Maturation of visual and auditory temporal processing in school aged children

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Abstract

Purpose: To examine development of sensitivity to auditory and visual temporal processes in children and the association with standardized measures of auditory processing and communication.

Methods: Normative data on tests of visual and auditory processing were collected on 18 adults and 98 6- to 10-year-olds. Auditory processes included detection of pitch from temporal cues using Iterated Rippled Noise (IRN) and frequency modulation detection (FM) at 2 Hz, 40 Hz and 240 Hz. Visual processes were coherent form and coherent motion detection. Test-retest data were gathered on 21 children.

Results: Performance on perceptual tasks improved with age, except for fine temporal processing (IRN) and coherent form perception which were relatively stable over the age range. Within-subject variability (as assessed by track width) did not account for age-related change. There was no evidence for a common temporal processing factor, and no significant associations between perceptual task performance and communication level (CCC-2) or speech-based auditory processing (SCAN-C).

Conclusions: The auditory tasks had different developmental trajectories, despite a common procedure, indicating that age-related change was not solely due to responsiveness to task demands. The 2 Hz FM task, previously used in dyslexia research, and the visual tasks had low reliability compared to other measures.

Introduction

Auditory perceptual development

The peripheral auditory system – cochlea and brainstem - matures early in life (Abdala & Sininger, 1996; Eggermont, 1988). Nevertheless, there is protracted development of complex auditory processes such as recognizing degraded speech (Palva & Jokinen, 1975) or speech in noise (Elliott, 1979), modulation detection (Hall & Grose, 1994), gap detection (Trehub, Schneider, & Henderson, 1995; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989), backward masking (Buss, Hall, Grose, & Dev, 1999; Hartley, Wright, Hogan, & Moore, 2000), masked thresholds (Allen, Wightman, Kistler, & Dolan, 1989; Schneider & Trehub, 1992), minimum audible angle (Litovsky, 1997), masking level difference (Hall, Buss, Grose, & Dev, 2004) and auditory stream segregation (Sussman, Wong, Horváth, Winkler, & Wang, in press), where performance continues to increase throughout childhood, up to adolescence in some cases (Hartley et al., 2000; Stuart, 2005).

A major question is how far such findings reflect physiological immaturity of central auditory pathways, and how far they are explained by nonsensory factors, such as poor attention or motivation, or failure to listen strategically to specific cues. The difficulties of disentangling such factors are compounded by the fact that one typically has to use many fewer trials and limited practice when doing psychophysics with young children (Werner, 1992). Even when tasks are made more 'child friendly' by the use of game-like format and adaptive procedures that require fewer trials, one cannot rule out effects of attention, motivation and strategy (Sutcliffe & Bishop, 2005; Werner, 1992).

Attention is probably the most frequently mentioned non-sensory factor. Wightman and Allen (1992) simulated the effect of general inattention on a proportion of trials and found on adaptive psychophysical tasks this resulted in higher thresholds and flatter psychometric functions which were qualitatively similar to children's actual performance. They concluded that one could not reject the possibility that non-sensory factors could account for all of the observed adult-child differences in performance.

Attention itself is not a unitary concept. Attention encompasses both the ability to selectively attend to relevant stimuli and filter out irrelevant stimuli (Broadbent, 1958; Enns & Akhtar, 1989; Pastò & Burack, 1997) as well as maintaining focus on a particular task for an extended period (Dember & Warm, 1979). As an illustration of the former aspect, consider studies by Werner and Bargones (1991) and Oh et al (2001) that examined children's pure tone signal detection with and without maskers that were spectrally separated from the target tone. Adults are able to optimize detection of a tone by listening through a single filter centered on the target tone, and adult performance of detection of tone in noise is only substantially affected by noise that falls within the same auditory filter as the tone (i.e. when the masker is in the same spectral range as the target) (eg Dai, Scharf, & Buus, 1991; Schlauch & Hafter, 1991). However, children and infants displayed high levels of masking even when the masker was in a different spectral range to the target. This suggests that children and infants have less efficient attentional strategies in that they seem to monitor output from a wide range of auditor filter outputs.

The conclusion is that attentional effects are likely to be significant in contributing to age-related change in masked threshold (Werner, 1992).

In addition, although there is evidence that at least some aspects of attention, such as inattention and impulsivity, may extend across modalities (Aylward, Brager, & Harper, 2002), other aspects of attention (involving processing beyond noticing that a stimulus has occurred) may be specific to the auditory modality (Bedi, Halperin, & Sharma, 1994; Cooley & Morris, 1990; Kupietz & Richardson, 1978). Thus, it may be that a large proportion of developmental change in auditory performance during childhood is related to changes in modality specific, selective attention to sound.

However, although attention may play a role in children's performance, others have argued that it is not the whole explanation. Schneider et al (1989) noted that inattention should affect the slope of the group psychometric function for detection of tones in noise, yet this does not change with age. Some of the age-related change in auditory thresholds may reflect neurophysiological maturation. Particularly strong evidence for prolonged maturation of the central auditory system comes from electrophysiological and neuroanatomical studies (Eggermont & Ponton, 2003). Latency and morphology of auditory ERP waveforms change substantially throughout childhood and into adolescence (Ponton, Eggermont, Kwong, & Don, 2000; Wunderlich & Cone-Wesson, 2006) along with patterns of refactoriness (Coch, Skendzel, & Neville, 2005).

Perceptual maturation and developmental disorders

Studies of central auditory maturation assume particular importance in the context of studies of developmental disorders. A range of auditory impairments including processing of brief or rapidly presented tones (Tallal, 2004; Tallal & Piercy, 1973), FM detection (Witton et al., 1998), backward masking (Wright et al., 1997) and auditory stream segregation (Helenius, Uutela, & Hari, 1999) have been associated with language and reading problems in a large body of research. It is hypothesised that a deficit in auditory processing might lead to speech perception difficulties, which in turn would have effects on the development of phonological representations and impact upon language and reading. Although highly influential, theories that attribute language and literacy problems to nonverbal auditory deficits remain controversial, in part because the proposed deficits are found only in a minority of affected children, and in part because questions remain as to whether they genuinely reflect auditory perceptual problems, or are due to nonsensory deficits that affect performance (Bailey & Snowling, 2002; McArthur & Bishop, 2001; Ramus, 2003, 2004; Roach, Edwards, & Hogben, 2004; Rosen, 1999, 2003).

The maturational aspect of central auditory processing has seldom been considered in the course of this debate, but was highlighted by Wright and Zecker (2004), who suggested that the pattern of auditory processing deficit seen in developmental disorders is related to neurodevelopmental immaturity, with some deficits persisting into adulthood if development in that area has not reached completion by the onset of puberty. Bishop and McArthur (2004) also found auditory ERP evidence that supported the idea of immature auditory processing in their study of teenagers with SLI. These two groups of researchers found that the pattern of performance on auditory tasks was dependant on a child's age, the specific task and the child's clinical status ('Language-based learning disability' or not). The critical idea here is that if a child's central auditory maturation is, say, three years behind age level, then one needs to know the trajectory of normal development on an auditory task, on order to be able to detect and interpret disordered performance.

Similar arguments have been recently proposed by researchers investigating development of visual function. Human and primate research suggests a division of the early visual system into two parallel pathways, magnocellular and parvocellular (Milner & Goodale, 1995). These are also known as form and motion, dorsal and ventral streams or 'what' and 'where' pathways. Sensitivity to form and motion can be measured psychophysically in terms of the proportion of coherent line segments or dots in a background noise that is required to detect a shape (Braddick, Atkinson, & Wattam-Bell, 2003). The line segments or dots are either all static (for form) or all in motion (for motion). The threshold of coherence required for detection of the hidden shape is taken as an index of sensitivity to visual cues of either form or motion, and the task itself is thought to tap dorsal or ventral processing. Both visual processing streams continue to develop throughout school age, with sensitivity to form reaching adult levels earlier than motion sensitivity (Parrish, Giaschi, Boden, & Dougherty, 2005). Research in a variety of pediatric disorders also suggests that the later-maturing magnocellular pathway is more vulnerable to disruption than the parvocellular system, or that there is 'dorsal stream vulnerability' (Braddick et al., 2003).

These parallels between visual and auditory systems have led some to propose a general account of dyslexia and related disorders in terms of a temporal processing deficit that affects both visual and auditory systems (e.g. Stein, 2001). In support of this, Witton and colleagues (1998) found higher thresholds for 2 Hz and 40 Hz FM as well as visual motion thresholds in children with dyslexia. Talcott and colleagues (Talcott et al., 2002; Talcott et al., 2000) then found that FM sensitivity related to reading skill in two samples of unselected children. Visual motion sensitivity explained independent variance in orthographic skill but not phonological ability while auditory FM sensitivity covaried with phonological skill but not orthographic skill. Finally, Witton and colleagues (2002) found that adults with a history of dyslexia were less sensitive to 2 Hz FM and 20 Hz AM, and that these tasks were also significant predictors of reading skill for their sample of both normal reading adults and those with a history of dyslexia. However, others have argued that auditory and visual temporal processing tasks do not cluster coherently, and that deficits on these tasks may be due to attentional factors and problems with task demands, rather than reflecting impaired magnocellular function (Gibson, Hogben, & Fletcher, 2006).

However, another possible explanation for discrepant findings is that children suffer from a maturational lag in temporal processing. If this hypothesis is correct, performance of children with language or reading disorders should match that of typically developing children 2-4 years younger on temporal processing tasks; significant differences from an age-matched control group would be apparent only on tasks that have a long developmental trajectory. Currently, however, there is a dearth of information on normal development on the temporal processing tasks that are used in the study of disorders.

Hypotheses and aims

The first aim of this study was to characterise the development of performance on temporal processing tasks in the auditory and visual modalities in children aged 6 to 10 years as well as adults, and to assess retest reliability. We focused predominantly on those tasks that have been used in the study of language and reading disorders, namely FM detection in the auditory modality and coherent motion detection in the visual modality. In addition, we used one non-temporal auditory task (detection of FM at 240 Hz, see below) and one non-temporal visual task (coherent form detection). We also used a new auditory temporal task, detection of pitch in iterated rippled noise (IRN). For the auditory tasks we examined within-subject and within-group variability in thresholds as well as mean thresholds, to test the hypothesis that fluctuating attention might account for age-related differences in thresholds.

As well as documenting developmental trends, we were interested in testing the hypothesis that processing of dynamic stimuli relies on common mechanisms in visual and auditory modalities (Stein, 2001; Witton et al., 1998); if this were so, one might expect development of sensitivity to dynamic visual and auditory stimuli to be associated. Thus the second aim of this study was to establish whether thresholds on auditory tasks were independent of those on visual tasks. Finally, it has been suggested that that for some children, poor processing of dynamic auditory stimuli could impact upon speech perception with knock-on effects on language and literacy (Tallal, 2000; Witton et al., 1998). If auditory development underlies speech perception and language development, one might expect correlation between auditory psychophysical performance and speech-based measures of auditory processing and communicative ability. A final aim of this study was to relate performance on perceptual tasks to a widely used speech-based clinical measure of auditory processing, the SCAN-C, and also to a measure of communication skills, the CCC-2.

Methods

Participants

Local schools were approached to help recruit children with normal hearing. The goal was to recruit 20 children per year band from 6 to 10 years with approximately equal numbers of boys and girls in each group. This was achieved for all age groups except 6 year olds ($N = 18$). 18 adults were also tested. For children, testing was carried out at school in a specially outfitted testing van with a sound attenuating cabin. Adults were tested in a quiet room. All participants had normal hearing as indicated by pure-tone audiometric screening test (at 20dB HL).

Assessments

Experimental Tests of Auditory Processing

Apparatus

Tones were presented by a laptop computer (Dell Latitude D505) via Sennheiser HD600 headphones.

Stimuli

Three temporal processing subtests were selected from the Newcastle Auditory Battery (NAB) (Griffiths, Dean, Woods, Rees, & Green, 2001). These were detection of FM tones at 2 and 40 Hz and detection of Iterated Rippled Noise (IRN). Detection of FM 240 Hz – not a NAB task - was also selected. For FM at low modulation rates (0.5 to 5Hz), the percept experienced is one of a pure tone with fluctuating pitch, or a 'wobbly sound' (Moore, 2004; Moore & Sek, 1996; Sek & Moore, 2000). For intermediate modulation rates (5 to 150Hz), the sensation is of a trill or vibrato ('motorboating'). At high rates of modulation two or three separate pitches are heard which correspond to the pitch of the carrier and the rate of modulation. Both temporal and spectral mechanisms are thought to contribute to FM detection, although relative contributions very depending on modulation rate (Kay, 1982). For low modulation rates temporal mechanisms are dominant, though spectral mechanisms become more significant with higher carrier frequencies and modulation rates. At the highest rates of modulation, detection is thought to depend on detection of spectral sidebands in the presence of the carrier component, which acts as a masker (Moore, 2004; Moore & Sek, 1996; Sek & Moore, 2000). Witton and colleagues had used 240 Hz as a control task, as detection of FM at this rate of modulation is thought to draw especially on spectral rather than temporal processes (Witton, Stein, Stoodley, Rosner, & Talcott, 2002; Witton et al., 1998). In this study, sensitivity to FM at several different rates – low, medium and high (2, 40 and 240 Hz) - was selected for assessment. IRN is a new temporal auditory stimulus that has been used to examine the neuroanatomical basis of fine temporal processing (Griffiths, Buchel, Frackowiak, & Patterson, 1998; Griffiths, Uppenkamp, Johnsrude, Josephs, & Patterson, 2001; Patterson, Uppenkamp, Johnsrude, & Griffiths, 2002) as well as psychophysical investigations of pitch perception (Patterson, Handel, Yost, & Datta, 1996; Yost, Patterson, & Sheft, 1996). Pitch perception is thought to take place via two mechanisms; a 'spectral' or 'place' mechanism based on activity at specific locations along the basilar membrane according to frequency and a 'temporal' mechanism based on the pattern of firing within and across neurons over time (Moore, 2004). Both spectral and temporal information is thought to be significant, but that their relative contribution changes depending on the frequency range and type of sound with temporal information becoming more significant at higher frequencies. Temporal pitch processing is thought to take place beyond the auditory periphery and involves analysis of the temporal pattern of nerve firings in the form of autocorrelation or pattern-matching type of function that extracts an overall pitch. Pitch processing based on temporal processes might be expected to have a longer developmental time course than spectral processing, as peripheral mechanisms tend to develop earlier than central ones, as reviewed above. It was therefore of interest to examine the development of sensitivity to IRN. IRN is constructed by a repeated delay-and-add process of a random noise (Yost et al., 1996). A random noise is delayed by d milliseconds and added to the original noise. This process is repeated n times. These stimuli produce a sensation with two components; a pitch sensation that corresponds to the inverse of the delay d, and a hiss sound like that of the original noise. With an increasing number of iterations n, the salience of the pitch becomes stronger and the noise component weaker. Based as it is on random noise, IRN contains no consistent spectral pattern. There are no stable, harmonically related peaks in the auditory spectrum or the associated pattern of neural activity. An autocorrelation is thought to be applied to the neural activity pattern, whereby the pattern of neural activity is compared with a delayed version of itself. The peaks in the resulting 'summary autocorrelogram' are associated with the most salient pitch (which corresponds to the inverse of *d* for IRN).

IRN in this study was constructed as in the Newcastle Auditory Battery (Griffiths, Dean et al., 2001) with bandpass noise with a passband of 1-4 KHz. The target stimuli contained IRN with 8 iterations plus bandpass noise while the control contained bandpass noise only. Threshold for detection of IRN was in terms of gain, the ratio of IRN to noise.

Carrier frequency was 500Hz for FM 2 Hz and 40 Hz and 1000Hz for FM 240 Hz. Stimuli were generated using Matlab 6.1 (The MathWorks Inc, 2001) at a sampling rate of 44100, scaled to have equal root mean square values (0.2), and calibrated using a sound level meter. All stimuli were 1 second in duration with 20 ms rise/fall times. Note that these parameters are the same as those used by Witton and colleagues (Talcott et al., 2000; Witton et al., 2002; Witton et al., 1998) and the Newcastle Auditory Battery (Griffiths, Dean et al., 2001). For the FM tasks, threshold of detection is in terms of the modulation index. All stimuli were presented at 60 dB SPL.

Procedure

It was decided to use an adaptive threshold estimation procedure rather than a full function estimation as used in the NAB, because an adaptive method was thought to be less time consuming and thus more suitable for use with young children. Apart from the stimuli themselves, the testing procedure was similar to that used by Sutcliffe and Bishop (2005) and was as follows.

Modulation depth (for FM) and gain (for IRN) were adaptively altered using an adaptive PEST (parameter estimation by sequential testing) procedure (Taylor & Creelman, 1967). Very easy discriminations are presented initially with large step sizes that increase the difficulty until an error is made. When an error is made, discrimination is made easier in the manner of a staircase procedure. Step size is systematically reduced until a specified threshold level is reached. A 3-interval, 2-alternative forced-choice paradigm (3I2AFC), was used with the format AXB, where X is always a standard and the target randomly occurs in either position A or B, with another standard tone in the remaining position; ie 'boop, boop, beep' or 'beep, boop, boop'. Participants must choose between A or B. There were a maximum number of 8 reversals with the threshold calculated from the last four reversals. Thresholds were obtained at the 75% correct point on the psychometric function. The maximum number of trials possible was 80, although this was never reached. Tones were separated by 500 ms silent gaps.

For younger children, the examiner initiated each trial when the child was attentive. Older children capable of attending to the task were allowed to initiate trials themselves. For each trial, three cartoon characters (dinosaurs, owls or kangaroos) appeared on the screen each sitting on a colored box. Two lower characters to the left and right of a higher central character produced the A and B tones (target tones) while the central character produced the X tone (reference tone). A trial consisted of each character jumping on its box while producing a tone. The interval containing the modulated/IRN-containing tone was randomly allocated across each trial. Younger children pointed to the character that produced the "wobbly noise" or the "funny noise" and the experimenter entered the response by selecting the character by mouse click. Older children were allowed to select the character themselves. Correct identification of the target tone was rewarded with a small colorful picture and a cheerful noise while incorrect answers elicited a cross and a sighing noise. Five easy examples were presented initially as training and the test run proceeded if the child was able to identify the easy examples.

Two thresholds were obtained for each of the four auditory hearing tasks, with the average of the two taken as the threshold estimate. The order of presentation of the auditory and visual tests was counterbalanced between children.

B Visual Form and Motion Processing Tests

Visual form and motion

The two experimental tests of visual processing in this study are similar to those used in earlier research by Braddick and colleagues (Braddick et al., 2003; Gunn et al., 2002) which were designed to tap form and motion processing. Sensitivity to form and motion was measured psychophysically in terms of the proportion of coherent line segments or dots in background noise that is required to detect a shape. The line segments or dots are either all static (for form) or all in motion (for motion). The threshold of coherence required for detection of the hidden shape was taken as an index of sensitivity to visual cues of either form or motion.

Apparatus:

Tasks were generated on a laptop computer (Dell Latitude D505) using Lua scripting language. The laptop was connected to an external monitor (Iiyama Visionmaster 450), with a display 36 cm x 27 cm (45 cm diagonal) and a screen resolution of 1600 (horizontal) x 1200 (vertical) pixels at 60 frames per second.

Stimuli:

Form and motion coherence stimuli were viewed on the external monitor at a distance of 90 cm (visual angle 22.91° x 17.19°). Both stimuli contained a circular target area 14.4 cm (9.17° in diameter) that appeared with equal probability centrally on the left or right half of the display. The proportion of coherently moving dots amongst randomly moving dots (Motion) or coherently oriented line segments (Form) amongst randomly oriented segments in the target area defined the coherence value for each trial. Dots or line segments were arranged to form concentric circles within the circular target area. For the motion stimulus, the direction of rotation of the coherent rotational motion varied at random (clockwise or anticlockwise). Figure 1 illustrates the form and motion displays.

The form stimulus was a static array of randomly oriented short line segments (white lines on a black background, density 7.62 segments/deg^2). Short line segments were generated by plotting simultaneously the positions that individual dots 0.18 cm in diameter (0.114°) in motion would have moved over a lifetime randomly chosen between 1 and 8 frames (0.02 to 0.13 seconds) along an arc trajectory of 3.37 cm/s (2.14°/s) resulting in segment lengths between 0.24 to 0.63 cm (0.15° to 0.40°) in length.

The motion stimulus was a random dot kinematogram (white dots on a black background, density 7.62 dots/ deg^2). Dots 0.18 cm in diameter (0.114°) had a velocity of 3.37 cm/s (2.14°/s) and had a limited lifetime of 8 frames (0.13 seconds). To prevent flicker caused by replacing each dot at the same frame, initial dot lifetimes were chosen at random between 1 and 8 frames (0.017 and 0.100 seconds) at the start of each stimulus presentation. To avoid judgments based on local cues, for both form and motion stimuli, both signal and noise dots had curved paths. Coherent dots curved around the centre of the target area, while noise dots curved around a different randomly chosen point for each dot.

Procedure:

Procedure was similar to that used by Gunn et al (2002). Stimuli were presented with room lights off and curtains drawn. Perceptual thresholds were obtained using two-alternative forced choice (2AFC) paradigms whereby participants were required to locate the target regions, which were presented either in the left or right half of the display. In order to ensure that the children understood the tasks, descriptions such as ‘can you see the ball hidden in the grass?’ were used. Children responded by pointing to the location of the ‘ball’. In between presentations the subjects’ attention was drawn to the midline with a set of three coloured flashing dots.

In each task, the initial coherence level on each task was set to 100% and 3-6 practice trials were conducted. Coherence threshold values were established using the Ψ method (Kontsevich & Tyler, 1999) for obtaining the slope and threshold of psychometric functions. This method maximizes efficiency of threshold estimation by using progressively updated probabilities to select stimulus intensities at a level that maximizes information to be gained by completion of that trial. The motion and form coherence tasks were run successively for each participant, with the order of presentation of the two tasks counter-balanced across subjects. Thirty trials were completed for each task. Following Gunn et al (2002), one threshold estimate was obtained for each visual task.

<Insert Figure 1 here>

Test-retest reliability

21 children aged 7 to 10 years were re-tested between 2 weeks and 4 months after initial testing (*M* = 8.5 weeks, *sd* = 4.6 weeks). Four each of 7, 8 and 9 year-olds and nine 10 year-olds were re-tested. Selection of the re-test sample was not random as selection of children for re-test depended on which children were at school and available for re-testing. No differences between the re-test sample and the rest of the normative sample were apparent on examining demographic and test performance data.

C. Other measures.

i) SCAN-C

The SCAN-C (Keith, 2000), is a commonly used standardized test of auditory processing with population-based norms for the US. It is individually administered either in audiometric conditions or in a quiet room to children between aged between 5 and 11:11 years. Stimuli are recorded on CD and played over headphones. The SCAN-C provides and overall score as well as scores for its four subtests, Filtered Words (FW), Auditory Figure-Ground (AFG), Competing Words (CW), and Competing Sentences (CS). The SCAN-C seems to tap two auditory skills; a ‘monaural low-redundancy speech’ factor

(FW and AFG) and a ‘binaural separation/competition’ factor (CW and CS) (Dawes & Bishop, 2007; Schow & Chermak, 1999). Note that despite being widely used, there are concerns over the reliability of the SCAN-C - particularly the impact of language level and phonological skill on SCAN-C performance (Dawes & Bishop, 2007; Marriage, King, Briggs, & Lutman, 2001). As there is currently no gold standard to compare against (ASHA, 2005), the SCAN-C has uncertain validity in auditory processing assessment. Thus it was of interest to examine whether performance on the speech-based measures of the SCAN-C would correlate with performance on the non-speech auditory measures used in this study.

ii) CCC-2

The Children’s Communication Checklist, second edition (Bishop, 2003) is a parent-completed screening instrument that is sensitive to communication disorders in children aged 4 to 16. It can be used to screen for children who are likely to have language impairment or to identify pragmatic impairment in children with communication problems.

Results

CCC-2

Valid Children’s Communication Checklists (CCC-2) were received for 83 children. The mean General Communication Index score for the standardisation sample was 81.19 (*sd* 18.59). This suggests that the sample as whole is typical in terms of communication skill; an average score is 82.

SCAN-C

UK children tended to score worse than US-produced norms reported with the SCAN-C. On the overall composite standard score, UK children scored close to one standard deviation more poorly than the US norms although the distribution of scores was the same (based on single sided probability that variances are equal, *F* test). An error analysis revealed that the poorer performance of UK children was largely due to accent effects; UK children miss-heard SCAN stimuli recorded with a US accent. A correction must be therefore applied to SCAN-C scores for use in identifying auditory processing problems in British children (Dawes & Bishop, 2007).

Psychophysical tests

Auditory and visual test data were analysed in four parts. First, examination of the impact of procedural factors such as attention and practice effects on psychophysical test performance was carried out. Second, examination of age effects on task performance. Third, re-test reliability of the psychophysical tests, and finally correlations between auditory and visual psychophysical tests, CCC2 and SCAN-C tests were examined.

Auditory processing tests

Procedural factors

Examination of children's responses at easy levels revealed that none were operating at chance levels (ie all were close to 100% correct on first 5 trials). Children understood the task and weren't simply guessing.

To examine the effect of practice, an Age (6) by Run (2) ANOVA with threshold as DV was run. 2Hz, 40Hz and 240Hz threshold data were log transformed in order to obtain a normal distribution and to equalise variances between groups. For 2Hz and IRN, there was a significant main effect for run, with better thresholds on the second run ($F(1,1) = 5.53$, $p < 0.05$, $F(1,1) = 5.81$, $p < 0.05$). There was no interaction with age group and run for any task; where significant, practice effects were no more important for any one age group than another.

To examine the effect of attention and other procedural factors, track width (the standard deviation of the average of the last four reversals used to compute the threshold in the adaptive procedure) was used. Wider tracks (higher values) reflect 'guessing' of responses (Wightman et al., 1989), representing lapses of attention or memory or poor motivation. The 3I2AFC method used for the auditory tasks in this study is thought to have minimal memory requirements compared to other methods (Sutcliffe & Bishop, 2005) and the task itself was motivating; children enjoyed playing the 'listening game'. Track width may thus represent largely attentional factors. To compare track width between age groups, an ANOVA was carried out. Track width data for 2Hz, 40Hz and 240Hz were log transformed to equalize variances. Track width was significantly different between age groups for 40Hz only ($F(5,113) = 2.52$, $p < 0.05$). Post hoc comparisons revealed significantly higher track width for 6 year-olds compared to 8 and 9 year-olds and adults. Except for the 240Hz task, there were low significant correlations between track width and threshold (2Hz: $r = .35$; 40Hz $r = 0.44$; IRN $r = 0.23$ (p's $< .05$); 240Hz $r = 0.18$ (ns)).

Age trends in task performance

Performance in each subtest by age group is represented graphically in Figure 2.

There was a significant linear regression of performance on age between 6 and 10 for all auditory psychophysical tests (2, 40 and 240 Hz, F's (1,96) = 21.6, 14.4, 11.43, $p < 0.01$) except for IRN (F (1,96) = 0.28, p >0.05). The magnitudes of threshold estimates for the adults in this sample are similar to those obtained by Witton and colleagues (Witton et al., 2002; Witton et al., 1998) and for the Newcastle Auditory Battery (NAB) (Griffiths, Dean et al., 2001).

<Insert Figure 2 here>

Task performance improves with age, though how much of this improvement is due to maturation of non-auditory factors (such as attention and motivation) and how much due to maturation of auditory processes? A multiple regression on threshold was carried out with track width entered first, followed by age. After track width, any unique variance accounted for by age should then relate to age-related development of auditory skills. Multiple regression was carried out for the age range 6 to 10 only as adult ages had a disproportionate effect on regression. Table 1 shows the amount of variance in threshold accounted for by track width and the improvement in prediction of threshold by the addition of age. Age made a significant additional contribution to prediction of threshold for all tasks except IRN. For IRN, track width had a small impact while age accounted for no variance in threshold. For the rest of the tasks, age tended to make a higher contribution to threshold variance than track width, despite being entered into regression later. Interestingly, though age had a significant contribution, track width made no significant contribution to prediction of threshold variance for 240Hz.

<Insert Table 1 here>

Overall patterns of performance on tasks differed. Auditory task data were log transformed in order to equalize variances between groups and analysed by means of a repeated measures ANOVA with task and age group as factors. There were significant interactions between age and task for IRN and all the other tasks; the pattern of development for IRN differed to that of the other tasks. There were also significant interactions between 2 Hz and 40 Hz as well as 2 Hz and 240 Hz, but not between 40 Hz and 240 Hz. While 40 Hz and 240 Hz had similar developmental trajectories, 2 Hz and IRN differed from the other tasks.

For 2 Hz FM, there was an improvement in average performance with age, with most children at adult levels of performance by age 9. Post hoc analysis (Tukey HSD) showed a significant difference between adult performance and 6, 7 and 8 year-olds' performance on the 2 Hz task.

For 40 Hz and 240 Hz most children performed at adult levels by age 7. For these two tasks, there was a significant difference between adults and 6 year olds only. In line with the regression analysis, complex pitch perception (IRN) was most indifferent to age effects, with adult-like performance across the age range. There were no significant differences in performance between any age group.

Visual processing tests

Procedural factors

As for the auditory tests, examination of children's responses at easy levels revealed that they had understood the task; none were operating at chance levels (ie all were close to 100% correct on first 5 trials).

For the visual tests, only one threshold estimate was obtained, so no estimate of within-session practice effects is possible. However, the small non-significant improvements seen in re-test data (examined below) suggest no substantial practice effects.

The threshold estimation program for the visual tests did not report track width. In order to examine the impact of procedural factors (attention, memory and motivation) on visual tasks, track width data for the auditory tasks were standardised across groups and averaged to provide a general index of procedural factors. There were no significant correlations between this general index and visual thresholds (*r*'s .10, ns).

Age trends in visual thresholds

There was a significant linear improvement with age for motion (F (1,100) = 19.12, $p <$ 0.01), but not form (F (1,100) = 2.17, $p >$ 0.05) (Figure 3). Post hoc analysis (Tukey HSD) revealed significant differences between adult performance and all other age groups on the coherent motion test. For visual form, there were significant differences between adults and 6 year-old and 10 year-olds.

<Insert Figure 3 here>

Test-retest reliability

Three of the tests (40 Hz, 240 Hz and IRN) had moderate re-test reliability (r's 0.50, 0.83 and 0.61, respectively, $p < 0.05$). Detection of 2 Hz FM was the most unreliable auditory test ($r = 0.25$, $p > 0.05$), with thresholds quite variable from one occasion to another. The re-test reliability of the two visual tasks was disappointingly low ($r = 0.07$ and 0.31, $p > 0.05$ for form and motion, respectively). Retest reliability may very with age, however we did not have the resources to re-test all the children. Re-test data for the subset of children we did re-see were examined, and there was no association with age.

For all tests, there was a small non-significant improvement in average performance between test and retest. It would seem that the low reliability of some of these tests is not because there are large practice effects.

Correlations between tests

Scores on all psychophysical tests were converted to age-standardised scores by year band. The only exception was IRN; as performance did not change with age, scores were standardized with reference to the pooled sample. Age standardized scores were then correlated with age-standardised CCC2 and SCAN-C scores. Table 2 shows correlations between tests. The four auditory tests have low significant correlations with each other, as do the two visual tests.

Better performance on the SCAN-C was associated with better (lower) psychophysical threshold, although correlations are low. Examination of the SCAN-C factor structure revealed two factors; monaural low redundancy degradation and binaural separation/competition (Dawes & Bishop, 2007; Schow & Chermak, 1999). Correlations with psychophysical thresholds were generally low for both factors, which were similar in magnitude to those for total SCAN-C scores, with neither factor more strongly associated with psychophysical test performance than the other. The SCAN-C does not seem to be very sensitive to performance on these psychophysical tasks.

Grammatical impairments are a hallmark of language problems (Leonard, 2000) and auditory processing problems are commonly associated with language problems. However, there was no correlation between the syntax subscale score on the CCC-2 and any auditory or visual psychophysical test. There was a low significant correlation with syntax and SCAN-C score, perhaps reflecting the contribution of language skill to SCAN-C test performance. The level of general communicative competence, as measured by the CCC-2 was unrelated to performance on the perceptual tasks.

<Insert table 2 here>

Discussion

For the auditory tasks, 2Hz, 40Hz and 240Hz (but not IRN) showed age-related improvements after attempting to account for the effect of procedure-related skills. Age accounted for 16%, 19% and 11% of unique variance in threshold for 2Hz, 40Hz and 240Hz respectively. A large amount of variance in threshold remained unaccounted for by either auditory or procedure-related skills. This might be ascribed to individual differences in auditory processing. As detection of FM improved over the age range studied here while IRN detection did not improve, it seems that complex pitch perception indexed by IRN is an early developing skill already fully developed by age 6. In contrast, temporal mechanisms underlying detection of FM, whether reliant on phase locking, spectral mechanisms or both, seemed to be developing over the age range studied here. 2 Hz sensitivity was adult-like in most children by age 9, whereas sensitivity to 40 Hz and 240 Hz was adult-like by age 7. This is in line with Hall and Grose's (1994) finding that children's sensitivity to modulation of a noise carrier improved from age 4 to 10 with children's performance on backward masking also improving over the same age range (Buss et al., 1999; Hartley et al., 2000; Wright & Zecker, 2004).

Increased variability in younger children's performance was also apparent. For 2, 40 and 240 Hz, there was a noticeable skew in distribution towards poorer performance which reduced with age such that by age 9, the spread of scores was symmetrical and of a similar magnitude to that of adults. For these three tests but not for IRN or the visual tests, there is a marked drop in variance between ages 7 and 8. As seen in the regression analysis, variability of performance was due to age-related development of both auditory and non-auditory factors for 2Hz and 40Hz and mostly auditory factors for 240Hz. This is in line with Hall & Grose's (1994) finding that efficiency of processing the information underlying modulation detection develops over school age.

Track width, thought to be mainly an index of attention, had a significant association with threshold across age groups. Track width accounted for 11% and 16% of variance in 2Hz and 40Hz tasks respectively, but very little variance for 240Hz and IRN tasks. Except for 40Hz, where six year-olds had a significantly higher track width, the size of track width was similar across age groups. It is interesting that procedure-related effects and auditory processing development had different impact on different auditory tasks. Where they were significant, procedural factors had a similar impact across age groups. Some discrimination tasks were more age-sensitive (especially 240Hz but also 2 and 40Hz), while some were more susceptible to procedure-related factors (2 and 40Hz), despite using the same paradigm.

Why should there be a different contribution of procedure-related factors between tests? One explanation may be that some discriminations may be more dependent on the child knowing what to focus their attention on and when to listen (Oh, Wightman, & Lutfi, 2001; Sutcliffe & Bishop, 2005). For example, IRN and 240Hz FM, were relatively unaffected by procedure-related factors while 2 Hz FM was more affected. If a child only begins attending part way through the signal, then this could be especially detrimental to detection of the slower changes associated with 2 Hz FM. However, this explanation does not seem to account for why 40 Hz FM was as susceptible to procedure-related factors as

2 Hz FM was; one might expect 40 cycles a second to be less susceptible than 2 cycles a second to fluctuations in attention.

For the visual tasks, although the observed difference between adults and 10 year-olds on the form task is difficult to explain, it seems development of performance on the form task is complete around by age 7, while performance on the motion task is still developing at age 10. This replicates the work of Gunn and colleagues (2002) who found similar results with similar visual processing tasks.

One aim of this study was to examine whether the observed performance deficits on psychophysical tasks in some people with language and reading problems might be ascribed to developmental delays. Wright et al's (2004) hypothesis was that a halt of development of auditory processes seen at age 10 may explain why some people show persistent and specific auditory deficits. This hypothesis predicts that performance of adults with language or reading problems should match that of typical adults on tasks for which performance reaches asymptote before puberty, but should be more similar to performance of children at the age of puberty on measures that continue to develop during adolescence. Witton et al (2002) reported group performance data concerning deficits in adult dyslexic's detection of 2Hz and 240Hz compared to controls.Witton et al's 17 dyslexic adults had a mean threshold of 2.04 (*sd* 1.14) while 21 controls had a mean of 1.01 (*sd* 0.38) on the 2 Hz FM task. The adults in our study had a mean threshold of 0.92 (*sd* 0.5), not statistically different from the controls in Witton et al's study, though different from the dyslexics ($t(21) = -3.73$, $p < 0.01$). Witton et al's dyslexics scored significantly more poorly than 9 and 10 year-olds in our study, but not significantly differently to 8 year olds (*M* 1.67, *sd* .78) on the 2 Hz task. In contrast, for the 240 Hz task, there was no significant difference in mean threshold between Witton et al's adult controls or dyslexics and the adults in this study. If auditory development is halted at around age 10, as Wright et al (2004) suggested, then it seems Witton et al's dyslexic adults may have been experiencing a delay in 2 Hz development of around 2 years when their further development was halted at age 10. In the current study, 240 Hz detection matured earlier (age 7) while 2 Hz matured later (by age 9). The current results are thus not incompatible with a hypothesis of developmental delay, though this conclusion is very speculative. These results are discussed here merely to stimulate interest in this hypothesis and illustrate how developmental data might be used to investigate the nature of perceptual deficits seen in a proportion of people with language and reading problems.

Re-test reliability

The reliability of the auditory tests (except for FM 2 Hz) is acceptable, though not impressive while the visual tasks are too unreliable for use at individual level. For the auditory tests in general, the two tasks with the highest reliability (240 Hz and IRN) were also the two tasks that had the least amount of variance explained by track width (2% and 5% for 240 Hz and IRN) while the two least reliable auditory tests (2 Hz and 40 Hz) had a higher proportion of variance accounted for by track width (11% and 16%, respectively). Higher impact of procedure-related factors on threshold is associated with low re-test reliability for the auditory tests.

Detection of 2 Hz FM was the most unreliable auditory test, with thresholds quite variable from one occasion to another. Researchers at the MRC Institute of Hearing Research working on developing a battery of peadiatric auditory processing tests also report disappointingly low reliability for a 2 Hz FM detection task (Cowan, 2006)**.** The unreliability of detection of 2 Hz FM tasks is of interest, given that impaired detection of 2 Hz FM has been reported as evidence of a deficit in auditory processing in various studies of language and reading impairment (Talcott et al., 2000; Witton et al., 2002; Witton et al., 1998).

In contrast to the auditory tests, a general estimate of procedure-related factors did not account for any variation in visual form or motion detection threshold, so the poor reliability of the visual tests may not be because of sensitivity to variation in procedure-related factors. However, the general estimate of procedure-related factors used here may not be a good measure of these factors, as it was derived from average track widths from the auditory tests.

Given the theoretical interest in being able to measure behaviourally the purportedly separate mechanisms of visual form and motion detection as well as the long standing research interest in relating deficits in visual motion sensitivity to various developmental disorders, it would be worthwhile to discover why children's re-test variability on these tasks is so great. While reliability of the visual tests is too low for meaningful interpretation of performance at individual level, group performance trends for the motion task does support maturation of underlying mechanisms over the target age range.

Inter-test correlations

The low correlations between auditory and visual psychophysical tests suggested that they may in fact be measuring different processes rather than being four indices of the same thing. There was little support for there being a common temporal processing factor indexed by the dynamic auditory tasks (2 Hz and 40 Hz) and the visual motion detection task; none of the correlations was especially high. If anything, there seemed to be a tendency for stronger correlation with visual motion and the 240 Hz task, a supposedly 'static' auditory measure and with visual form and 2 Hz and 40 Hz, supposedly 'temporal' tasks.

Where present, associations between auditory or visual perceptual measures and the measures of language (CCC2) and speech-based auditory processing (SCAN-C) chosen in this study were low. General intelligence may account for much of this association (Watson, 1991). There was no convincing association between perceptual skill and speech perception or language.

In summary, this study demonstrates the importance of taking age and procedure-related factors into account when doing auditory testing with children and the need for collecting large scale, population-based child performance data over a range of ages for clinical audiometric procedures. In addition, the specific discrimination is important in determining developmental patterns of performance with different impact of procedure-related and auditory factors on different discriminations, despite using the same methodology.

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Table 1. Amount of variance accounted for in threshold by Track width in multiple regression and the improvement in contribution to threshold prediction by addition of Age.

	Track width R^2 (model: track width only	Beta†	Age R^2 (model: track width and age)	Beta†
2Hz	.11*	.30*	.27#	-.41*
40Hz	.16*	.35*	.35#	-.29*
240Hz	.02	.13	.13#	-.33*
IRN	.05*	.22*	.05	-.04

* significant at $p<0.05$
# Significant addition of Age to prediction of threshold variance, $p < 0.05$
† Standardised beta values for the regression model containing Track Width and Age.

Table 2. Correlations between tests.

	2 Hz FM	40 Hz FM	240 Hz FM	IRN	Visual Form	Visual Motion	CCC2	CCC2 Syntax	SCAN-C
2 Hz FM		.217(*)	.315(**)	.261(**)	.260(**)	.098	.103	.094	-.371(**)
40 Hz FM	.217(*)		.288(**)	.080	.285(**)	.172	-.118	.057	-.325(**)
240 Hz FM	.315(**)	.288(**)		.173	.114	.225(*)	-.121	-.157	-.329(**)
IRN	.261(**)	.080	.173		.097	.140	-.006	.042	-.263(**)
Visual Form	.260(**)	.285(**)	.114	.097		.360(**)	-.002	-.047	-.243(*)
Visual Motion	.098	.172	.225(*)	.140	.360(**)		.022	-.052	-.229(*)
CCC2	.103	-.118	-.121	-.006	-.002	.022		.744(**)	.201
CCC2 Syntax	.094	.057	-.157	.042	-.047	-.052	.744(**)		.262(*)
SCAN-C	-.371(**)	-.325(**)	-.329(**)	-.263(**)	-.243(*)	-.229(*)	.201	.262(*)	

Pearson's *r*
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Figure 1. Screen shots of the visual form and motion tests

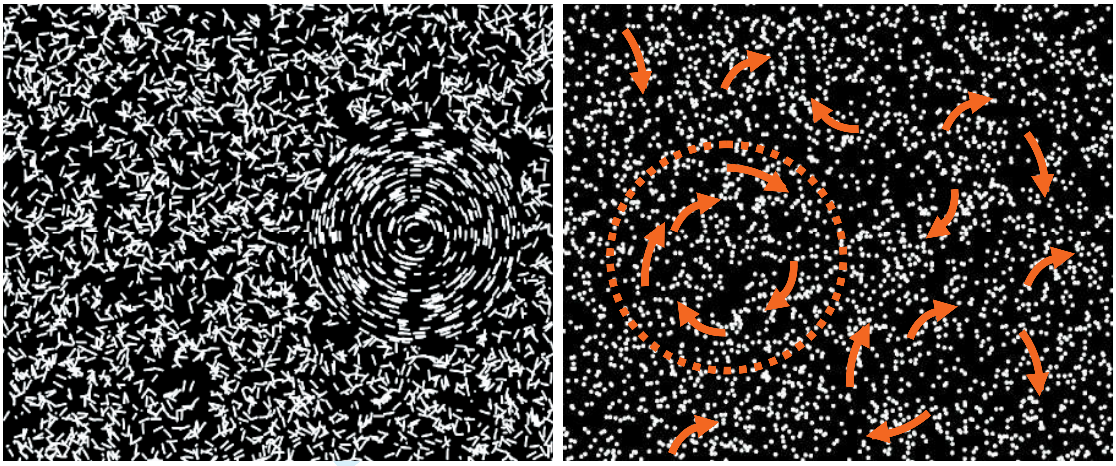

Figure 2. Auditory Psychophysical test performance: boxplots by age group

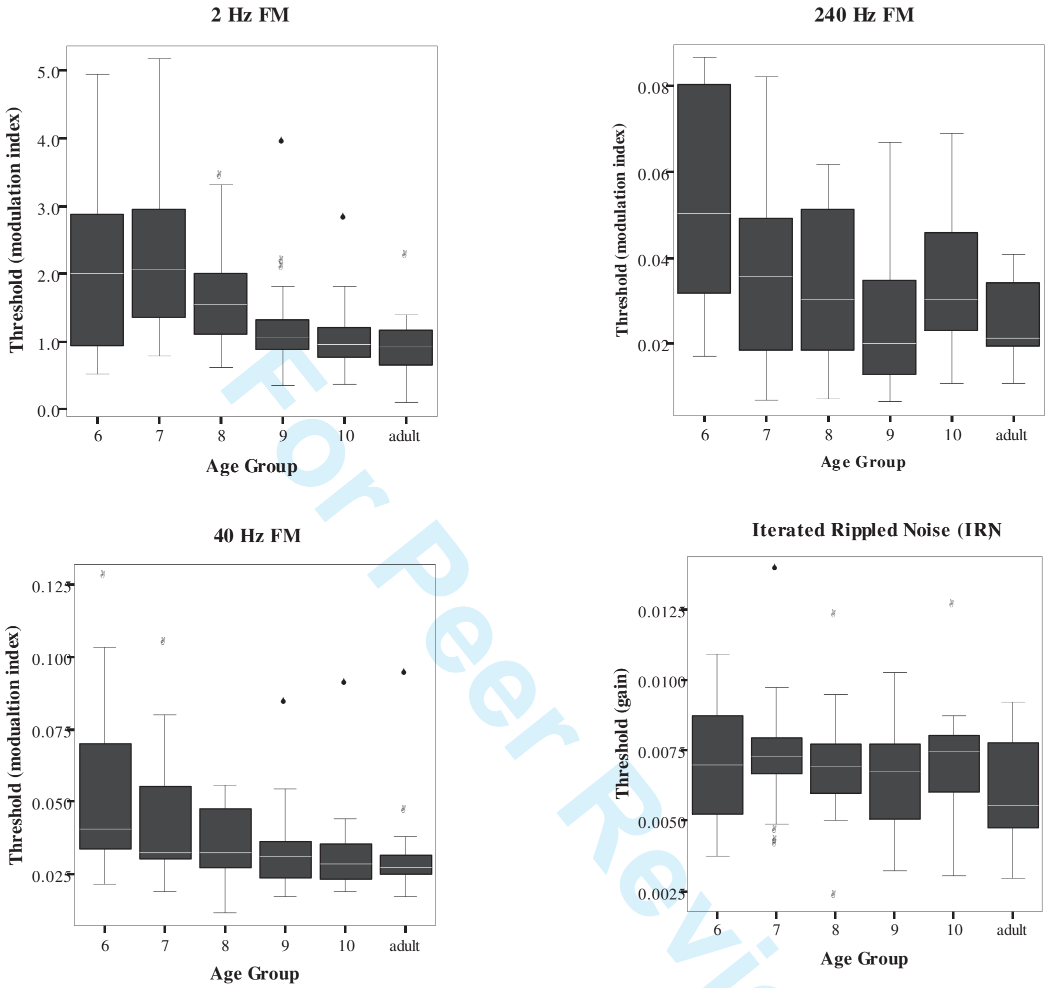

Figure 3. Visual psychophysical test performance: boxplots by age group