Initial submission date: 30th November, 2011

Revisions submitted: 11th January, 2012

Development of an adaptive low-pass filtered speech test for the identification of auditory processing disorders

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ABSTRACT

Objective: One type of test commonly used to examine auditory processing disorders (APD) is the low-pass filtered speech test (LPFST), of which there are various versions. In LPFSTs, a monaural, low-redundancy speech sample is distorted by using filtering to modify its frequency content. Due to the richness of the neural pathways in the auditory system and the redundancy of acoustic information in spoken language, a normal listener is able to recognize speech even when parts of the signal are missing, whereas this ability is often impaired in listeners with APD. One limitation of the various versions of the LPFST 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. The purpose of this study was to counter these effects by modifying the LPFST using a computer-based adaptive procedure, and to evaluate the performance of normal-hearing participants of varying ages on the test.

Methods: In this preliminary study, 33 adults and 30 children (aged 8 to 11 years) with no known history of listening difficulties were tested. The University of Canterbury Adaptive Speech Test (UCAST) platform was used to administer a four-alternative forced-choice adaptive test that altered a low-pass filter (LPF) to track the corner frequency at which participants correctly identified a certain percentage of the word stimuli.

Results: Findings on the University of Canterbury Adaptive Speech Test – Filtered Words (UCAST-FW) indicated a significant maturational effect. Adult participants performed significantly better on the UCAST-FW in comparison to the child participants. The UCAST-FW test was reliable over repeated administrations.

Conclusions: An adaptive low-pass filtered speech test such as the UCAST-FW is sensitive to maturational changes in auditory processing ability.

Key Words: Audiology; Auditory Processing Disorder; Speech Perception; Hearing Disorders; Speech Acoustics; Algorithms

INTRODUCTION

Auditory processing refers to the neural processing of auditory stimuli in the central nervous system [1]. In line with position statements from both the American Speech-Language-Hearing Association and the British Society of Audiology, Auditory Processing Disorder (APD) is conceptualised as a condition which has its origins in impaired neural function, and is characterised by poor perception of both speech and non-speech sounds which is not attributable to intellectual impairment or peripheral hearing loss [1,2].

APD has been described in adults, e.g. [3] and children, e.g. [4,5,6]. The prevalence of APD has not yet been firmly established, reflecting the lack of consensus regarding the current criteria for assessment and diagnosis of APD. Nonetheless it is estimated that 23% of older adults [7] and 70% of adults over the age of 60 in the clinical population have some form of APD [7,8]. In the paediatric population, the estimated prevalence rate of APD is approximately 2 to 3% [9].

An important step towards effective identification and treatment of individuals with APD is to develop improved methods of assessing listening skills and differentially diagnosing APD. However, APD is a heterogenous disorder and presentation varies widely across individuals. No single test is sufficient in scope to adequately challenge the variety of functions of the auditory system [10]. Thus, assessment and diagnosis of APD typically involves a test battery consisting of a variety of sub-tests each presumed to examine the integrity of different underlying auditory processes.

One category of tests commonly used to examine auditory processing skills is the monaural, low-pass filtered speech test (LPFST), whereby a speech signal is distorted by using filtering to modify its frequency content, e.g. [11,12,13]. Due to the richness of the auditory neural pathways and the redundancy of acoustic information in spoken language, a normal listener is able to comprehend speech even when parts of the signal are missing [14,15]. This ability is often impaired in listeners with APD [14], presumably reflecting an underlying central auditory nervous system dysfunction. Reduced performance on a filtered words test may therefore indicate the presence of APD [12,16,17].

There are at least three test batteries currently commercially available that include a LPFST [11,12,13,18] and several studies have supported the use of LPFSTs in the diagnosis of APD in children [12,16,17,19,20]. The difficulty of a LPFST depends on both the specific frequency at which the filter is applied and the rejection rate of the filter - as both affect the degree with which the speech signal is distorted [21,22]. A filtering condition that clearly differentiates between listeners with and without APD is the most desirable, however the different versions of LPFSTs currently available have varied greatly in their filter cut-off frequency [21,23], i.e. the corner frequency at which the low-pass filter is implemented. While some research has compared the effect of different cut-off frequencies [23], few studies have systematically investigated the most effective filter cut-off frequency for clearly differentiating between individuals with and without APD.

Furthermore, a major limitation of these commercially available tests is that they are carried out using a constant level of low-pass filtering, and, like any method-of-constant-stimuli test, are therefore vulnerable to ceiling and floor effects [23]. That is, if the low-pass filter is set too low, the test may prove too difficult for normal children; if the filter is set too high, children with APD will perform within the normal range – in either situation, the two groups are poorly discriminated from one another [24]. Accordingly, the efficacy and sensitivity of this category of tests has been questioned [25].

These limitations can be avoided by using an adaptive testing procedure. An adaptive procedure is a method in which the subsequent presentation of a test item is determined by the subject's responses to the preceding test items [26,27,28]. In the case of low-pass filtered speech testing, an adaptive procedure measures the corner frequency at which an individual correctly identifies a predetermined percent-correct point on a response curve, instead of generating a percentage correct score at a specific low-pass filter level. Consequently, adaptive testing results in the presentation of stimuli that are neither too difficult nor too easy for an individual participant. Because the threshold level is determined by the listener's performance, there is no need to predetermine an optimal fixed presentation level [29]. The adaptive procedure is also very efficient [28], as it quickly eliminates measurements taken far from an individual's threshold. Greater efficiency generates more accurate results, as the test becomes less susceptible to variables such as attention span, fatigue, and motivation [26,27,28,29,30].

The purpose of this preliminary study was to determine whether an adaptive computerised version of a low-pass filtered speech test would produce results that were reliable over repeated administrations of the measure; and to compare the performance of younger and older participants.

METHODS

Participants: 33 adult participants (mean age 28.5 ± 9.4 years) and 30 child participants (mean age 10.1 ± 1.0 years) participated in the study. Each participant was required to be free of known motor skill problems and had passed a pure-tone air-conduction screening test at 15 dB HL at octave intervals of 500 Hz through 4000 Hz. All child participants had passed either i) the SCAN-C screening test for APD or ii) a full APD test battery performed at the University of Canterbury Speech and Hearing Clinic. No attempt was made to control for gender throughout this study, as previous studies [13,31] suggested similar outcomes for males and females on tests of auditory processing. The male:female ratio was 1.7:1 and 2.2:1 for the child and adult participants, respectively. All protocols were approved by the University of Canterbury Human Ethics Committee (HEC Approval No. 2006/32).

Stimulus delivery: Recordings of the Northwestern University Children's Perception of Speech (NU-CHIPS) test [32] were taken from "Speech Recognition Materials" CD 1 (National Acoustic Laboratories, Chatswood, NSW, Australia). Stimulus delivery was controlled by UCAST software developed by one of the authors (G.O'B.) using LabVIEW 8.0 to 8.20 (National Instruments, TX, USA). The stimulus word was presented monaurally to the participant just prior to four test alternatives being displayed on the monitor in written form (see Figure 1). Participants selected the visually displayed test item that corresponded to the word presented acoustically. Presentation order of the 200 test items and screen location of the four alternatives were both randomised. Sound output from the PC was attenuated to 60 dB HL by an audiometer (either a GSI-61 audiometer, Grason-Stadler Corp., USA, or CE10 Clinical Hearing Evaluator, Interacoustics Corp, Denmark) and delivered by Telephonics TDH-39P supra-aural headphones in MX 41/AR cushions. The peak level of the stimulus file was normalised with each presentation to partially compensate for the effect of the low-pass filtering. The average ambient sound level in the test environment was less than 40 dB A.

Test procedure: Using the Monosyllabic Adaptive Speech Test (MAST) of Mackie and Dermody [29] as a starting point, we implemented a 4AFC procedure using NU-CHIPS test items. The first test item was low-pass filtered at 1 kHz using a very steep 32nd order Butterworth filter. The starting low-pass filter (LPF) corner frequency was selected based on a preliminary study exploring optimal parameter configurations [33]. Participants responded via an Elo ET1715L touch screen (Tyco Electronics Corp., USA).

INSERT FIGURE 1 ABOUT HERE

The LPF corner frequency for subsequent test items was determined by the adaptive algorithms. The 50% correct target was tracked using a simple 1-up-1-down method. Because adaptive procedures that track higher target levels have been found to produce less variable threshold estimates [34], the 70.7% correct target was also tracked, in this case using the 1-up-2-down transformed response method [26]. Two different step size variations, referred to as *initial* and *working* increments/decrements were employed. The initial step size of 12.5% of filter frequency reduced to 5% of filter frequency after the first 3 reversals (that is, a transition from an incorrect to a correct response, or vice versa). Again, these values were selected based on preliminary data [33]. The larger initial steps meant that the threshold was approached more rapidly, while the smaller working steps helped determine the threshold more precisely. The test was stopped after 13 reversals at the working increment, and the threshold was calculated as the average of the mid-points of these reversals. An example adaptive track for an adult participant is shown in Figure 2.

INSERT FIGURE 2 ABOUT HERE

A binaural 'practice run' in which the 50% threshold was tracked was administered first. 70.7% thresholds were then established for the right and left ears monaurally, followed by 50% thresholds for those ears. The 70.7% thresholds were re-established following an interval of 1 week and this set of data from the second monaural presentations was used in the analyses shown in Figures 3 and 5 below.

RESULTS

There was no significant ear difference between the 70.7% thresholds obtained at the second presentation of the test for either adults or children; nor was there a difference between the right and left ear 50% thresholds obtained in either adults or children. The data from the two ears was averaged to produce a mean 50% and 70.7% threshold for both children and adults for the purpose of displaying this data graphically in Figure 3.

INSERT TABLE 1 ABOUT HERE

INSERT FIGURE 3 ABOUT HERE

As illustrated in Figure 3, there was a significant ($p < 0.05$) difference in the LPF corner frequencies at which children and adult participants scored either 50% or 70.7% correct, with adults achieving an average score of 50% when stimuli were low-pass filtered at 438 ± 118 Hz (compared to 679 ± 185 Hz for children), and a score of 70.7% when stimuli were low-pass filtered at 682 ± 157 Hz (compared to 988 ± 224 Hz for children).

The test-retest reliability of the 70.7% task was also assessed for both adult and child participants. To counter any learning effects on the UCAST-FW (that is, an improvement in score with increased experience using the test), a binaurally presented 'practice run' was administered to familiarise participants with the task prior to the collection of the monaural data. Despite the incorporation of this binaural practice run, child participants showed a significant improvement in performance between the first and second monaural trials (paired t-test, $p<0.001$), as shown in Figure 4. Adult participants showed no such learning effect. The test-retest reliability for child participants in this study was moderate once performance had reached a plateau (i.e. beyond the first trial).

INSERT FIGURE 4 ABOUT HERE

The distribution of LPF corner frequencies as a function of age is shown in Figure 5. The performance of the child participants (aged 8.2 to 11.9 years) tended to improve with age, with the LPF corner frequencies at which they scored either 50% or 70.7% decreasing by around 5.3% per year. In contrast, the performance of the adult participants (aged 18 to 55 years) slowly deteriorated with age, with LPF corner frequencies increasing at about 0.9% per year.

INSERT FIGURE 5 ABOUT HERE

The mean 70.7% thresholds for 8 year old children were significantly higher (two tailed t-test, p = 0.0241) than those for children aged 11, indicating better test performance with increasing maturity during childhood. The reverse trend was noted in the adult cohort, with the 70.7% thresholds for adults over 35 years of age being significantly higher, that is, poorer (two tailed t-test, p = 0.0238) than for adults under 35 years. As shown in Table 2, the general improvement in performance with increasing age up to the 17-34 years age group, and the subsequent decline in performance in the over 35 years group, was associated with a similar trend in variability of score, as indicated by standard deviation size.

INSERT TABLE 2 ABOUT HERE

DISCUSSION

The purpose of the present study was to develop a computer-based, adaptive version of a low-pass filtered words test, the UCAST-FW, and to evaluate the performance of normal-hearing participants of varying ages on the test. The UCAST-FW showed high test-retest reliability in adults, and moderate reliability in children once the initial learning effect had reached a plateau. This result suggests the need for a longer practice session prior to test administration in children to provide sufficient familiarity with the test material and format, and to therefore establish a plateau of performance that gives an accurate indication of their low-pass filter thresholds.

Although it is largely recognised that a broad frequency region of about 125 to 8000 Hz is important for speech recognition [35], Figure 3 shows that both adult and child participants required only a small portion of the speech spectrum to be audible to obtain percentage correct scores of 50% and 70.7%. As with previous studies [36,37,38], a relationship was evident between reduced spectral bandwidth and speech intelligibility, i.e., both the adult and child participants required more spectral content to be present to obtain a 70.7% correct score than they required for a 50% score. However, as shown in Figure 3, the performance of adults was superior to that of children, for both the 50% and 70.7% trials. That is, adults required less of the speech spectrum to be audible than children to correctly identify the same percentage of words. In fact, the low-pass filter corner frequency at which adults scored 71% correct is approximately equivalent to the frequency at which child participants scored 50% correct, for both left and right ears. This may reflect an improvement in so-called 'bottom-up' auditory processing skills with maturity, and/or in 'top-down' language or other cognitive skills. These top-down factors include prior familiarity with accent, vocabulary and the rules of language, prior knowledge of a topic and knowledge of the phonemic aspects of speech [14]. For example, Flexer [39] suggested that children listen to degraded signals differently to adults, as they do not possess the same degree of life and language experience to allow them to 'fill in' missing information, an ability referred to as auditory closure. Children, with their less well developed auditory closure abilities, require more complete, detailed auditory or acoustic information compared to adults in order to comprehend a message [39].

These top-down factors were controlled for as much as possible in the present study. The stimuli used (the Australian recording of the NU-CHIPS word lists) were recorded in an accent not too dissimilar to the New Zealand English accent, and were designed to be appropriate to the vocabulary of children as young as three years of age. In addition, stimuli consisted of individual words, minimising the influence of general world knowledge and syntactic abilities on test performance.

Thus, performance on the UCAST-FW is likely to be largely reflective of an individual's ability to make use of the limited amount of phonemic information available in the distorted acoustic signal. In the present study, children clearly required more of that phonemic information to be present, in other words, a greater speech bandwidth, in order to correctly identify the target word compared to adult participants. This is consistent with previous studies comparing the performance of adults with children on low-pass filtered words tests [23].

A comparison between 8 and 11 year old children showed a general improvement in performance with age, which is consistent with suggestions that neuromaturation of some portions of the auditory system may not be complete until age twelve or later [40,41]. A similar improvement in performance with age (from 6 - 10 years) was reported by Willeford for his fixed 500 Hz low-pass filtered speech test [42].

We found an associated decrease in variability of score with age, consistent with the findings of Willeford [42] and Keith [43] who both found similar relationships between age and test score variability. In contrast, the reduced performance shown by the older adult participants (over 35 years) compared to younger adults (under 35), all of which had normal hearing below 4 kHz, suggests that at least some aspects of auditory processing may decline with age. This finding, and the use of the UCAST-FW as a test of auditory processing in older adults, warrants further investigation. While this test cannot in isolation distinguish between age-related declines in auditory processing ability and amodal cognitive function, the use of test items with spectral content almost entirely below 1 kHz does eliminate the well-documented influence of high-frequency audiometric threshold on test performance [44].

Table 1 indicates that participants achieved very similar thresholds in the left and right ears, for both the 50% and the 70.7% threshold tracks. The lack of any obvious right ear advantage in any of the participants is an interesting finding that warrants further investigation, particularly among children with known auditory processing difficulties. . The LPF corner frequency at which adult listeners achieved 50% correct was approximately 440 Hz (compared to approximately 680 Hz in children). At this very low frequency, the phonemic cues available to listeners are limited largely to prosodic cues, first formant cues from high vowels, and cues for the identification of stop consonant and nasals. Under these challenging listening conditions, one might have expected a right ear advantage to emerge, but the difference between the right and left adult 50% thresholds was not significant ($p = 0.0946$). Again, this finding warrants further investigation, to determine whether low-pass filtering can reveal a right-ear advantage, and if so, how the corner frequency of the filter correlates to the features present in the acoustic signal.

It may also be preferable to track a target level that represents the midpoint of the psychometric function, rather than the 50% or 70.7% threshold. For a four-alternative forced choice test, a target of 62.5% correct is midway between 100% correct and the chance score of 25%, and may be tracked using a weighted up-down staircase procedure (WUDR) similar to that described by Kaernbach [45].

Future studies will further refine the test, and importantly, compare the performance of children with and without auditory processing difficulties on the UCAST-FW. Given the heterogenous nature of APD, any attempt to improve our ability to characterise the precise nature of an individual's listening difficulties are warranted and have potential clinical applications. For example, should a child with listening difficulties prove to have a significantly poorer UCAST-FW score than is typical for their age, the management of that child's difficulties in the educational environment should include strategies that aim to enhance access to a greater speech bandwidth - such as the use of a personal amplification or soundfield system that boosts the high frequency components of a speech signal - in conjunction with strategies that target the child's auditory closure abilities. Moreover, the adaptive nature of the UCAST-FW enables the corner frequency at which an individual achieves a predetermined level of speech intelligibility to be determined. This provides a quantitative measure of the degree of difficulty a particular child has on the task compared to their peers, providing more specific information about that individual than would a constant-level version of a low-pass filtered words task.

Furthermore, given the age-related decline in performance among adult participants, future studies will also explore the use of the UCAST-FW in older adults with and without high frequency hearing loss, to determine the clinical applicability of the UCAST-FW as a test of auditory processing in older adults.

Summary and Conclusions:

The current study involved the design and development of an adaptive, computerised version of the traditional filtered words test – the UCAST-FW, with the aim of overcoming some of the limitations of constant-level versions of the test. The UCAST-FW was found to be reliable over repeated administrations for both adults and children, provided sufficient practice was provided to overcome an initial learning effect in children. Adults performed the task significantly better than children, consistent with the current literature on the maturation of the central auditory nervous system and auditory processing abilities. The UCAST-FW shows promise as a test of auditory processing in both children and adults. It is both quick to perform and interactive. Future studies will further refine the test, compare the performance of children with and without auditory processing difficulties, and explore the use of the UCAST-FW in older adults with and without high frequency hearing loss.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Emily Lin for her statistical advice, and Dr Sarah F. Poissant for her helpful comments.

CONFLICT OF INTEREST STATEMENT

The authors are not aware of any conflict of interest relating to this work.

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Figure 1

UCAST-FW screenshots

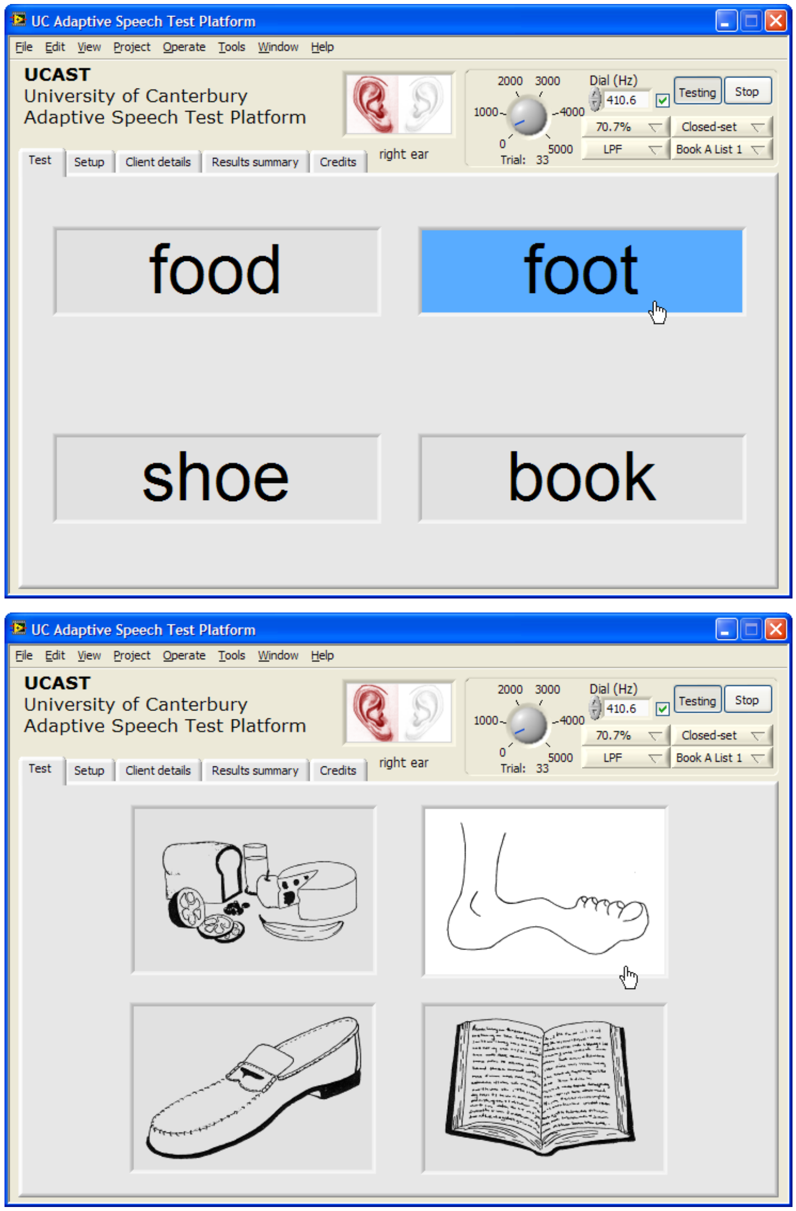

Figure 1: In this implementation of the four-alternative forced-choice (4AFC) test, participants used a touch-screen to select the word they thought they heard. The dial displaying the low-pass filter (LPF) corner frequency was hidden from view. This version of the test used written words (top), but subsequent versions incorporate pictures from the NU-CHIPS test book (bottom) to remove literacy as a confounding variable.

Figure 2

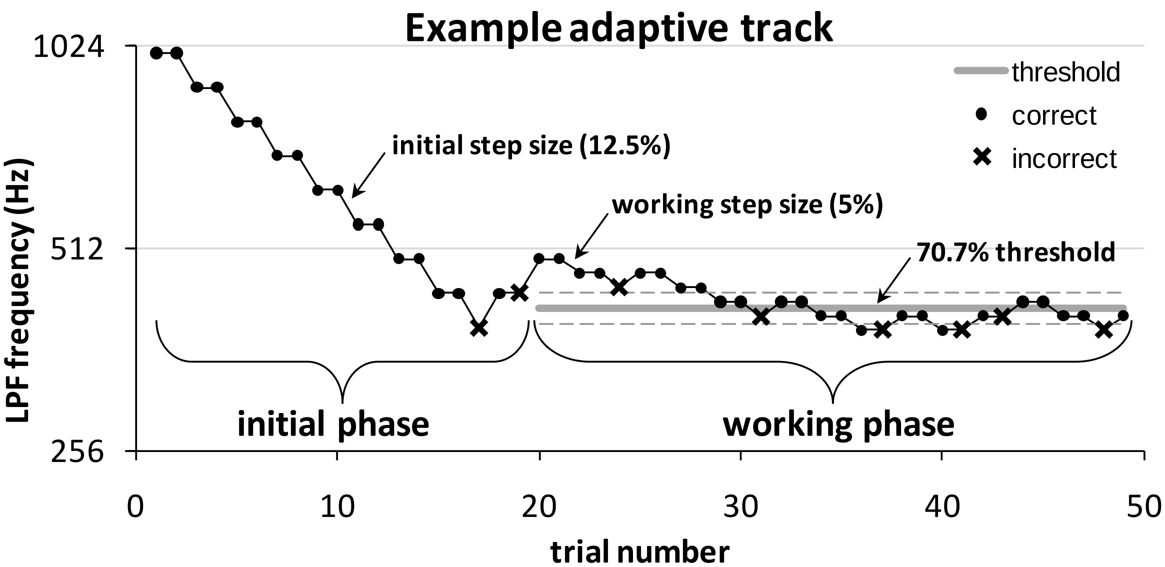

Figure 2: An example of an adaptive track for an adult participant. The 50% correct targets were tracked using a simple 1-up-1-down method, while 70.7% correct targets were tracked using the 1-up-2-down transformed response method [26]. The initial step size of 12.5% of filter frequency reduced to 5% of filter frequency after the first 3 reversals. Threshold was calculated as the average of the mid-points of the last 13 reversals. In this example, the measured 70.7% threshold of 417 Hz took 2 min 10 s (49 trials) to obtain.

Figure 3

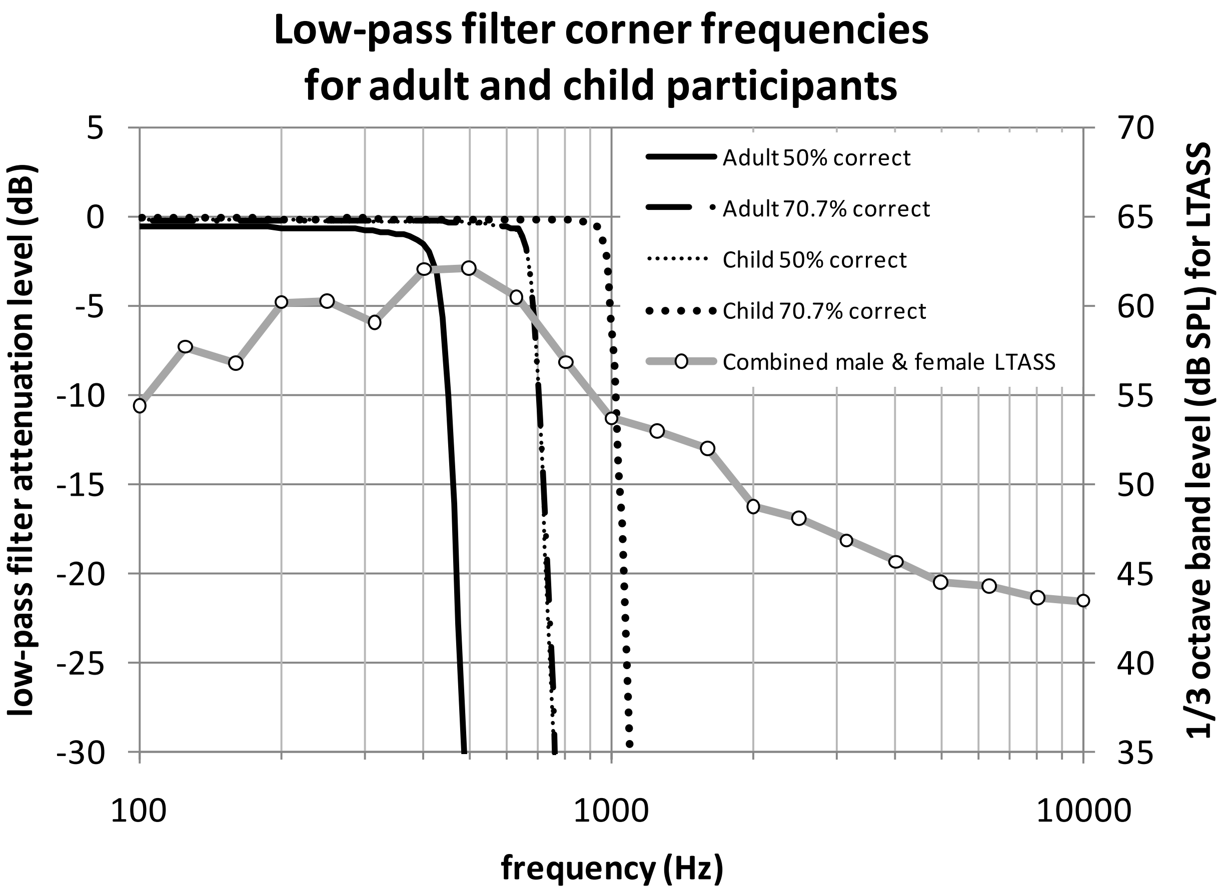

Figure 3: This figure shows the mean low-pass filter corner frequencies at which adult and child participants scored 50% and 70.7% correct. These filter functions are superimposed on the combined long-term average speech spectrum for males and females [46]. The area to the right of each filter function is removed from the speech stimuli in each condition. Adults performed better on both the 50% and 70.7% threshold tasks than children, as indicated by the larger amount of spectral information that needed to be removed from the stimuli for them to achieve those scores. Mean adult LPF corner frequencies were 438 ± 118 Hz and 682 ± 157 Hz for 50% and 70.7% respectively, compared to the child scores of 679 ± 185 Hz and 988 ± 224 Hz for 50% and 70.7%.

Figure 4

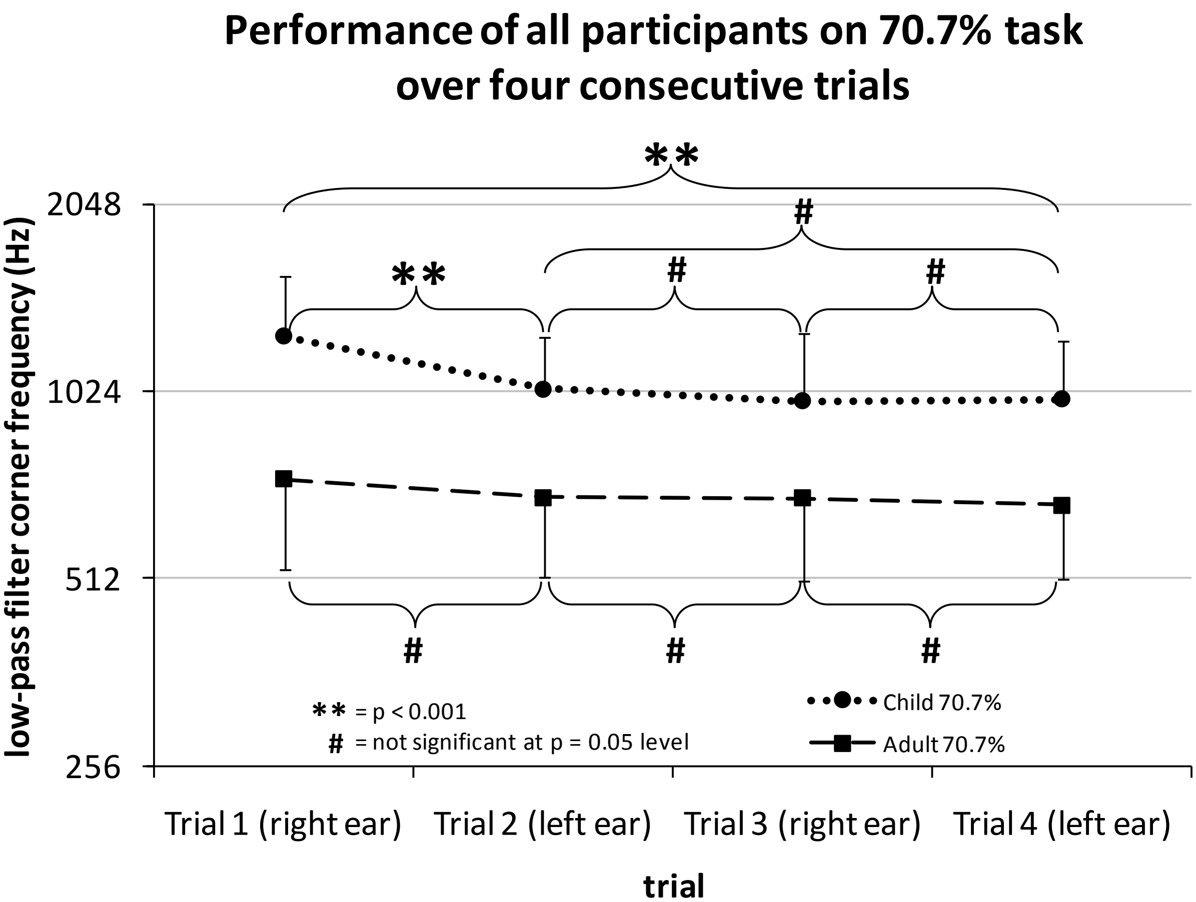

Figure 4: Means and standard deviations of 70.7% UCAST-FW threshold scores for the child and adult participants over four consecutive trials of the test. Testing was performed in two sessions, with trials 3 & 4 taking place one week following trials 1 & 2. Adult participants showed no significant learning effect across the trials, but child scores significantly improved between trials 1 and 2 (paired t-test, $p < 0.001$). There was no subsequent improvement in child scores following this initial improvement, with scores obtained at trials 2, 3 and 4 producing a plateau.

Figure 5

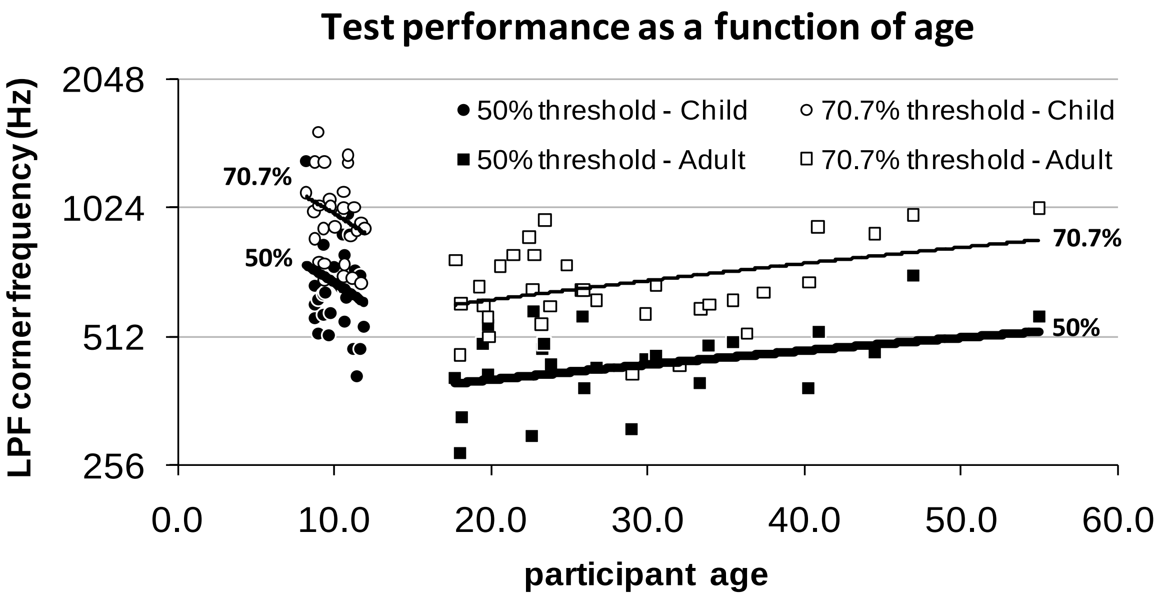

Figure 5: Test performance on the UCAST-FW plotted against the age of the participant. Data points shown are the mean of the left and right ears for each participant, for the 50% trial and the second 70.7% trial. Performance improved with increasing age in the child participants (circles), while in adults, a slight deterioration with age was evident (squares).

Table 1

		Right			Left			Monaural average	
		Mean	StDev		Mean	StDev		Mean	StDev
Adult	**50%**	411	± 115		465	± 137		438	± 118
	70.70%	690	± 181		674	± 163		682	± 157
Child	**50%**	682	± 232		676	± 167		679	± 185
	70.70%	983	± 277		994	± 243		988	± 224

Table 1: The 50% and 70.7% thresholds from the second monaural presentation of the UCAST-FW for right and left ears, and the monaural average, for both adult and child participants.

Table 2

Age group / UCAST-FW test condition	8 years	9 years	10 years	11 years	17 - 34 years	35 - 55 years
Monaural 50% (Hz)	792 (±356) *n = 4*	618 (±102) *n = 8*	739 (±134) *n = 9*	606 (±173) *n = 7*	423 (±102) *n = 20*	481(±157) *n = 7*
Monaural 71% (Hz)	1168 (±265) *n = 6*	948(±205) *n = 8*	1025 (±235) *n = 8*	865 (±128) *n = 7*	647(±131) *n = 25*	789 (±191) *n = 8*

Table 2: The mean UCAST-FW threshold scores for each age group. Values in brackets are standard deviations and all values are in Hertz.