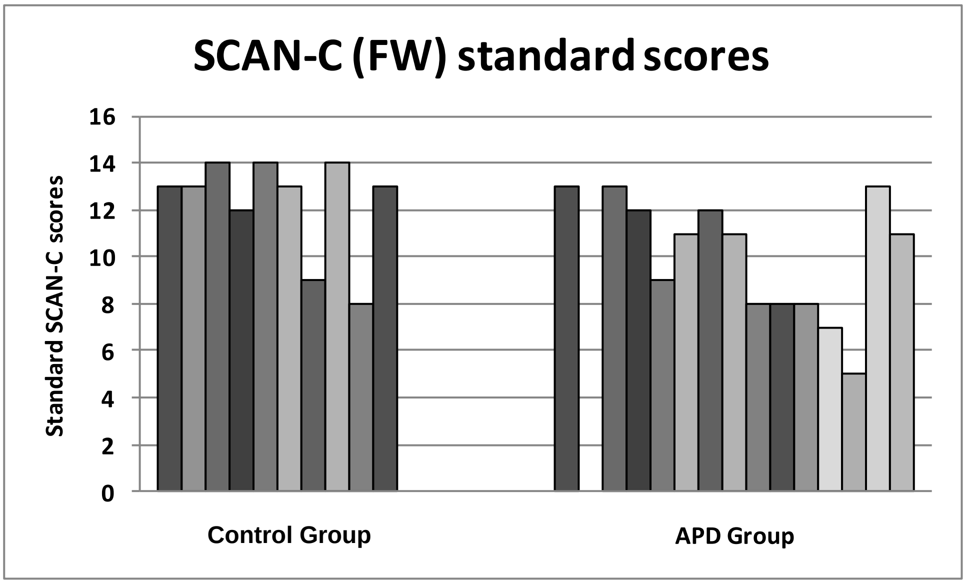

Figure 16. Individual SCAN-C (FW) standard scores for APD Group and Control Group (CG). Each column indicates the SCAN-C (FW) standard score which is based on an average score for right and left ear presentation.

4.5 Comparison of UCAST Results versus TAPD and SCAN-C (FW)

4.5.1 Scatter plots

To examine how the UCAST correlates with each subtest of the TAPD and the SCAN-C (FW), Pearson Product Moment Correlation coefficients (*r* values) were calculated and the results are plotted in Figure 17 and Figure 18.

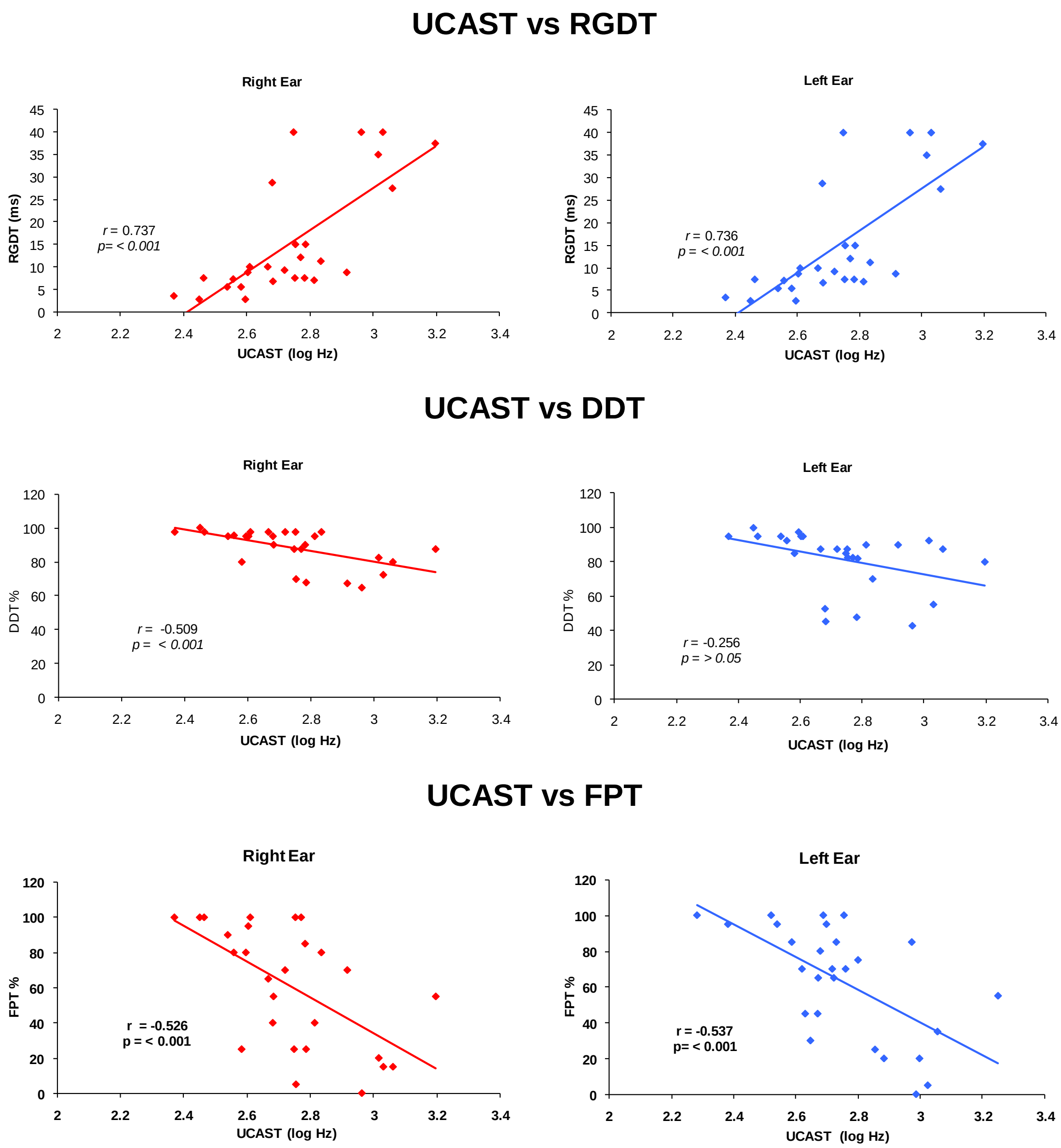

Figure 17. UCAST scores (presented in log Hz) plotted against the scores for each subtest of the TAPD for right and left ears for all participants.

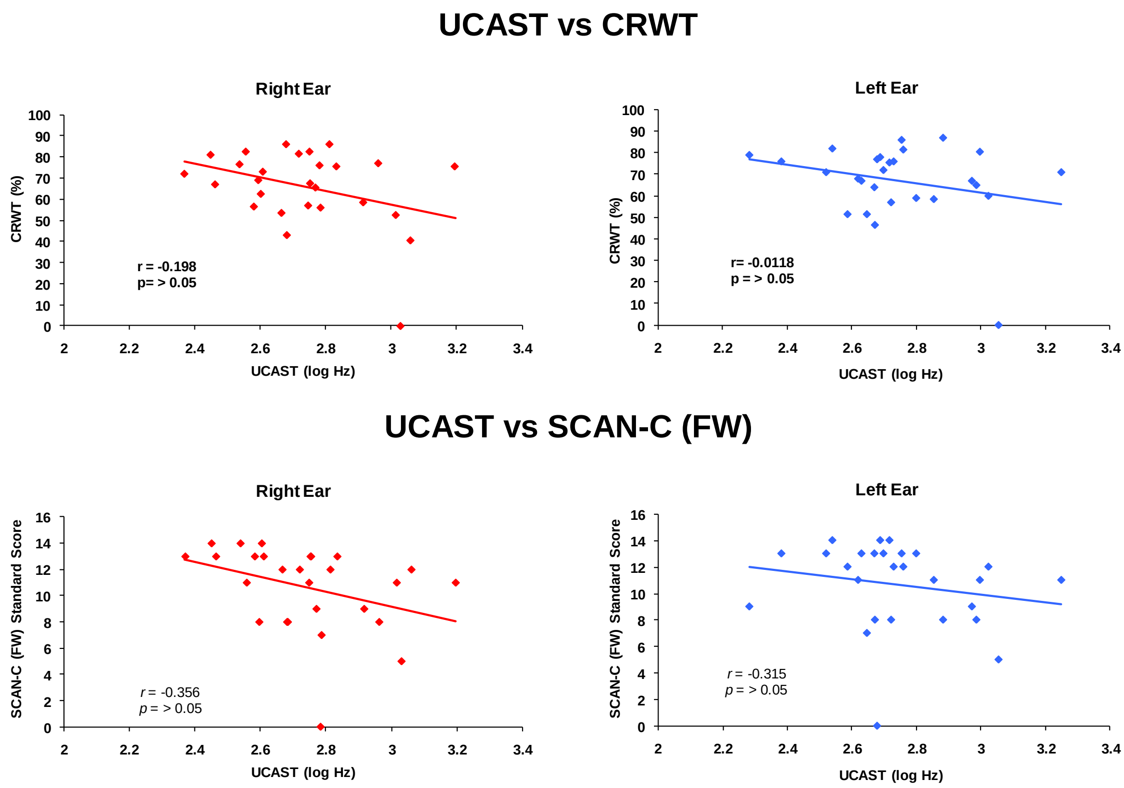

Figure 18. UCAST scores (presented in log Hz) plotted against the score for the CRWT and the SCAN-C (FW) for right and left ears for all participants.

Correlation and *p* values are summarized in Table 6 for all sub-tests of the TAPD test battery and the SCAN-C (FW). Large correlations were evident between the UCAST and the RGDT for both ears; and between the UCAST and the FPT. The SCAN-C (FW) showed no correlation with the UCAST scores; similarly, no correlation was found to exist between the CRWT scores and the UCAST. The DDT scores for the right ear had a large correlation to the UCAST whereas the left ear scores for the DDT showed no correlation to the UCAST.

Table 6. Correlations between UCAST, TAPD sub-tests and SCAN-C (FW).

Sub-test	ear	r	p	correlation
CRWT	R	-0.198	> 0.05	none
	L	-0.0118	> 0.05	none
RGDT	R	0.737	< 0.001	large
	L	0.736	< 0.001	large
DDT	R	-0.509	< 0.001	large
	L	-0.256	> 0.05	none
FPT	R	-0.526	< 0.001	large
	L	-0.537	< 0.001	large
SCAN-C (FW)	R	-0.356	> 0.05	none
	L	-0.315	> 0.05	none

4.5.2 Overview of test results

Figure 19 shows box and whisker plots depicting the median and inter quartile range for all right (R) and left (L) ear APD measures for the 15 participants in the APD Group. Results are shown relative to the mean scores of children in the Control Group for each subtest, expressed as deviation from mean normal performance (i.e. z-scores). Thus the ‘0’ line in the figure indicates the mean performance of the Control Group for each subtest, and the box and whisker plots indicate the performance of the APD Group in comparison to this mean. Boxes show median (red horizontal bars), 25th and 75th percentiles (limits of the box) and minimum and maximum scores (extreme ends of whiskers).

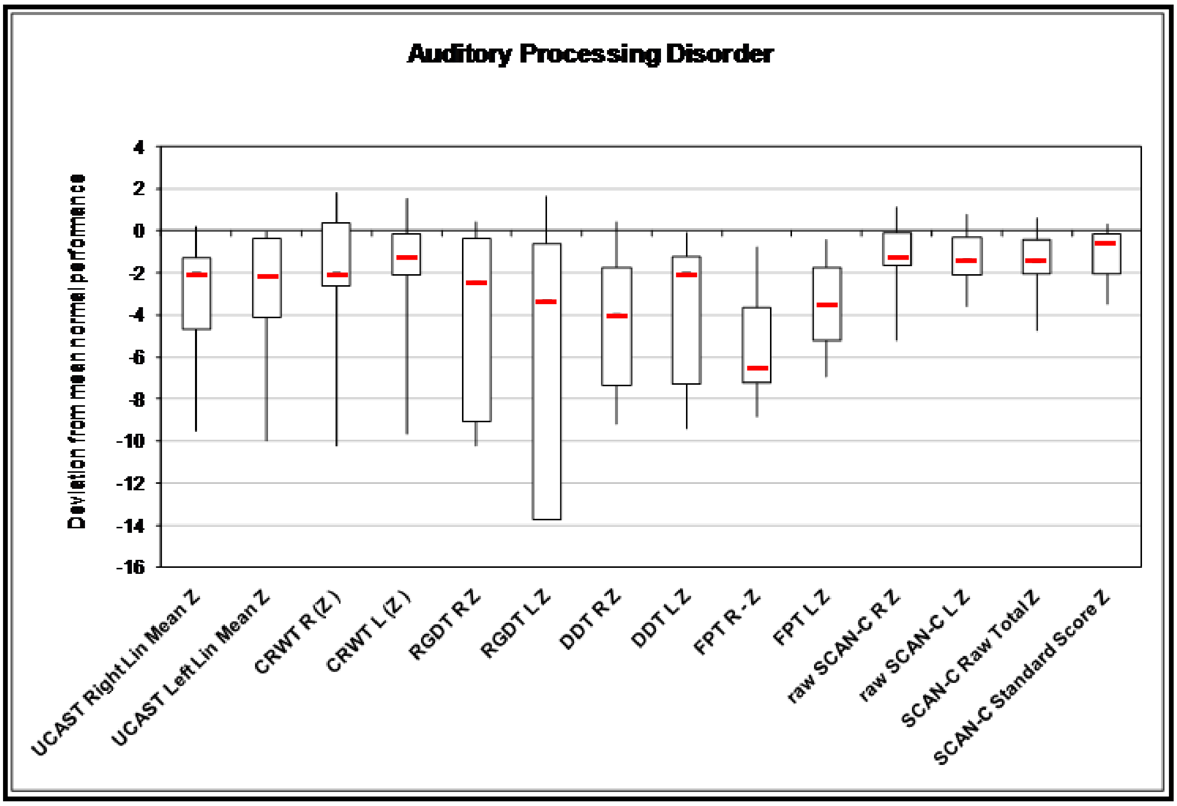

Figure 19. Box and whisker plots showing median test scores of the APD Group on entire test battery.

The outlier of the RGDT R and RGDT L are due to most APD participants failing on the RGDT by at least three standard deviations.

4.6 Parent Questionnaire Results

Otologic History

The majority of parents from both groups reported some occurrence of ear infections in their child's past: 80% in the CG and 87% in the APD Group. The number of incidences varied from 1 to over 10, and there did not appear to be any particular pattern of results across the two groups. Parents' responses are displayed in Table 7. None of the10 CG group participants reported any history of other otological complaints. Three of the 15 APD Group participants reported a history of otological complaints (see Table 7).

Table 7. Parent Questionnaire: Otologic history.

S	Otologic History		
	No of ear infections	Sets of grommets	Other ontological complaints
Control Group			
S01	1 - 2	0	no
S02	> 10	1	no
S03	> 10	2	no
S04	3 - 5	0	no
S05	6 - 10	0	no
S06	6 - 10	1	no
S07	1 - 2	0	no
S08	3 - 5	0	no
S09	0	0	no
S10	0	0	no
APD Group			
S13	3 - 5	1	Narrow, slit-like ear canals
S14	3 - 5	0	no
S15	6 - 10	0	no
S16	1 - 2	0	no
S17	3 - 5	0	no
S18	0	0	no
S19	> 10	2	no
S20	> 10	several	no
S21	1 - 2	0	no
S22	> 10	0	no
S23	0	0	no
S24	1 - 2	0	Turbinoplasty
S25	3	0	Adenoidectomy and sub mucosal turbinate reduction
S26	3 - 5	1	no
S27	3 - 5	0	no

Developmental History

Parents were asked to report on the birth and developmental history of their child (see Appendix IV) and a summary of key points is shown in Table 8. The birth was described as complicated in 53% (n=8) of APD case histories; compared to 20% (n= 2) of CG histories. None of the CG participants were reported to have had any developmental delays, compared to 46% (n=7) in the APD Group.

Table 8. Parent questionnaire: Developmental history.

Developmental History		
S	**Birth**	**Developmental delays**
Control Group		
S01	normal	no
S02	normal	no
S03	normal	no
S04	normal	no
S05	normal	no
S06	5 weeks premature	no
S07	normal	no
S08	5 weeks premature	no
S09	normal	no
S10	normal	no
APD Group		
S13	normal	Late talker
S14	normal	no
S15	6 weeks premature, NICU 7 days, antibiotics,	no
S16	normal	no
S17	normal	Speech and language delay
S18	normal	no
S19	Pneumothorax immediately after birth, time at NICU	Late walker, speech and language delay
S20	Emergency caesarean, kidney problems, cleft palate and lip	Late walker speech and language delay
S21	normal	no
S22	Apgar score of 4, wasn't breathing required oxygen	Speech and language delay, (began talking at 4 ½ years)
S23	4 weeks premature	no
S24	Normal birth, but had neurological trauma due to a viral infection when 3 or 4 years old	no
S25	Required resuscitation at birth, low Apgar score	Speech and language delay
S26	normal	no
S27	normal	Late talker

Learning history

Responses on the learning history are summarised in Table 9. None of the CG participants were reported to have a history of learning difficulties. In contrast, all APD Group participants (100%) (n=15) were reported to have a history of learning and/or developmental difficulties. Of these, five (n=5) participants (S14, S17, S23, S25 and S26) were reported to have been diagnosed with a learning disorder, such as developmental and/or verbal dyspraxia, Specific Learning Difficulty (SLD) and dyslexia. One (n=1) participant (S21) reported to have been diagnosed with Irlen Syndrome (visual tracking disorder). A further two participants (n=2) were suspected of having dyslexia and were awaiting appointments for assessment.

A visual disorder affecting eye tracking was reported in three (n=3) participants who also were reported to have reading difficulties. Participant S15 who was reported to have anxiety related learning difficulties was undergoing assessment for Anxiety Disorder NOS (Not Otherwise Specified). Participant S13 had not been diagnosed with a specific learning disorder but presented with stenotic ear canals and a long history of difficulty comprehending speech in the presence of background noise.

Almost half (47%; n=7) of all APD Group participants were reported to have a family history of learning difficulties. In contrast, one (n=1; 10%) of the CG participants were reported to have an older brother being diagnosed with dyspraxia.

Table 9. Parent questionnaire: Learning history.

Learning history		
S	**History of learning difficulties**	**Family history of learning difficulties**
Control Group		
S01	no	no
S02	no	no
S03	no	Brother with diagnosed dyspraxia
S04	no	no
S05	no	no
S06	no	no
S07	no	no
S08	no	no
S09	no	no
S10	no	no
APD Group		
S13	Great difficulty comprehending speech in the presence of background noise	no
S14	Diagnosis of Specific Learning Disability (SLD)	Sister, mother, grandmother had problems spelling
S15	Suspected Anxiety Disorder NOS*	No
S16	Concerns about spelling and focusing in class	Brother, mother, grandmother had problems spelling
S17	Diagnosis of Dyspraxia	Two older brothers diagnosed with learning difficulties and dyspraxia
S18	Eye tracking issue, suspected dyslexia	Father and mother struggled with reading
S19	PAT assessment: poor phonemic awareness, visual, auditory, speech delayed	no
S20	Reading problems, fine motor skill problems	no
S21	Diagnosis of with mild Irlen Syndrome (visual disability)	no
S22	Speech and language difficulty	Not stated
S23	Diagnosis of verbal dyspraxia	Father and uncle are stutterers
S24	Learning difficulties	no
S25	Diagnosis of developmental and verbal dyspraxia, receives SLT	no
S26	Diagnosis of dyslexia	Father had learning problems; eldest brother is mildly dyslexic
S27	Reading difficulties, Eye tracking issue	Father and cousin struggled with reading, brother was late talker

*NOS = not otherwise specified

Listening and Understanding

Figure 20 displays graphically responses to questions about participants' listening and understanding. In response to questions relating to listening and understanding (Appendix VI) parents of 80% of APD Group participants stated that their child had difficulties following multiple instructions or directions.

Behaviour & Skills

In response to questions on behaviour and skills (Figure 21 on page 63), the most frequently stated problems were 'paying attention or keeping their mind on the teacher' (100%; n=15), 'easily distracted by other events in the background' (93%; n=14) and 'difficulty taking notes in class' (80%; n=12). The least encountered deficits were 'poor musical ability' (80; n=12), 'problems with space perception/coordination (67%; n= 12) and 'poor social skills and peer relationships' (67%; n= 12).

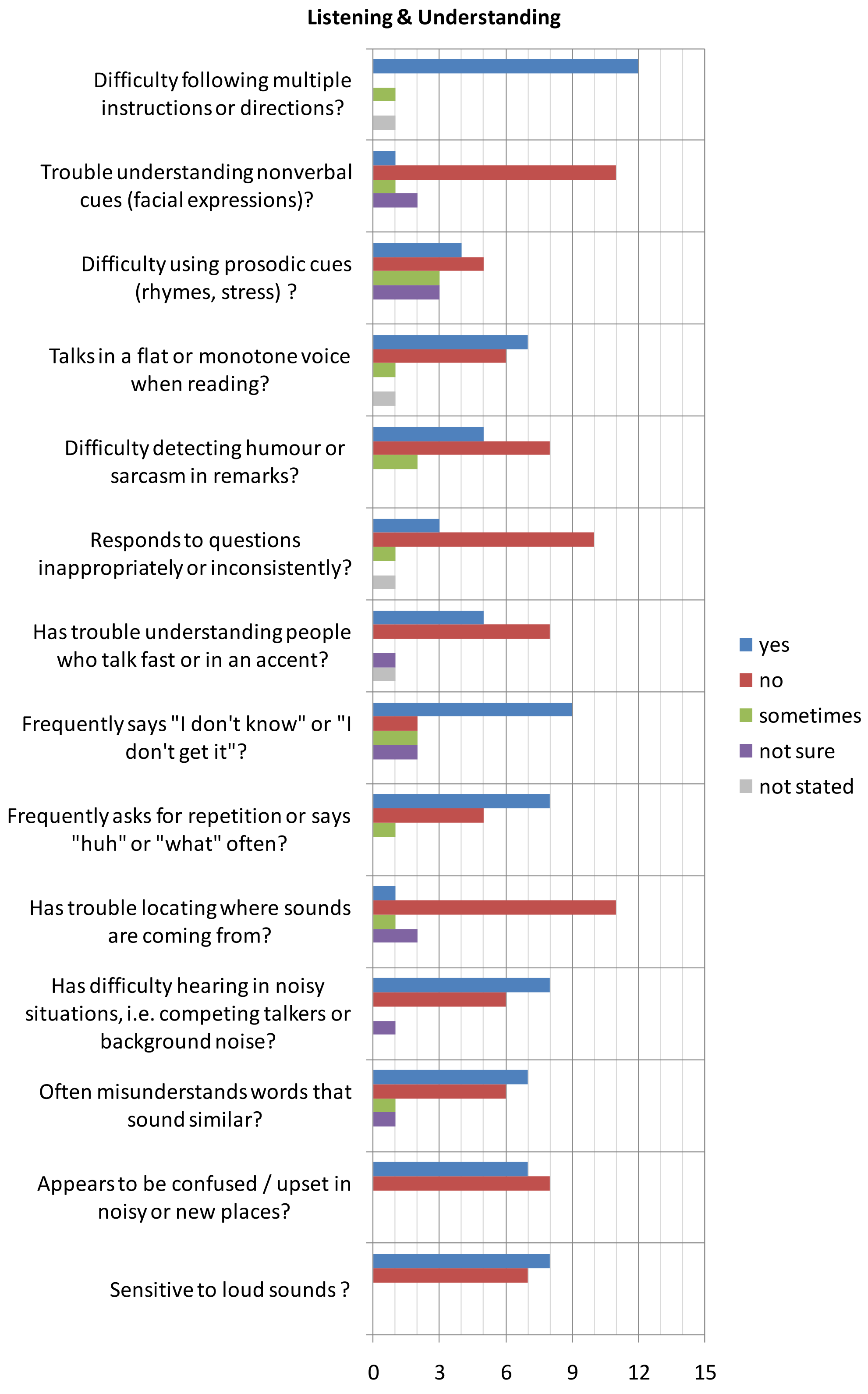

Figure 20. Parent questionnaire: Listening and understanding.

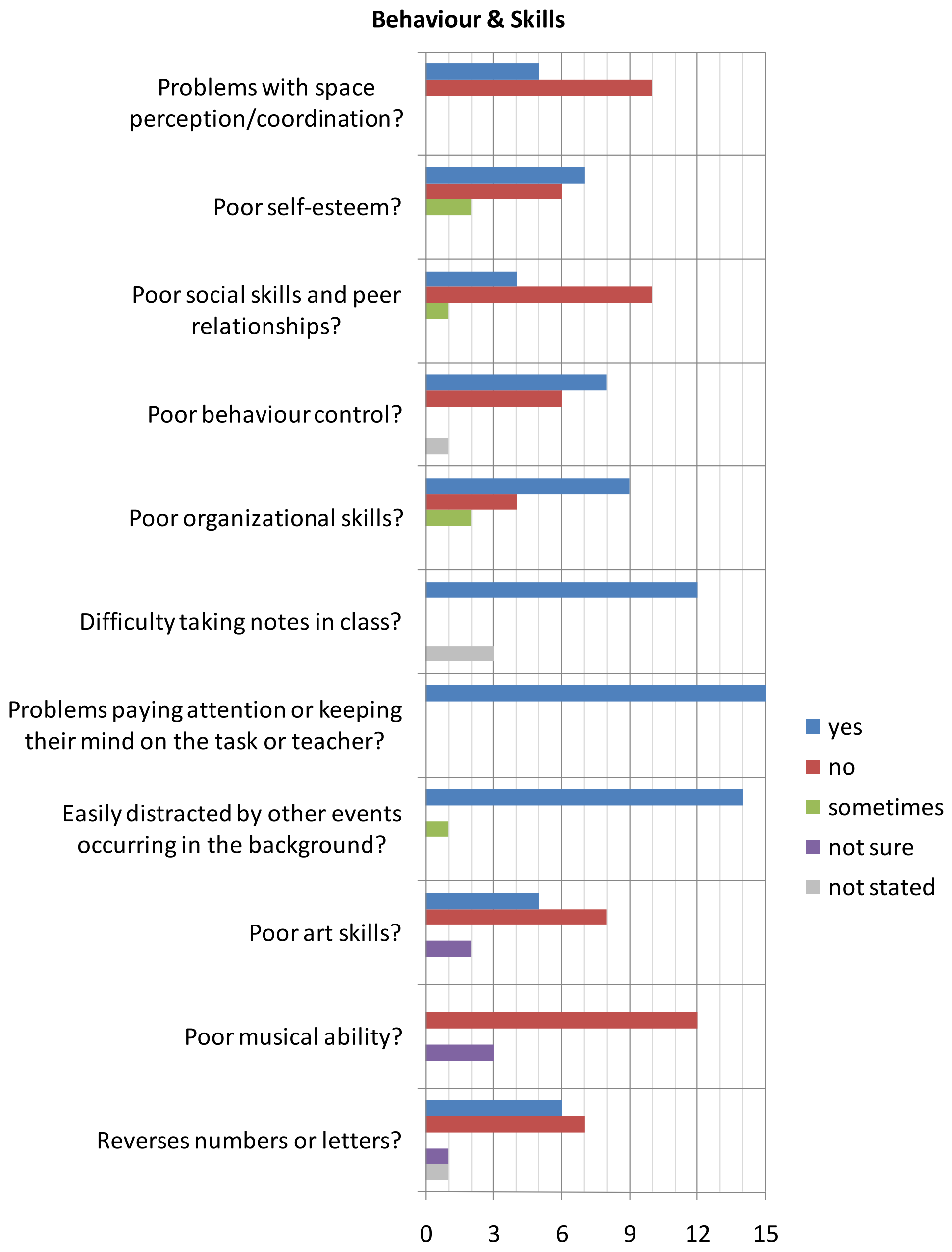

Figure 21. Parent questionnaire: Behaviour and skills.

4.7 Teacher Questionnaire Results

Seven (n=7) teacher questionnaires were completed. The CHAPS raw score range of -12 to -130 indicates at risk performance (see Table 10). All participants were within that range with S17 having the highest score of -49 and S22 had the lowest score of -157.

Table 10. CHAPS raw scores across different listening conditions.

Listening Condition / Subject	Noise	Quiet	Ideal	Multiple inputs	Auditory memory/sequencing	Auditory attention span	Total raw score
S17	-18	-7	-1	-2	-10	-11	**-49**
S19	-19	-13	-1.7	-4	-23	-11	**-75**
S20	-25	-9	-1	-2	-22	-15	**-74**
S22	-30	-28	-11	-11	-37	-40	**-157**
S25	-15	-7	-3	-7	-22	-19	**-73**
S26	-12	-9	-3	-3	-17	-9	**-53**
S27	-23	-14	0	-9	-19	-6	**-71**

Note: CHAPS raw score range for normal auditory performance is +36 to -11), and the range for at risk performance is -12 to -130. All participants for whom a teacher questionnaire was returned scored within the risk performance range.

5 DISCUSSION

This study examined the ability of an adaptive filtered speech test, the UCAST, to distinguish children with APD from those without auditory processing deficits. For that purpose, a traditional APD test battery (TAPD) was administered to an experimental group (EG) of 18 children suspected of APD and to a control group (CG) of 10 normally developing children. The TAPD comprised the following four sub-tests: Compressed and Reverberated Words Test (CRWT); Random Gap Detection (RGDT), Dichotic Digits Test (DDT), and the Frequency Pattern Test (FPT). Based on ASHA criteria (ASHA, 2005) for the interpretation of APD assessment, 15 out of the 18 EG participants were diagnosed with APD. This study further compared the test results of the UCAST to the Filtered Words sub-test of the SCAN-C (SCAN-C (FW)) administered to the same group of participants.

5.1 Hypothesis 1: APD Group and Control Group UCAST Scores

The first hypothesis tested was that performance on the UCAST, an adaptive version of a low-pass filtered speech test, would be significantly different in those children who failed an APD test battery compared to normal control children with no evidence of APD. This hypothesis was supported by the data which showed that participants in this study who failed the TAPD test battery required significantly more frequency information to score 62.5 % correct on a psychometric function than the CG participants required. This implies that compared to normal children, children with APD are less able to understand speech when high frequency information is removed from the speech signal. This may reflect one of the most frequently reported difficulties that children with APD present with. That is the difficulty to understanding speech in a noisy classroom or in any situation where background noise masks the predominantly high frequency consonants of speech.

Why do children with APD appear to need a wider band of frequencies present in the speech signal in order to understand that signal? There are several possibilities. As access to the high frequency consonants of speech is reduced in a degraded signal, a listener is required to ‘fill in the gaps’ in order to predict the likely target word or phrase, a process commonly referred to as ‘auditory closure’. The results of this study suggest that the APD Group participants were, as a group, less able to apply auditory closure skills in predicting the presented target word, requiring a significantly broader portion of the signal to be intact in order to achieve the required 62.5% correct. This may reflect so-called ‘bottom-up’ temporal processing deficits or ‘top-down’ processing deficits such as cognition, language and memory; or it may reflect a combination of the two. Each of these possibilities will be considered in turn.

A strong positive correlation in this study was found between performance on the UCAST and performance on the RGDT, a non-speech based test of temporal processing, suggesting that participants who perform poorly on the UCAST are more likely to have temporal processing difficulties. Over half of all APD Group participants in this study (n=8; 53%) failed the RGDT and those subjects with the highest (i.e. worst) UCAST scores were also those subjects with the longest gap-detection thresholds. All participants with UCAST scores between 900 Hz and 1700 Hz failed the RGDT binaurally. Temporal processing skills are important in extracting information from subtle contextual cues surrounding phonemes, such as consonant-vowel transitions (Mody, Studdert-Kennedy, & Brady, 1997; van Wieringen & Pohls, 1995). When a speech signal is degraded some of the more robust frequency cues are removed or diminished. In this instance the listener may be more dependent on subtle formant transition cues for consonant recognition. Temporal processing difficulties may therefore result in a greater reliance on a robust acoustic signal for speech understanding (Pichora-Fuller & Souza, 2003).

Language abilities, while not specifically assessed in the present study, may well play an important role in performance on the UCAST. Auditory closure depends not only on temporal processing abilities for detecting within-signal cues, but on a child’s vocabulary and knowledge of language. For example, a child with age-appropriate language abilities may be able to make a reasonable ‘best guess’ on a four-alternative forced choice task by ruling out several alternatives based on their vocabulary and knowledge of semantics. A child with poor language skills may not be as well equipped to apply such a strategy and may therefore rely more heavily on an intact acoustic signal.

A deficit in temporal resolution or discrimination skills has been shown to be related to phonological processing deficits and receptive language and reading skills (Rawood, 2006; Tallal, Miller, Jenkins, & Merzenich, 1997). However, there is some debate regarding the specific relationship between temporal processing deficits and language disorders (Hartley, Hill, & Moore, 2003; Rosen, 2003). Regardless of whether temporal processing deficits are causative of language disorders, it is likely that both temporal processing and language skills may be necessary for good performance on the UCAST. Children with deficits in either ability may require a wider band of frequencies present in order to achieve a score of 62.5% correct on the UCAST.

The poorer performance on the UCAST of the APD Group participants may further reflect more global or multimodal processing deficits. While literacy has been removed as a confounding variable from the UCAST by using picture cards rather than words as the response mode, the four-alternative forced choice closed response format (4AFC) requires cognitive skills such as conceptualization, memory and prior knowledge. The extent to which extra-auditory factors influence performance on APD tests is a major source of controversy in the field (Cacace & McFarland, 2005; Musiek, et al., 2005). APD frequently co-exists with other language and learning disorders such as ADHD, dyslexia and specific language delay (Sharma & Purdy, 2009) and a high proportion of the APD Group participants in the current study presented with co-morbid learning difficulties. Whether APD is causative or symptomatic of other neurological or sensory disorders, or whether co-existing difficulties result from a common underlying cause, is currently unclear (Moore, et al., 2009), but the influence of such extra-auditory factors on performance on any test of auditory processing must be considered.

It is interesting to note that four (n=4) APD Group participants and one (n=1) CG participant scored better on the binaural UCAST practice run than on monaural presentation of the test stimuli. The purpose of the practice run was to allow for the effect of learning on test performance, thus it was expected that participants' performances would improve on subsequent monaural presentation. Yet, it appeared that for some participants binaural presentation provided a significant advantage over monaural presentation, regardless of any learning effects. The advantages of binaural over monaural listening are well documented in the literature (Bess & Tharpe, 1984; Colletti, Fiorino, Carner, & Rizzi, 1988; Yost, 1997), but to the author's knowledge, no study has systematically compared monaural and binaural presentation of a low-pass filtered speech task in children with APD.

5.2 Hypothesis 2: Correlation between UCAST and TAPD Scores

The second hypothesis tested in this study was that the performance on the UCAST will correlate significantly with performance on other tests of central auditory processing: the RGDT, the FPT, the DDT, and the CRWT. This hypothesis was partly supported by the data. Significant correlations between the UCAST scores and scores on the FPT, the

RGDT and the DDT were found. However, this study did not find a correlation between the UCAST and the CRWT. The correlation between the UCAST and the RGDT was discussed above. The following section discusses the remaining tests in detail.

UCAST and CRWT

The present study found no correlation between the UCAST and the CRWT. This result was somewhat surprising since both tests are monaural low-redundancy speech tests using a degraded signal. However, the acoustic stimulus used in the CRWT is degraded by compression and the addition of reverberation; whereas the UCAST uses low-pass filtering to remove extrinsic redundancy. Both tests are presumed to assess a listener's auditory closure abilities. However, research has documented that the type and degree of the degraded signal used in a speech recognition test has a significant impact on test results (Farrer & Keith, 1981; Gordon-Salant & Fitzgibbons, 1993; Miller, et al., 1951; Willeford, 1977; Wilson, Preece, Salamon, Sperry, & Bornstein, 1994). Miller and his colleagues (1951) found normally hearing listeners were able to achieve a score of 100% correct on meaningful words but only 70% correct on nonsense words, highlighting the importance of the degree of redundancy of a speech stimulus in test performance. Wilson et al. (1994) concluded in their investigation on the effects of varying time compression and reverberation conditions on speech recognition scores that the degree of compression and reverberation has a multiplicative rather than additive effect. This has led to some speech tests using compressed and reverberated speech stimuli being too difficult, even for listeners with normal hearing.

Based on the normative data developed by Kelly (2007), all participants in the present study, in both the Control and the APD Group, scored better than two standard deviations above the age mean and therefore, the CRWT did not identify auditory closure deficits in any participant. The Kelly data for the CRWT is based on a relatively small number of participants (N= 19, 18, and 13 for each of the three age groups) and as a result of large deviations in scores across children in that study, the cut-off score for determining a pass/fail on the CRWT is very low. The finding in the current study that all children with APD (as determined by their performance on the remaining sub-tests of the TAPD) passed the CRWT supports the need for a larger sample on which to base normative data for this test.

The distribution of CRWT raw scores for both groups in the present study is displayed in Section 4.2, Figure 13. There is a somewhat larger spread of data for the APD Group, and the mean score (68% in the right ear / 59.75% in the left ear) was lower than in the Control Group (73.05% in the right ear / 75.25% in the left ear). However, there is a significant overlap between the groups, and as stated above, all participants, regardless of group, scored better than two standard deviations above the age mean based on Kelly (2007). This clearly indicates that both the specificity and the sensitivity of the CRWT were inadequate to discriminate between participants with and without APD in the present study.

The absence of any correlation between the UCAST and the CRWT, and the greater overlap between groups on the CRWT compared to the UCAST, may also be attributed to differences in scoring paradigm between the two tests. The phoneme based scoring method of the CRWT awards points correct when a word is only partially understood by the listener, whereas the UCAST is based on whole word correct or incorrect. This means a listener can pass the CRWT without having identified any whole word correctly – the more stringent whole word scoring schema used in the UCAST may result in improved separation between groups.

Correlation between UCAST and DDT

The DDT was used to examine the participants' binaural integration abilities (Broadbent, 1954; Musiek, 1983). A large negative correlation was found between the UCAST and the DDT scores for the right ear; no correlation was found between the UCAST and the DDT results for the left ear. The difference in degree of correlation between the left and right ears can be explained by some participants (S14, S21 and S24) having obtained relatively low scores on the DDT for their left ear while obtaining relatively high (i.e. poor) scores on the UCAST. For example, S14 had a low score of 47.5% for the DDT left ear, while his mean left ear UCAST score was 477.5 Hz. The opposite performance pattern was also observed in two APD Group participants (S18 and S19). For example, S18 had a mean left ear UCAST score of 1778.43 Hz and a DDT left ear score of 87.5%.

In terms of individual DDT results, 10 of the 15 APD Group participants failed based on comparison to normative data (Kelly, 2007). Of those, six performed poorer on the UCAST than the 'working pass criteria' of 667 Hz (see Section 4.3.3 on page 49). That means 67% who failed the DDT also 'failed' the UCAST. In contrast to the monaurally presented UCAST, the binaurally presented DDT is used to examine inter-hemispheric transfer of information and also assesses short-term auditory memory storage and retrieval (Keith & Anderson, 2007; Musiek & Chermak, 2007). Difficulties hearing in background noise or in the presence of a competing speaker are associated with low performance on dichotic listening tasks (Musiek, 1983).

It is interesting to note that all of those APD Group participants in this study who failed the DDT were reported by their parents to have either a diagnosed or suspected learning disorder such as dyslexia or dyspraxia, except S13 who was reported to have great difficulty comprehending speech in the presence of background noise (see Table 9, Section 4.6). In contrast, those who passed the DDT were reported with other difficulties such as eye tracking issues, suspected anxiety disorder or a more global learning difficulty, excluding APD Group participant S18 who was suspected of having dyslexia. The DDT bears very little linguistic loading. This suggests that binaural auditory integration deficits may play a crucial part in the learning difficulties encountered by those APD Group participants in this study, who failed the DDT. On the other hand, good performance on the DDT, and indeed the FPT, depends on intact working memory abilities (Musiek & Chermak, 2007; Musiek, Pinheiro, & Wilson, 1980; Pinheiro & Musiek, 1985). Assessments of the working memory abilities of participants in the present study were not made, but the possibility exists that those APD Group participants who failed the DDT failed because of a working memory deficit or other, more global cognitive factors. The contribution of such factors to the learning disorders so prevalent among the APD Group participants in this study (and indeed, among children diagnosed with APD in general) (Sharma & Purdy, 2009) is beyond the scope of the present work.

Correlation between UCAST and FPT

A large degree of correlation was found between the FPT and the UCAST. As a test of temporal processing, the FPT assesses temporal pattern recognition and sequencing, an important auditory function necessary for the discrimination of subtle changes in stress, rhythm and intonation patterns of speech. A deficit in temporal pattern or sequencing abilities is thought to relate to difficulties recognizing and using prosodic features of speech (Bellis, 2003). The large correlation between the UCAST and the FPT may reflect an overlap in the underlying auditory function each test assesses (temporal processing skills) or, it may simply be that children with APD tend to do poorly on both tests, reflecting more fundamental underlying deficits in working memory or other amodal processes.

To summarize, if it is presumed that the various TAPD sub-tests examine different auditory processing skills than the UCAST, it may be expected that children who perform poorly on the UCAST do not necessarily perform equally poorly on all other APD sub-tests. However, the results obtained in this study show a significant overlap between the UCAST, the RGDT, the FPT and the DDT. These findings are suggestive of either multi – level auditory processing deficits underlying the cause of the difficulties encountered by the APD Group participants in this study or higher level amodal/global processes (such as working memory) which impinge on performance of multiple subtests. This results in correlations between tests which merely serve to reflect the pervading influence of such factors.

5.3 Hypothesis 3: Correlation between UCAST and SCAN-C (FW) Scores

The third hypothesis tested in this study was that the UCAST would discriminate between children with and without APD with greater specificity and sensitivity than the Filtered Words subtest of the SCAN-C. This hypothesis was supported by the data. Based on the SCAN-C norms (Keith, 2000b), all CG and APD Group participants passed the SCAN-C (FW), apart from one (S25) who had a 'borderline' result. This finding suggests that in this study the sensitivity and specificity of the SCAN-C (FW) was significantly lower compared to the 'working pass/fail criterion' of the UCAST (see Figure 18, Section 4.5).

A comparison of test sensitivity and specificity between the UCAST and the SCAN-C (FW) must be made with caution. The present study included a small sample size and no normative data is as yet available for the UCAST. A larger sample of children than this study could accommodate would be required to establish these norms. However, for the purpose of this study, a 'working definition' of a pass/fail criterion of two standard deviations above the mean for the CG (667 Hz) was applied and is indicated by the red horizontal line in Figure 22 below. Based on this criterion, the UCAST 'passed' all CG participants and 'failed' 60% of APD Group participants showing a high specificity at this pass criterion. Moreover, if the pass/fail criteria were set at 600 Hz instead of 667 Hz (as indicated by the green line in Figure 22) all CG participants would still 'pass'. However, 80% (12 out of 15 APD Group participants) would 'fail'. Thus, while maintaining maximum specificity, the sensitivity of the UCAST would be improved at this pass criterion.

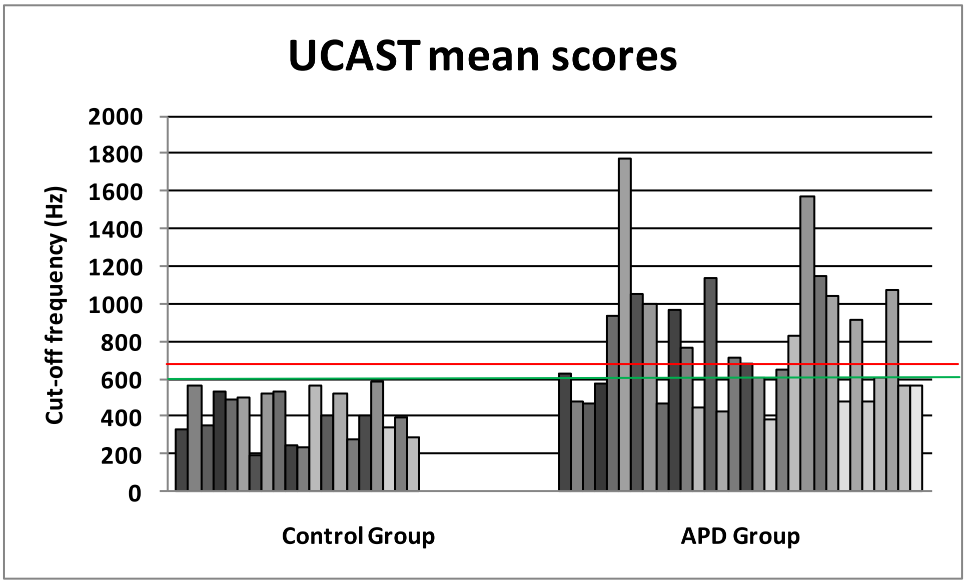

Figure 22. Mean UCAST scores for CG and APD Group participants. Two standard deviations below the mean are indicated by the red horizontal line. The green horizontal line indicates the pass/fail criteria at 600 Hz.

It is important to note SCAN-C (FW) test results were interpreted by applying age appropriate standardised scores (Keith, 2000b), whereas the UCAST results in this study are raw scores that were not corrected for age. However, no age effect was found for the UCAST.

Consistent with these results, no correlation between the UCAST and the SCAN-C (FW) was found. This is interesting and again, surprising, as both tests are monaural-low-redundancy speech tests utilising the same type of degraded acoustic stimulus, i.e. low-pass filtered speech. The crucial difference between the tests is that of constant versus adaptive speech stimuli presentation. The SCAN-C (FW) employs a constant filter cut-off frequency of 1000 Hz; whereas the UCAST begins with a cut-off frequency of 1000 Hz. The UCAST adjusts the cut-off adaptively according to the listener's responses. Only four APD Group participants in the present study obtained mean scores above 1000 Hz on the UCAST. That implies that had the UCAST employed a fixed filter cut-off frequency of 1000 Hz, 11 out of 15 APD Group participants would have 'passed' the test. This clearly demonstrates the significant advantages of employing an adaptive algorithm in a filtered speech test. Such a test is not prone to floor and ceiling effects and is therefore more specific in identifying underlying auditory processing deficits. The low sensitivity of the SCAN-C has been demonstrated in a previous study (Domitz & Schow, 2000). However, the current study focused on one of the four SCAN-C sub-tests only; whereas in other studies the combined scores of all SCAN-C subtests was analysed.

It is interesting to note that even though there was a large overlap between SCAN-C (FW) scores from each group, in the present study the SCAN-C (FW) standard scores showed that two (n=2) of the APD participants scored lower than the CG participants. However, none of the participants failed based on the SCAN-C (FW) norms. This suggests that the sensitivity of the SCAN-C (FW) was insufficient to distinguish between groups in the present.

Finally, the effect of the difference in acoustic stimuli between the UCAST and the SCAN-C (FW) is an important consideration. SCAN-C stimuli are recorded in a North American accent, and research has clearly shown that speech stimuli should be familiar to the participant in terms of vocabulary and accent (Brandy, 2002; Wright, 1987). Since all participants in this study were native speakers of New Zealand English, confusion between words like ‘own’ and ‘on’, was evident in many participants. However, it is an apparent paradox that despite the added difficulty of a foreign accent, all children still passed the SCAN-C (FW) test. For the UCAST, the Australian recording of the NU-CHIPS word lists was utilized. While there are differences between Australian and New Zealand English (NZE) they are not as significant as the difference between NZE and North American English (Gordon, 1991). Therefore, differences in performance level on the UCAST among the participants are unlikely to be due to a ‘foreign accent effect’.

In summary, the above comparison between the UCAST and the SCAN-C (FW) have clearly demonstrated that the UCAST holds promise to be a speech test of monaural low-redundancy that discriminates between children with and without APD with greater sensitivity and specific than its constant level stimuli counterpart, the SCAN-C (FW).

5.4 Case Examples

Children who are referred for auditory processing assessment present with a diverse range of various presenting difficulties, which may include academic and learning difficulties, ADHD, dyslexia and specific language delay (Dawes, Bishop, Sirimanna, & Bamiou, 2008; Sharma & Purdy, 2009). Until our ability to differentially diagnose APD from other co-morbid conditions improves (Moore, 2006), the results of the current behavioural test battery should be interpreted in conjunction with other multidisciplinary assessment results (Bellis, 2003). To illustrate the heterogeneous nature of APD and issues surrounding the co-morbidity and co-existence of other disorders, the following case examples from participants in this study are presented.

Case example S 28: 'Borderline' ADHD

As stated earlier, data obtained from EG group participant S28 was excluded from data analysis of the present study due to this child's test performance being significantly influenced by ADHD symptoms. This participant had previously been diagnosed with 'borderline ADHD'. Yet, he did not receive medication and was not receiving any specific therapy to help him to control his behaviour at the time of APD testing. It was further reported that he had difficulties staying on task at school and following instructions. He also had some difficulties with fine and gross motor skills.

Despite all best efforts by the clinicians and the child's genuine willingness to participate he could not keep his attention and focus long enough to complete the tests. The summary of his test results illustrates his struggles (see Table 11). While he performed on the CRWT within normal range for his age, it should be noted that the test was reduced to the presentation of one list instead of two for each ear. Results for the DDT show a score of less than three standard deviations below normal for the right ear with a better score for the left ear. This participant had great difficulty staying on task during the RGDT and FPT, to the extent that insufficient responses were collected to interpret the results conclusively. While this participant showed great interest in the UCAST and willingly selected images presented to him on the touch screen, he developed a selection pattern that included 'all means of transport', i.e. pictures of the bus, train, truck, irrespective of the acoustic stimulus presented. If a screen did not include a vehicle he tended to select the picture in the bottom right quadrant, often using his nose instead of his hand to touch the screen. His scores were consequently elevated to a degree that did not express his auditory skills but reflected his inability to focus on the task. The right ear presentation was therefore not carried out. On the SCAN-C (FW) this participant scored a 'borderline' result.

This case illustrates that neither the TAPD test battery approach nor the interactive adaptive nature of the UCAST succeeded in obtained conclusive results of auditory processing ability for a child with significant attention deficit problems. This case highlights the ongoing discussion amongst researchers about the co-morbidity issues surrounding APD and approaches to differentially diagnose APD from other co-morbid conditions (Cacace & McFarland, 2005; Musiek, et al., 2005).

Table 11. Summary of results for participant S 28.

Age (yrs)	CRWT (%)		RGDT (ms)		DDT (%)		FPT (%)		SCAN-C (FW) raw score		UCAST (Hz)		
	R	L	R	L	R	L	R	L	R	L	PR	R	L
9	51	43	**40**	**40**	**37.5**	87.5	**0**	**0**	12	17	**2564.64**	**DNT**	**3258.51**

Case example S 11: Normal APD results

This girl was referred for APD assessment by her mother who described some concern about her daughter's ability to focus on tasks in the classroom and her ability to follow verbal directions or instructions. The results of all TAPD sub-tests showed performance well within normal limits and therefore no evidence of APD. Her scores on the UCAST exemplify good auditory closure abilities (see Table 12).

Table 12. Summary of results for participant S 11.

Age (yrs)	CRWT (%)		RGDT (ms)		DDT (%)		FPT (%)		SCAN-C (FW) raw score		UCAST (Hz)		
	R	L	R	L	R	L	R	L	R	L	PR	R	L
10.1	82.5	68	7.25	10	95.5	92.5	80	70	17	18	584.24	360.76	417

Case example S 25: Verbal dyspraxia

This boy was referred for APD assessment following concerns about his learning, hearing and understanding of speech in background noise at school and at home. He had a history of speech and language difficulty, with a confirmed diagnosis of developmental dyspraxia (including significant verbal dyspraxia) and learning difficulties. He also had some history of otitis media, with several episodes having occurred during his toddler years. This boy was fitted with hearing aids at the age of 5 ½ years, following a hearing test which indicated a severe hearing loss. However, at the 7 years of age, he discontinued wearing the aids following a hearing assessment which indicated normal hearing levels.

At the time of APD assessment pure tone audiometry revealed a mild sensorineural hearing loss bilaterally (25 dB HL at 4000 and 8000 Hz). Impedance audiometry revealed bilateral type C tympanograms (-100 daPa, right ear; -205 daPa, left ear). TAPD results show significant auditory processing difficulties, with this boy performing below his age-appropriate range on the RGDT, the DDT and the FPT. Because of his articulation difficulties, the CRWT was not administered, because scoring would not have been accurate. His scores on the UCAST were the second highest (i.e. worst) obtained by any of the APD Group participants (1071.14 Hz / 1136.51Hz) suggesting major deficits in auditory closure skills (Bellis, 2003). His test results are summarized in Table 13.

This case clearly demonstrates the advantage of the UCAST over the SCAN-C (FW) and the CRWT. Firstly, due to the non-verbal response format of the UCAST, the boy's auditory closure abilities could be assessed despite his articulation dysfunction which was not possible using the CRWT. In addition, the adaptive scoring method of the UCAST indicated the degree of difficulty this participant had when applying auditory closure skills. In contrast, the SCAN-C (FW) did not even fail this participant.

However, given the presence of a mild sensorineural hearing loss and the mild middle ear pathology, the clinical interpretation of his results was given as 'suspected APD'. A retest was carried out following adenoid/nasal surgery which significantly improved his breathing and nasality, and at this second test session, impedance audiometry revealed bilateral type A tympanograms and the same pattern of results on the TAPD as was seen earlier. A clinical diagnosis of APD was then made and an FM system recommended.

Table 13. Summary of results for participant S25.

Age (yrs)	CRWT (%)		RGDT (ms)		DDT (%)		FPT (%)		SCAN-C (FW) raw score		UCAST (Hz)		
	R	L	R	L	R	L	R	L	R	L	PR	R	L
8.4	**CNT**	**CNT**	**40**	**40**	72.5	**55**	**15**	**35**	12	13	**1083.77**	**1071.14**	**1136.51**

Case example S 18 suspected dyslexia

Participant S18 was an 8.4 year old boy with outstanding expressive and receptive language skills. However, he was identified with suspected dyslexia, and was undergoing language assessment at the time of participation in this study. It was further reported that he had difficulties following multiple instructions and staying focussed on tasks. He presented as a very bright, well articulated and motivated individual who remained well focused on all listening tasks throughout the APD assessment session. As displayed in Table 14, his scores on the RGDT were outside the normal range for his age indicating problems with temporal acuity. Even though he passed on the FPT his results were borderline for his age group. It is interesting to note, that this boy scored well above the mean on the CRWT suggesting intact auditory closure skills. On the UCAST however, while his score of the binaural practice run (542.35 Hz), was consistent with his good CRWT score, he required the highest low-pass filter frequency of all the participants in the monaural conditions (1568.50 Hz in the right ear; 1778.34 Hz in the left ear). The effect of possible fatigue or loss of attention is unlikely to account for these results as the boy remained motivated and focussed throughout. The cause of the poor scores in the monaural listening conditions is unknown. It is also interesting to note that immittance testing of this participant revealed all contra-lateral reflexes to be absent. Subsequent ABR testing showed normal waveform morphology and wave latencies (data not shown); however, the absence of contralateral reflexes remains an abnormal finding, and may relate to this subject's auditory processing difficulties.

Table 14. Summary of results for participant S18.

Age (yrs)	CRWT (%)		RGDT (ms)		DDT (%)		FPT (%)		SCAN-C (FW) raw score		UCAST (Hz)		
	R	L	R	L	R	L	R	L	R	L	PR	R	L
8.4	75.5	71	**37.5**	**40**	87.5	80	55	55	18	15	542.35	**1568.5**	**1778.34**

5.5 Questionnaires

5.5.1 Parent Questionnaire

The parent questionnaire forms an integral part of the overall APD assessment process (ASHA, 2005). The parent questionnaire used at the University of Canterbury, Speech and Hearing Clinic for APD assessments is divided into four sections, namely Developmental History, Otological History, Listening and Understanding, and Behaviour & Skills. Parents of CG and EG participants completed the parent questionnaire prior to their appointment which was then used in guiding the parent interview.

Notably, the parent questionnaire revealed a significant difference between the birth histories and the family history of both groups. While no birth related complications were reported by the parents of the CG participants, five (n=5; 33%) of the 15 APD Group participants were reported to have experienced complications at or immediately after birth. A further striking difference between the two groups concerned the family history which was more frequently reported by parents of APD Group participants than by CG participants.

Responses to the otologic history revealed no apparent correlation between incidence of otitis media and APD. There was no apparent difference between groups, either in terms of number of otitis media episodes, nor in the number of those who received grommets. In both groups the number of ear infections reported for each participant ranged from 0 to more than 10. Therefore, the findings in this study do not provide evidence for the numerous studies documenting a link between APD and OME (Chermak & Musiek, 2006; Moore, et al., 2003; Pillsbury, Grose, & Hall, 1991), although it must be noted that the sample size of this study was very small. This was not examined in detail as it was not the focus of this research. Other studies have found no evidence of OME as a factor predicting the presence of APD (e.g. Dawes, et al., 2008), and debate exists regarding the link between childhood OME and APD.

While none of the CG participants reported any developmental delays, seven of the 15 APD Group participants were described as having had various developmental delays, with speech and language delays being the most commonly reported. This illustrates the co-existence of other learning disabilities in the majority of APD cases in this study. The co-existence and co-morbidity of APD with other learning disorders is well documented (Baran & Musiek, 1999; Cacace & McFarland, 2005; Moore, et al., 2009; Sharma & Purdy, 2009; Tallal, 1980). Most of the APD Group participants in this study presented with symptoms that are common to various learning disorders. However, the TAPD test battery used in this study was based on NZ norms (Kelly, 2007) and performed in accordance with ASHA guidelines (2005) which suggests that the APD Group participants have specific auditory deficits. In addition, although no normative data yet exists for the UCAST, the preliminary results in this study support the presence of auditory processing deficits in the majority of the APD Group participants.

5.5.2 **Teacher Questionnaire**

The *Children's Auditory Processing Performance Scale (CHAPPS)* is a questionnaire created by Smoski, Brunt, and Tannahill (1998) that is used to screen for APD by assessing a parent's and/or a teacher's judgment of a child's listening ability as compared to his or her peers. CHAPPS was developed to systematically collect and quantify listening behaviours observed in children ages seven and older (Hutton, 1990). The responses of the teacher questionnaires returned for six (n=6) of the APD participants in the current study supported the diagnosis of APD for these participants, as established by the TAPD. There is general consensus in the literature that there is no currently available questionnaire that may be used as a stand-alone screening tool for APD. However, it is acknowledged that the information provided by teachers and parents about a child's auditory performance contribute to the overall assessment process of APD (Bellis, 2003; Drake, et al., 2006; Musiek, Gollegly, Lamb, & Lamb, 1990; Smoski, et al., 1998).

5.6 Theoretical and Clinical Implications

The current study has demonstrated that the UCAST, an adaptive filtered speech test, discriminated between children with and without APD with very good specificity and good sensitivity based on a working pass/fail criterion for the UCAST and a comparison with a traditional APD test battery. The results demonstrate that the UCAST is a potentially useful addition to a clinical APD test battery.

The findings of this study have a number of implications with regards to the selection of APD sub-tests currently employed clinically. This study has highlighted the inadequacy (at least in their present form and using available normative data) of two monaural-low-redundancy speech tests, namely the CRWT and the SCAN-C, to discriminate children with APD from those without APD. In contrast, the UCAST was shown to have significantly higher sensitivity and specificity than the CRWT and the SCAN-C, at least for the cohort of children who participated in the current study, although a larger sample size is required to substantiate this finding. Based on this data, it is suggested that the UCAST may replace the CRWT as the monaural low-redundancy subtest of choice in an APD test battery.

The adaptive and computer-based design of the UCAST has several advantages over its constant stimuli non-interactive counterparts. Computerized and interactive test methods engage the children in the task, minimising fatigue and loss of attention. In addition, participants are in control of their response time. The computerized scoring method used in the UCAST eliminates tester bias and scoring errors. Moreover, the non-verbal response format of the UCAST means that possible articulation difficulties in a participant do not hinder the administration and correct scoring of the test. A further advantage of the computer based UCAST is that response errors are recorded and can be analysed. This can provide information that may be beneficial in identifying response patterns indicative of a specific deficit.

5.7 Limitations and Directions for Future Research

This study has clearly illustrated that the UCAST, a computerized adaptive filtered speech test, holds promise as a clinically viable monaural low-redundancy speech test in the clinical diagnosis of APD. The UCAST performed with greater specificity and sensitivity than two other tests of monaural low-redundancy. Future research involving a large sample of typically developing children is needed to establish age-appropriate and ear specific normative data for the UCAST. In addition, the robustness of the current version of the UCAST should investigated by examining its test/retest reliability.

Several limitations of the current study relates to the UCAST software. Firstly, the peak normalization process for the UCAST presentation level employed in this study incurred a slope in level of 6 dB /octave below 1000 Hz. In order to further improve the accuracy of the normalization procedure further correction factors derived from the un-normalized data will be applied in future applications of the UCAST.

A further limitation was the unavailability of acoustic stimuli presentations in New Zealand English. Previous studies have documented the importance of speech stimuli being presented in a familiar accent and vocabulary (Wright, 1987). The Australian recording of the NU-CHIPS stimuli employed in this study correlated with New Zealand English more closely than the American English version (Gordon, 1991). However, the words presented by the NU-CHIPS test are based on their frequency of occurrence in North America rather than New Zealand (Dengerink & Bean, 1988; Elliott & Katz, 1979). Therefore, the word frequency which relates to the relative familiarity of the participant with the words may have effected participant's selection (Elliott, et al., 1983).

For the purpose of this study a diagnosis of APD was based on the administration of the four pre-selected APD sub-tests. Since APD is a heterogeneous disorder some participants who passed the TAPD test battery in this study may have failed on different APD subtests. Therefore, had the selection of sub-tests been individualized it is possible that some of the SG participants would have been identified with APD (Baran, 2007).

Because of the computer-based platform, the UCAST parameters can be modified to include additional test measures such as the time required by each listener to respond to the task. For example, this information can provide insight into the speed of temporal processing.

The findings of this study highlight the need for further research into the development of adaptive procedures for APD assessment. Currently, a typical APD test battery consists of sub-tests that employ constant-stimuli methods. The limitations of these include floor and ceiling effect, and due to their monotonous nature do not engage the young listeners to the task, resulting in loss of motivation and attention.

This study has provided evidence that an adaptive filtered word test can discriminate between children with and without APD with a significantly greater specificity and sensitivity than the CRWT and the SCAN-C (FW). It provides a small but significant contribution to the inherently complex field of auditory processing assessment. The heterogeneity of auditory processing disorder and the lack of a diagnostic gold standard justify the use of a test battery approach coupled with a multidisciplinary approach as currently applied in most clinical settings (ASHA, 2005). Therefore, to gain a deeper understanding of the multi-layered processes that appear to contribute to the various listening and learning difficulties children experience, such as memory and language, further research on the clinical utility of the UCAST and other adaptive APD tests would benefit from multidisciplinary team work involving educational psychologists, speech and language therapists and audiologists.

Appendices

Appendix I: Ethical Approval

Human Ethics Committee

Secretary

Tel: +64 3 364 2241, Fax: +64 3 364 2856, Email: human-ethics@canterbury.ac.nz

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Ref: HEC 2009/84

1 July 2009

Uta Heidtke
Department of Communication Disorders
UNIVERSITY OF CANTERBURY

Dear Uta

The Human Ethics Committee advises that your research proposal "Diagnosis of auditory processing disorder (APD) using an adaptive filtered words test" has been considered and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your correspondence of 26 June 2009.

Best wishes for your project.

Yours sincerely

Dr Michael Grimshaw
Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. *www.canterbury.ac.nz*

Appendix II: Project Information Sheet for Parents

University of Canterbury

Department of Communication Disorders

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

PROJECT INFORMATION SHEET FOR PARENTS

FOR THE RESEARCH STUDY

DIAGNOSIS OF AUDITORY PROCESSING DISORDER (APD) USING AN ADAPTIVE FILTERED WORDS TEST

PARENT INFORMATION

Your child is invited to participate in the research project; *Diagnosis of Auditory Processing Disorder (APD) using an adaptive filtered words test.*

AIM OF PROJECT:

The aim of this project is to design a more efficient and sensitive test for the diagnosis of central auditory processing disorder in children using an adaptive testing procedure.

DURATION:

Your child's involvement in this project will involve one session of approximately 2 ½ - 3 hours. Breaks will be provided as required. The following is an outline of the tasks required by your child:

PROCEDURE:

Prior to your appointment you will receive a parent questionnaire which will assist with the case history taking. We would ask you to complete the questionnaire at home and to bring it to your appointment. Should this questionnaire raise concerns about the existence of specific learning or listening difficulties in your child that you may have otherwise been unaware of, you will be counselled and appropriate referral will be made if applicable.

Case History:

A case history will be obtained for each child; however you will be the primary source for the case history information. The history taking will be based on the questionnaire that will have been sent to you and completed prior to your child's appointment. The clinician's questions are intended to clarify or extend on the responses made in the questionnaire where applicable. You will also been given the opportunity to add further relevant information about your child.

Time required: 10 - 15 minutes.

Otoscopy:

The child will have their ear canals examined using an otoscope (A specialised torch used for visual examination of the external ear and eardrum) to determine ear health.
Time required: 1 minute.

Audiometry:

A traditional hearing test will determine a child's eligibility for the study. This involves monitoring a child's response to stimuli presented at specific intensities.

Pure-tone audiometry: The child is seated in a sound booth, and tones are presented through head phones or insert ear phones at variable intensities. The child is asked to press a button each time they hear the tone, which indicates that they heard the sound and have responded.
Time required: 10 – 20 minutes.

Should a hearing loss be detected, the child is **not** eligible for APD testing, because the tests involved require normal hearing thresholds. However, the child will be offered an appointment for a comprehensive hearing test at the University of Canterbury Speech and Hearing Clinic at no charge.

APD testing:

Each eligible participant will undergo a test of auditory processing.
The *APD Test Battery* consists of four sub-tests administered to the participant via headphones or insert ear phones:

Subtest 1 Compressed and Reverberated AB Words: The participant is asked to repeat stimulus words that sound muffled (low-pass filtered).

Subtest 2 Dichotic Digits Tests: The participant is asked to repeat numbers that are presented simultaneously to each ear.

Subtest 3 Random Gap Detection: The participant is asked to listen to a series of beeps and to say how many beeps were heard in each series.

Subtest 4: Frequency Pattern Sequence Test: The participant is asked to repeat the pitch pattern of a number of sets each consisting of three beeps.
Time required: 45 minutes.

The above outlined procedure comprises the standard APD assessment protocol at the University Speech and Hearing Clinic. In addition, for the purpose of the current research study, the following additional tests will be administered:

SCAN-C (A test for Auditory Processing Disorders in Children – Revised (Keith 2000):
The commercially designed SCAN-C test subtest 1 will be administered to the participant via headphones or insert ear phones:
Subtest 1 of SCAN-C: Filtered Words: The child is asked to repeat stimulus words that sound muffled (low-pass filtered).

Time required: 10 minutes.

UCAST Adaptive filtered words test:
Each child will be seated in front of a computer. The child will wear supra aural headphones. Recordings of words of varying intelligibility will be presented verbally to the child through the headphones. As each word is presented acoustically, four pictures will be presented visually on a computer display, one of which will match the acoustically presented word. The task for the child is to choose the image that they think matches the acoustically presented word, using a computer mouse to select the word on the computer display or a touch screen. This procedure will repeat itself until the child's threshold is established. A practice session will precede the actual testing to help familiarise the child with the task.
Time required: 10-15 minutes.

TEST RESULTS
Test results will be verbally communicated to the parent after the completion of the tests. If applicable, a follow-up appointment will be made at no charge and appropriate referrals will be made. A comprehensive written report will be provided to all participants.

TEACHER QUESTIONNAIRE
To complement the interpretation of the test results information about your child's listening and related behaviours in the classroom environment may be obtained from his/her teacher in form of a questionnaire.

WITHDRAWAL & CONFIDENTIALITY
Your child has the right to withdraw from the project at any time, including withdrawal of any information provided.

The results of the project may be published, but your child is assured of the complete confidentiality of data gathered in this investigation: the identity of your child will not be made public without their consent. To ensure anonymity and confidentiality, the information gathered will be assigned a code number and all identifiable information removed. Data will be kept in a locked filing cabinet within a lockable room in the Department of Communication Disorders.

The project is being carried out as a requirement for a Masters of Audiology by Uta Heidtke, under the supervision of Dr. Natalie Rickard, who can be contacted at the University of Canterbury on +64 3 364 2987 ext. 3052. We will be pleased to discuss any concerns you may have about participation in the project.

The project has been reviewed ***and approved*** by the University of Canterbury Human Ethics Committee.

Uta Heidtke
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Appendix III: Project Information Sheet for Children

University of Canterbury

Department of Communication Disorders

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Diagnosis of Auditory Processing Disorder (APD) using an adaptive filtered words test.

PROJECT INFORMATION SHEET FOR CHILDREN

You are invited to help with a research project at the university.

What is this project for?

This project tries to find a better way of testing children who have difficulties with learning and understanding in school and at home. We want to find out why these children find it harder than other children to listen and learn so that we can help them.

What do I need to do?

You will be asked to do all sorts of listening activities. Depending on the activity you will hear some beeps, sounds or words. As you listen to these sounds we will ask you to push a button, repeat what you have heard or touch a special computer screen so that we know that you have heard the sound.

Before each new listening activity we will explain to you how it works. You can also ask questions and you get time to practice. The listening activities are not difficult – all you need to do is listening carefully.

Before we start you will have your ears looked at with a special torch. This is called otoscopy. We will also play a sound to your ear that checks your ears. This test is called tympanometry. Don't worry; it won't hurt at all!

Will someone from my family be there with me?

Yes. Someone from your family will stay with you the whole time.

Where do I have to come to?

Your parents will take you to the hearing clinic at the university. You will be seated in a comfortable room that is especially designed for testing someone's hearing. It is called a sound treated room.

How long does it take?

It will take about 2 ½ - 3 hours with some breaks in between.

At the end you will be given a small gift because we would like to thank you for helping us.

Appendix IV: Parent Consent Form

University of Canterbury

Department of Communication Disorders

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Parent Consent Form

TITLE OF RESEARCH:

Diagnosis of Auditory Processing Disorder (APD) using an adaptive filtered words test

Research Student: Uta Heidtke

Supervisor: Dr. Natalie Rickard

Co-supervisor: Dr. Greg O'Beirne

My child has been asked to participate in a research study to design a more efficient and sensitive test for the diagnosis of auditory processing disorder in children using an adaptive testing procedure.

I have been supplied with an information sheet outlining the details of the above named project, and the requirements of my child in this research study. I have read, and understood the requirements as described on the information sheet for the above-named project.

On this basis, I provide consent for my child to participate in this research project. I provide consent for the results of this research study to be published or presented publicly, provided my child’s identity is kept confidential and anonymity is preserved.

I understand that my child is free to discontinue participation in this project, and I am free to withdraw my consent at any time, without prejudice against further care that they may receive at this institution. This includes the withdrawal of any information my child or myself have supplied.

NAME OF PARENT:

NAME OF CHILD:

SIGNATURE OF PARENT:

DATED:

Appendix V: Child's Consent Form

University of Canterbury

Department of Communication Disorders

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Child's Consent Form

TITLE OF RESEARCH:

Diagnosis of Auditory Processing Disorder (APD) using an adaptive filtered words test

Research Student: Uta Heidtke

Supervisor: Dr. Natalie Rickard

Co-Supervisor: Dr. Greg O'Beirne

I have been asked to help in a project to help identify a learning problem. My parents have told me about the project. I understand how I will be helping. I would like to help with this project. If I do not want to help with the project at any stage, I understand I can stop helping with the project.

I understand that this project might be put in a book for other people to read. I understand that my name will not be in that book. I understand that information about who I am will be kept secret.

NAME:

SIGNATURE:

NAME OF PARENT *(if applicable)*:

SIGNATURE OF PARENT ON BEHALF OF CHILD *(if applicable)*:

DATE:

Appendix VI: Parent Questionnaire

University of Canterbury

Department of Communication Disorders

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Parent Questionnaire

The following information will help us in assessing your child. Please complete as much of the following information as you can and bring the completed form to your appointment.

Name of Child:……………………………….…….. DOB………… Age……..

Developmental History

Were there complications during or after your child's birth including abnormalities present at birth (hyperbilirubinemia)? Yes / No

If yes, describe:

Were there delays in your child's development including walking? Yes / No

If yes, describe:

Does your child or anyone in the family have a history of learning problems or difficulty in school achievement? Yes / No

If yes, describe including their reading & spelling ability:

Has your child completed an educational assessment? Yes / No

If yes, where & when:

Results

Are there delays in your child's speech & language development? Yes / No

If yes, describe:

Has your child had a speech and language evaluation? Yes / No

If yes, where & when:

Results

Has your child had any serious illnesses or accidents including neurological problems, psychological disorders, head trauma or injury? Yes / No

Has your child had a psychological evaluation? Yes / No

If yes, where & when:

Results:

Does your child require any medications? Yes / No

If yes, describe:

Otologic History

Has your child ever had his/her hearing tested by an audiologist? Yes / No

If yes, where & when:

Results:

How many ear problems has your child had? (Circle)

None 1-2 3-5 6-10 10 or more

Has your child had an ear problem in the last 6 months? Yes / No

Does your child have any of the following? (Please circle)

frequent runny nose frequent colds or sinus infections

Allergies ringing or buzzing in the ear

Dizziness

Has your child ever been seen by an Ear, Nose & Throat (ENT) doctor? Yes / No

If yes, where & when:

Listening and Understanding

Does your child show any of the following behaviours?

Sensitive to loud sounds? Yes / No

If yes, describe:

Appears to be confused / upset in noisy or new places? Yes / No

If yes, describe:

Often misunderstands words that sound similar? Yes / No

If yes, describe:

Have difficulty hearing in noisy situations, i.e if others are talking at the same time or if there is noise in the background? Yes / No

If yes, describe:

Have trouble locating where sounds are coming from? Yes / No

If yes, describe:

Frequently asks for repetition or says "huh or what" often? Yes / No

If yes, describe:

Frequently says "I don't know" or "I don't get it"? Yes / No

If yes, describe:

Have trouble understanding people who talk fast or in an accent? Yes / No

If yes, describe:

Responds to questions inappropriately or inconsistently? Yes / No

If yes, describe:

Difficulty detecting humour or sarcasm in remarks? Yes / No

If yes, describe:

Talk in a flat or monotone voice when reading? Yes / No

If yes, describe:

Difficulty using of prosodic cues (rhymes, stress) Yes / No

If yes, describe:

Trouble understanding nonverbal cues (facial expressions)? Yes / No

If yes, describe:

Difficulty following multiple instructions or directions? Yes / No

If yes, describe:

Behaviour & Skills

Reverses numbers or letters? Yes / No

If yes, describe:

Poor musical ability? Yes / No

If yes, describe:

Poor art skills? Yes / No

If yes, describe:

Easily distracted by other events occurring in the background? Yes / No

If yes, describe:

Problems paying attention or keeping their mind on the task or teacher? Yes / No

If yes, describe:

Difficulty taking notes in class? Yes / No

If yes, describe:

Poor organizational skills? Yes / No

If yes, describe:

Poor behaviour control? Yes / No

If yes, describe:

Poor social skills and peer relationships? Yes / No

If yes, describe:

Poor self-esteem? Yes / No

If yes, describe:

Problems with space perception/coordination? Yes / No

If yes, describe:

Any other comments? Yes / No

If yes, please specify

This form has been completed by ……………………………………..

Date……………………………..

Appendix VII: Teacher Questionnaire

University of Canterbury

Department of Communication Disorders

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

University of Canterbury

Department of Communication Disorders

Speech and Hearing Clinic

Private Bag 4800

Christchurch 8140 New Zealand

Phone: +64 3 364 2431

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Teacher Questionnaire

Child's Name:___________________________________

Date of Birth:____________________________________

Dear Teacher,

The above child has been identified in our clinic as having specific listening difficulties, referred to as Auditory Processing Disorder (APD). As part of this child's assessment, we would appreciate some information regarding his/her listening and related behaviours in the classroom environment. If you could please complete the questionnaire below, it would greatly assist us in assessing this child.

Answer all questions by comparing this child to other children of similar age and background. Do not answer the question based only on the difficulty of the listening condition. For example, all children, to a certain extent, may not hear and understand when listening in a noisy room. That is, this would be a difficult listening condition for all children. However, some children may have more difficulty in this listening condition than others. You should judge whether or not this child has MORE difficulty than other children in each listening condition cited. Please make your judgement using the following response choices: (CIRCLE a number for each item.)

RESPONSE CHOICES	
LESS DIFFICULTY	+1
SAME AMOUNT OF DIFFICULTY	0
SLIGHTLY MORE DIFFICULTY	-1
MORE DIFFICULTY	-2
CONSIDERABLY MORE DIFFICULTY	-3
SIGNIFICANTLY MORE DIFFICULTY	-4
CANNOT FUNCTION AT ALL	-5

Listening Condition = NOISE:

If listening in a room where there is background noise such as a TV set, music, others talking, children playing, etc., this child has difficulty hearing and understanding (compared with other children of similar age and background).

When paying attention	+1	0	-1	-2	-3	-4	-5
When being asked a question	+1	0	-1	-2	-3	-4	-5
When being given simple instructions	+1	0	-1	-2	-3	-4	-5
When being given complicated, multiple, instructions	+1	0	-1	-2	-3	-4	-5
When not paying attention	+1	0	-1	-2	-3	-4	-5
When involved with other activities, i.e., colouring,etc	+1	0	-1	-2	-3	-4	-5

When listening with a group of children	+1	0	-1	-2	-3	-4	-5

Listening Condition = QUIET:

If listening in a room (others may be present, but are being quiet), this child has difficulty hearing and understanding (compared with other children of similar age and background).

When paying attention	+1	0	-1	-2	-3	-4	-5
When being asked a question	+1	0	-1	-2	-3	-4	-5
When being given simple instructions	+1	0	-1	-2	-3	-4	-5
When being given complicated, multiple, instructions	+1	0	-1	-2	-3	-4	-5
When not paying attention	+1	0	-1	-2	-3	-4	-5
When involved with other activities, i.e., colouring,etc	+1	0	-1	-2	-3	-4	-5
When listening with a group of children	+1	0	-1	-2	-3	-4	-5

Listening Condition = IDEAL:

If listening in a quiet room, no distractions, face-to-face, and with good eye contact, this child has difficulty hearing and understanding (compared with other children of similar age and background).

When being asked a question	+1	0	-1	-2	-3	-4	-5
When being given simple instructions	+1	0	-1	-2	-3	-4	-5
When being given complicated, multiple, instructions	+1	0	-1	-2	-3	-4	-5

Listening Condition = MULTIPLE INPUTS:

When, in addition to listening, there is also some other form of input (i.e., visual, tactile, etc.), this child has difficulty hearing and understanding (compared with other children of similar age and background).

When listening and watching the speaker's face	+1	0	-1	-2	-3	-4	-5
When listening and reading material that is also being read out aloud by another	+1	0	-1	-2	-3	-4	-5
When listening and watching someone provide an illustration such as a model, drawing, information on the chalkboard, etc.	+1	0	-1	-2	-3	-4	-5

Listening Condition = AUDITORY MEMORY/ SEQUENCING:

If required to recall spoken information, this child has difficulty (compared with other children of similar age and background).

Immediately recalling information such as a word, word spelling, numbers, etc.	+1	0	-1	-2	-3	-4	-5
Immediately recalling simple instructions	+1	0	-1	-2	-3	-4	-5
Immediately recalling multiple instructions	+1	0	-1	-2	-3	-4	-5
Not only recalling information, but also the *order* or *sequence* of the information	+1	0	-1	-2	-3	-4	-5
When delayed recollection (1 hour or more) of words, word spelling, numbers, etc, is required	+1	0	-1	-2	-3	-4	-5
When delayed recollection (1 hour or more) of simple instructions is required	+1	0	-1	-2	-3	-4	-5
When delayed recollection (1 hour or more) of multiple instructions is required	+1	0	-1	-2	-3	-4	-5
When delayed recollection (24 hours or more) is required	+1	0	-1	-2	-3	-4	-5

Listening Condition = AUDITORY ATTENTION SPAN:

If extended periods of listening are required, this child has difficulty paying attention that is being attentive to what is being said (compared with other children of similar age and background).

When the listening time is less than 5 minutes.	+1	0	-1	-2	-3	-4	-5
When the listening time is 5 to 10 minutes.	+1	0	-1	-2	-3	-4	-5
When the listening time is over 10 minutes.	+1	0	-1	-2	-3	-4	-5
When the listening is in a quiet room	+1	0	-1	-2	-3	-4	-5
When the listening is in a noisy room	+1	0	-1	-2	-3	-4	-5
When listening first thing in the morning	+1	0	-1	-2	-3	-4	-5
When listening near the end of the day	+1	0	-1	-2	-3	-4	-5
When listening in a room where there are also visual distractions	+1	0	-1	-2	-3	-4	-5

Thank you for your time and co-operation. Please return your questionnaires to the child's parents for return to our clinic.

Regards,

Natalie Rickard, PhD
Senior Lecturer
Department of Communication Disorders
University of Canterbury

Appendix VIII: Track Sheet

Name:……………………………………………………………

Listening Task Challenge

There are 8 different listening tasks to be done. After each one collect a ‘tick’.

When you have collected all 8 ‘ticks’ you will get a gift.

☐ Task 1

☐ Task 2

☐ Task 3

☐ Task 4

☐ Task 5

☐ Task 6

☐ Task 7

☐ Task 8

COLLECT YOUR GIFT

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