

Temporal auditory and visual motion processing of children diagnosed with Auditory Processing Disorder (APD) and dyslexia

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Abstract

Auditory processing disorder (APD) is diagnosed on the basis of listening difficulties despite normal audiogram, though the cause is unknown. **Objective:** This study examined the hypothesis that the underlying cause of APD is a deficit in auditory temporal processing, and also considered how far the auditory impairments in APD differ from those of children with dyslexia. **Design:** Performance of children diagnosed with APD ($N = 26$) was compared to that of a normative group ($N = 98$) as well as children with dyslexia ($N = 19$) on a battery of temporal auditory tasks; 2 Hz, 40 Hz FM and Iterated Rippled Noise (IRN) detection as well as a control task; 240 Hz FM, which is thought to draw on peripheral spectral mechanisms. Visual tasks were coherent form and coherent motion detection. **Results:** On average, both APD and dyslexia groups performed more poorly than controls on all tasks except for coherent form detection. Apart from on the 240 Hz task where the APD group scored more poorly, there were no significant differences between APD and dyslexia group performance, and no evidence for a specific temporal auditory impairment, although there was a non-significant trend for the APD group to do more poorly than the dyslexia group on all tasks. Auditory psychophysical performance correlated with performance on the SCAN-C, a standardized test of auditory processing, and nonverbal IQ, but not with reading ability. **Conclusions:** There was no qualitative distinction between children with APD and those with dyslexia. The diagnoses a child receives may partly depend on the profession of the consulting clinician. Auditory perceptual deficits may be better seen as part of a multi-factorial description of learning problems rather than as part of a diagnostic category in their own right.

Introduction

Auditory processing disorder (APD) is diagnosed when a child presents with unexplained listening difficulties despite a normal audiogram and shows impaired performance on tests of auditory processing, such as the SCAN-C (Keith, 2000b). The cause of APD is assumed to be subtle abnormalities in the auditory CNS that disrupt processing of sound (ASHA, 2005; British Society of Audiology, 2005). Although widely diagnosed in the US and Australia (Cameron & Dillon, 2005; Emanuel, 2002) and increasingly well known in the UK (Hind, 2006), there are controversies over definition and diagnosis of APD.

APD definitions list a range of auditory skills that are thought to be impaired, including recognition, discrimination, pattern recognition, performance with degraded or competing signals, temporal integration and temporal masking (ASHA, 2005; British Society of Audiology, 2005). However, critics have objected that these definitions are merely lists of tasks that people diagnosed with APD have difficulty with (McFarland & Cacace, 1995). The range of skills is broad, and they are likely to overlap as they draw on a common core of fundamental auditory skills. One of the most favored hypotheses for an impairment underlying many of these skills is a deficit in temporal resolution, in which temporal changes in the auditory signal are not accurately resolved (Jerger, 1998). Other possible explanations involve a specific deficit in auditory figure-ground discrimination, auditory memory or attention. As yet, there is no convincing evidence for any specific deficit underlying APD.

One long standing objection to APD is that ‘APD’ may not be a separate disorder, but rather is reflection of an attention deficit, a specific learning disability or a language disorder (Rees, 1973). If auditory processing (AP) test performance is substantially impacted by non-auditory factors, AP tests may lead to a diagnosis of APD in children whose listening difficulties are due to other causes. Use of linguistic stimuli in APD tests is problematic, and many supposed AP tests are likely to be sensitive to language level or familiarity with accent or dialect (Marriage, King, Briggs, & Lutman, 2001; D. R. Moore, 2006; Rosen, 2005). In an attempt to clarify the definition of APD and sidestep the difficulties of auditory assessment using linguistic stimuli, the British Society of Audiology (2005) defines APD as a hearing disorder that is presumed to affect processing of both speech and non-speech sounds, but to demonstrate an APD one needs to test auditory skills using non-speech stimuli. If an auditory deficit is seen only with speech processing or phonological categorization, then it would not fit the BSA’s definition of APD.

An additional issue with disentangling APD as a diagnostic entity distinct from other developmental disorders is the fact that auditory deficits are seen in a subset of children with dyslexia or SLI diagnoses (Tallal, 2000) and children with APD also commonly have language and reading difficulties (Bamiou, Musiek, & Luxon, 2001). Despite years of intensive research, the role of auditory impairment in language development is not clear. The difficulty is sorting out issues of cause and effect. Is the observed auditory deficit i) a primary cause of the child’s language problems, ii) a secondary consequence or iii) something that merely co-occurs with language problems but is not directly causally linked? In APD research, this issue is complicated by the suggestion that different groups

may be using different diagnostic labels for the same condition. In other words, the diagnosis a child receives is partly dependant on the professional they consult; audiologists diagnose APD where educational psychologists or speech and language pathologists would diagnose SLI or dyslexia (Friel-Patti, 1999). One aim of this study was to investigate whether temporal auditory processing skills of children diagnosed with APD resemble those of children with dyslexia. It is possible that APD and dyslexia share many similarities, however, it is possible that research focusing on children with identified auditory problems may shed light on the hypothesis that auditory problems may be associated with language and literacy problems. To date, the great majority of research has been concerned with investigating the auditory skills of children with language and literacy problems.

In research into the auditory skills of children and adults with ‘language learning problems’ a range of non-linguistic auditory processing tasks including FM and AM detection (Witton et al., 1998), frequency discrimination (Bishop, Carlyon, Deeks, & Bishop, 1999), backward masking (Wright et al., 1997), sequencing of brief or rapidly presented tones (Tallal, 2004) and auditory stream segregation (Helenius, Uutela, & Hari, 1999) have been used, and some of these may be informative for use with children with APD. Some researchers have explored the nature of APD using non-linguistic tasks, for example gap detection (Musiek et al., 2005) or tone sequencing (Musiek, 1994), and these may be useful to supplement information from linguistically based APD tests. However, tasks are often ambiguous in terms of what they measure; studies have used stimuli that could be detected using either spectral or temporal coding and different tasks have been used to measure

spectral (eg frequency discrimination) and temporal (eg gap detection) processing, making comparisons between tasks difficult. An aim of this research was to assess both temporal and spectral processing using the same task procedure.

Witton, Talcott and colleagues were interested in using FM detection tasks to investigate possible temporal auditory deficits underlying dyslexia. Their hypothesis was that impairment in perception of dynamic auditory stimuli would lead to problems in discrimination of speech sounds with knock on effects on phonological development and reading. In a series of studies, Witton and Talcott and colleagues found FM sensitivity was associated with reading skill. Dyslexic children and adults were also less sensitive than controls to FM (at 2 and 40 Hz), though there was no difference in performance on a control task thought to tax spectral processing (240 Hz) (Talcott et al., 2002; Talcott et al., 2000; Witton, Stein, Stoodley, Rosner, & Talcott, 2002; Witton et al., 1998).

In order to test the hypothesis that the cause of APD is a problem with temporal coding of sound, we selected a test battery derived from the work of Witton and Talcott and colleagues. Tasks were taken from the temporal subsection of the Newcastle Auditory Battery (NAB) (Griffiths, Dean, Woods, Rees, & Green, 2001) that assess temporal coding at different rates; 2 Hz FM, 40 Hz FM, and Iterated Rippled Noise (IRN), a stimulus thought to tap pitch perception based on temporal rather than spectral mechanisms. NAB subtests have also been used to investigate auditory processing in adults with acquired brain injuries (Griffiths et al., 1997). As with Witton et al's work, a control task – 240 Hz FM, which can be done without reliance on central auditory mechanisms - was included in

the battery. The hypothesis was that if children with APD have a problem with temporal coding of sound, they will have a deficit in performance on one or more of the tasks 2 Hz, 40 Hz and/or IRN with normal performance on the 240 Hz task, as compared to a normative group of children.

Attention does impact upon children's psychophysical and AP test performance (Gascon, Johnson, & Burd, 1986; Wightman & Allen, 1992). So are ADHD and APD equivalent diagnoses? A strong test of the impact of attention on AP test performance is to compare children's performance while on or off stimulant medication for ADHD, though findings in this area are mixed. Tillery and colleagues (2000) found that medication improved performance on attentional tests but not auditory tests, while Sutcliffe and colleagues (2006) found medication did improve performance on some auditory tests but not others. In this study, we used parental report measures to gauge the impact of attention on auditory test performance.

Leading on from this is the notion of 'modality specificity', or the idea that one must demonstrate specific auditory deficits in order to discount the effects of a general dysfunction that would affect performance across modalities, such as an attention deficit (Cacace & McFarland, 2005). McFarland and Cacace advocated the addition of comparable tests of processing in other modalities (eg visual or tactile) in addition to auditory tests so that the modality specificity of any auditory deficits can be established. However, other researchers answered that modality-specificity may be an unrealistic demand to make because multimodality is a basic feature of neural coding and

manipulation (Bellis & Ferre, 1999). The latest ASHA report (2005) acknowledged both points of view and recommended that APD should be recognized when the sensory processing deficit is *most pronounced* in the auditory domain. Although a topic of debate in the APD literature, we are not aware of any published studies that have investigated processing in other modalities in children with APD in comparison to auditory processing.

In accordance with McFarland and Cacace's recommendation that an analogous test in another modality should be employed alongside auditory tests, we chose to assess visual motion sensitivity. Primate and human studies suggest a division of the early visual system into two parallel 'parvocellular' and 'magnocellular' pathways (Milner & Goodale, 1995), with the magnocellular pathway specialized for detection of motion and the parvocellular specialized for recognition of form. Sensitivity to form and motion can be measured psychophysically in terms of the proportion of coherent line segments or dots in background noise that are required to detect a shape. Both pathways are thought to develop throughout childhood (Parrish, Giaschi, Boden, & Dougherty, 2005), although sensitivity to motion seems particularly susceptible to disruption (Braddick, Atkinson, & Wattam-Bell, 2003). Therefore, visual motion detection was thought to be a useful and sensitive measure to employ to test the modality specificity hypothesis in children diagnosed with APD. If the notion of a 'modality specific' APD is valid, then we should be able to find children who have impaired performance on auditory psychophysical tests and normal performance on visual ones.

In summary, the specific questions for this study were:

1. Is there evidence for specific problems with temporal auditory processing in children diagnosed with APD?
2. Are any processing problems specific to the auditory modality, or do children with an APD diagnosis do poorly visual processing tests also?
3. Do attentional problems impact significantly on auditory test performance to the extent that some children's poor performance might be attributed to an attentional deficit?
4. Given that many children with APD have poor reading, and conversely, temporal auditory problems have been described in dyslexia, are comparable problems seen in the two groups? More generally, are auditory problems more closely related to a child's literacy status or APD status?

Methods

Participants

APD Group

After excluding two children with non-verbal IQ less than 80, twenty-six children with a diagnosis of APD were recruited from four collaborating hospitals in London, Oxford and Manchester. Two additional children were referred to the study by word of mouth. All of these children had been diagnosed by an audiologist or auditory physician as having APD. Diagnosis at each of the referring centers was made on the basis of specific listening difficulties despite normal peripheral hearing with performance below recommended clinical cut-off scores on the SCAN-C (Keith, 2000b) plus failure on one or more additional tests of auditory processing (for example, the Random Gap Detection Test

(Keith, 2000a), Pitch Patterns Test (Musiek, 1994) or Duration Patterns Test (Musiek, 1994)). See Dawes, Bishop, Sirimanna, & Bamiou (submitted) for details of APD diagnosis. While there is currently no ‘gold standard’ for APD diagnosis, diagnostic methods in this study are typical of those commonly used in the US and UK (Emanuel, 2002; Hind, 2006).

Dyslexia Group

19 children were recruited either from local schools or as participants from previous studies conducted by the OSCCI lab. The key criterion for recruitment was a diagnosis of dyslexia by an educational psychologist. For inclusion in the study, presence of dyslexia was defined as performance IQ greater or equal to 80 and average of Test of Word Reading Efficiency (TOWRE) (Torgesen, Wagner, & Rashotte, 1999) word and pseudo-word reading subtest standard scores of less than 85 or OSCCI Spelling Test (see Assessments, below) standard score less than 85.

APD and dyslexia groups were not significantly different in age (means of 10.1 years, *SD* 1.6 and 10.2 years, *SD* 2.3 respectively for APD and dyslexia groups, $t(44) = -.25, p > 0.05$). There was a significantly higher proportion of females to males in the APD group (16 males, 10 females in the APD group versus 17 males and two females in the dyslexia group, Fishers $p = 0.046$). The two groups were not significantly different in performance IQ based on the Wechsler Abbreviated Scale of Intelligence (WASI) matrix reasoning and block design subtests (Wechsler, 1991) ($M = 102.21, SD 11.4$ and $M = 98.23, SD 14.7$, respectively for APD and dyslexia groups, $t(43) = .98, p > 0.05$).

Normative group

Local schools helped recruit children with which to collect performance norms for the auditory and visual tasks. Except for 6 year-olds ($N = 18$), the goal of 20 children per year band from 6 to 10 years was met. There were approximately equal numbers of boys and girls in each year group. A group of 18 adults were also tested. Children were tested at school in a specially outfitted mobile laboratory with a sound attenuating cabin. Adults were tested in a quiet room. All participants had normal hearing based on pure-tone audiometry (at 20 dB HL).

Assessments

A. Experimental Tests of Auditory Processing

Apparatus

Stimuli were presented by a personal computer (Dell Latitude D505) over Sennheiser HD600 headphones.

Stimuli

Three tests were selected from the temporal processing subsection of the Newcastle Auditory Battery (NAB) (Griffiths et al., 2001). These were detection of FM tones at 2 Hz and 40 Hz and detection of Iterated Rippled Noise (IRN). 240 Hz FM - not a NAB task - was included as a control task. Detection of FM at this rate of modulation is thought to draw on spectral rather than temporal processes (Witton et al., 1998). Carrier frequencies were 500 Hz for 2 Hz and 40 Hz FM and 1000 Hz for 240 Hz FM. All stimuli were sampled at a rate of 44100 and scales to have equal root means square values (0.2) before calibration using a sound level meter. Matlab 6.1 (The MathWorks Inc, 2001) was used to

generate the stimuli. All stimuli had durations of 1 second with 20 ms rise/fall times. For the FM tasks, detection threshold was in terms of the modulation index.

IRN is a temporal auditory stimulus thought to tap pitch processing based on temporal rather than spectral mechanisms and has been used experimentally to investigate the basis of temporal pitch processing (Griffiths, 2003). IRN is based on repeated overlaying of a random noise, with consecutive overlays delayed by n milliseconds. The resultant stimuli contains no consistent spectral pattern, though a pitch sensation is heard corresponding to the inverse of n . In this study, IRN was constructed as in the Newcastle Auditory Battery (Griffiths et al., 2001). The target stimuli was bandpass noise with a passband of 1-4 KHz iterated 8 times while the distracter stimuli contained passband noise only. Threshold for detection was gain, the ratio of IRN to noise. All stimuli were presented at 60 dB SPL.

Procedure

Adaptive methods are thought to be more suitable than full functions for use with young children as they are less time consuming while still providing reliable threshold estimates (Sutcliffe & Bishop, 2005; Werner, 1992). An adaptive procedure similar to that used by Sutcliffe and Bishop (2005) was used as follows:

Modulation depth (for FM and gain (for IRN) were altered adaptively using a PEST (parameter estimation by sequential testing) procedure (Taylor & Creelman, 1967).

Initially, very easy discriminations are presented with large step sizes that increase the difficulty until an error is made. When an error is made, the discrimination is made easier and step size is systematically reduced until a specified threshold level is reached. A three interval two alternative forced choice AXB format (3I2AFC) was used, where X is always

a standard tone and the target tone randomly occurs in either position A or B, with another standard tone in the remaining position; either “beep, boop, boop” or “boop, boop, beep”. Participants must then choose whether the target was in position A or B. Threshold was calculated from the last four reversals, with a maximum of 8 reversals in total. Thresholds were calculated from the 75% correct point on the psychometric function and the maximum possible number of trials was 80, though this was never reached. Tones were separated by 500 ms silent gaps.

Older children capable of attending to the task initiated the trial themselves. For younger children, the examiner initiated the trial when the child was attentive. In each trial, three cartoon characters (dinosaurs, characters from ‘the Simpsons’, kangaroos or owls) appeared on screen on top of a colored box. Two lower characters on the left and right of the screen produced the A and B (target) tones while a central character produced the X (reference) tone. A trial consisted of each character jumping on its box while producing a tone. The interval containing the target tone (FM/IRN) was randomly allocated on each trial. Older children were allowed to choose the target themselves by mouse click on the target character. Younger children pointed to the target character that produced the “wobbly sound” or the “funny noise” and the examiner entered the response by mouse click. Correct identification of the target was rewarded with a small picture and a cheerful noise, while incorrect identification elicited a cross and a disappointed sigh. Five easy examples were presented initially as training, and the trial proceeded if the child was able to correctly identify all five practice targets. For the auditory tasks, two thresholds per discrimination were obtained, with the average taken as the final threshold estimate. Order

of presentation was counterbalanced between children for both the auditory and visual tests.

B Visual Form and Motion Processing Tests

Apparatus:

Tasks were generated using Lua scripting language on a PC (Dell Latitude D505) connected to an external monitor (Iiyama Visionmaster 450). The external monitor display was 36 cm x 27 cm (45 cm diagonal) with 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 $22.91^\circ \times 17.19^\circ$). A circular target area 14.4 cm (9.17° in diameter) appeared with equal probability centrally on the left or right half of the display. The percentage of coherently oriented segments among randomly oriented segments (for Form) or coherently moving dots among randomly moving dots (for Motion) within the target area defined to coherence value on each trial. Line segments or dots formed concentric circles within the circular target area. For the motion stimulus, the direction of rotation of the coherently moving dots varied at random (either clockwise or anticlockwise). Figure 1 shows the form and motion displays.

The form stimulus was a static array of randomly oriented white line segments on a black background (density 7.62 segments/deg²). Line segments were generated by plotting simultaneously the positions that individual 0.18 cm diameter (0.114°) dots 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). Line segments thus varied in length from 0.24 to 0.63 cm (0.15° to 0.40°).

The motion stimulus was a random dot kinematogram with white dots on a black background at the same density as the form stimulus. Dots were 0.18 cm diameter (0.114°) and had a velocity of 3.37 cm/s (2.14°/s) with a limited lifetime of 8 frames (0.13 seconds). In order to prevent flicker caused by replacing each dot at the same frame, dots had an initial lifespan at the start of stimulus presentation that varied randomly between 1 and 8 frames (0.017 and 0.100 seconds). For both form and motion stimuli, both signal and noise dots had curved paths in order to avoid judgments. Coherent dots/line segments curved around the centre of the target area while noise dots/segments curved around a different randomly chosen point for each dot/segment.

Procedure:

Procedure was similar to that of Gunn et al (2002). Stimuli were presented with curtains drawn and room lights off. Detection thresholds were obtained using a two alternative forced choice (2AFC) method. Participants had to choose which half of the screen the coherent stimuli was present. So that children understood the task requirements, questions such as “Can you see the ball hidden in the grass?” were used. Children then responded by pointing to the location of the ball and the response was entered by the examiner. In between trials, the child’s attention was drawn to the midline of the screen by a set of three flashing colored boxes.

For each task, 3-6 practice trials at 100% coherence were carried out. Detection thresholds were then estimated using the Ψ method (Kontsevich & Tyler, 1999) for obtaining the

slope and threshold of psychometric functions. The Ψ method maximizes efficiency of threshold estimation by using continuously updated probabilities to select coherence at a level that maximized the information gained by completion of that trial. Form and motion coherence tasks were run successively for each child with the order of presentation of the tasks counterbalanced across children. Following Gunn et al (2000), one threshold was obtained for each task.

Insert Figure 1 here

C Other measures

i) SCAN-C

All children in the normative, dyslexia and APD groups were given the SCAN-C (Keith, 2000b), a commonly used standardized test of auditory processing. The SCAN-C is administered individually in either a quiet room or in audiometric conditions. It provides US population-based norms for children between aged between 5 and 11:11 years. Stimuli are recorded on compact disc and played over headphones. Children are asked to repeat target words and sentences which are then scored for accuracy. The SCAN-C provides an overall score as well as scores for its four subtests, Filtered Words (FW), Auditory Figure-Ground (AFG), Competing Words (CW), and Competing Sentences (CS).

ii) Strengths and Difficulties Questionnaire

In order to assess the possible contribution of attention to psychophysical test performance, parents of dyslexia and APD groups completed the Strengths and Difficulties Questionnaire

(SDQ) (Goodman, 1997). The SDQ is a brief screening questionnaire for behavior problems in children. The SDQ asks respondents to indicate to what extent each of 35 attributes, some positive, some negative, apply to their child. The 25 items are divided into 5 subscales; emotional symptoms, conduct problems, hyperactivity/inattention, peer problems and prosocial behavior. The SDQ also provides an overall index of behavior problems.

iii) Test of Word Reading Efficiency (TOWRE) (Torgesen et al., 1999). The TOWRE contains two subtests: 'Sight word efficiency', which assesses the number of real printed words that can be accurately identified within 45 seconds, and 'Phonetic decoding efficiency', which assesses the number of legal non-words correctly identified in 45 seconds. The TOWRE assesses 'sight word' reading, or the ability to recognise familiar words as a whole, as well as the ability to 'sound out' unfamiliar words, two essential reading skills. All children in the APD and dyslexia groups were administered the TOWRE subtests.

iv) The OSCCI spelling test was developed within the OSCCI laboratory a quick and efficient means of testing spelling ability. Children are asked to write a list of regular and irregular words within a two minute time limit. Performance norms are based on 58 typically developing British school children aged 6 to 15, using the regression of score on age to convert to age-adjusted z-scores.

Results

Prevalence of reading, auditory processing and attentional difficulties

48 % of the APD group (12 of the 25 for whom complete literacy test information was available) also met criteria for dyslexia, as defined for the dyslexia group.

Auditory processing difficulties within the APD and dyslexia groups were compared based on SCAN performance. In an earlier study, we found that UK children scored significantly more poorly than the US norms due to a strong effect of accent familiarity on performance (Dawes & Bishop, in press). We therefore adjusted the SCAN scores of the children in this study in accordance with the method outlined in Dawes & Bishop (in press). After adjustment, children were classified on the basis of their SCAN score according to recommended clinical cut-offs. One would expect around 16% of a random sample to score within the clinical range. Using UK adjusted scores, 24% of the dyslexia group and 29% of the APD group scored in this range. The surprisingly good performance of the APD group may be partially attributed to the use of unadjusted SCAN scores in these children's original diagnosis. In addition, although reliability estimates for the SCAN-C range from .65 to .82 by subtest based on population-based testing (Keith, 2000b), we suspect that reliability may be lower for clinical groups. SCAN-C re-test scores were available for 9 APD children less than 9 months after testing at each child's respective referring centre (median time interval, 4.5 months). 4 of these children scored within 1 standard deviation of their initial score while 5 children scored more than 1 standard deviation different (4 better, 1 worse). We are currently investigating reliability of the SCAN-C within this clinical population. For the current study, note that APD diagnosis was not solely based on the SCAN; other (mostly non-linguistic) AP tests as well as case history were used.

Inattention/hyperactivity was identified using parent-completed SDQ using recommended cut-off scores according to 'normal', 'borderline' and 'abnormal' categories (Goodman, 1997). Approximately 10% of the general population would be expected to score in the 'abnormal' range, with a further 10% in the 'borderline' range. The proportion of abnormal cases was 37% and 46% for the dyslexia and APD groups, respectively. The proportion of abnormal and borderline cases combined was around 50% for both dyslexia and APD groups.

Psychophysical test performance

Average threshold scores were standardised by year group for all psychophysical tests except for IRN. As performance was found not to change with age, IRN thresholds for all participants were standardised according to pooled normative group performance. For participants aged 11 and over, thresholds were standardised with reference to the normative sample 10 year-old age group. This represents a more conservative method of standardisation than possible alternative methods (such as using adult norms or extrapolation via linear regression). Some children scored very poorly (< -4 sd), though these were not the same children in every case (2 Hz, 1 dyslexia and 1 APD case; 40 Hz, 3 dyslexia and 5 APD; 240 Hz, 3 APD; IRN 2 APD; visual motion, 1 APD case). It is potentially informative that these children had such trouble with the task, whether due to task or procedural demands. Thus, rather than exclude them from analysis as outliers, all scores were standardized with a minimum score of 70, so that all those with scores more than 2 SD below the mean were given score of 70.

Comparison of group performance on psychophysical tests

Group performance after adjustment is displayed graphically in Figures 2 and 3.

A high proportion of participants in both clinical groups scored below -1 standard deviation on the psychophysical tests. Note that there is skew toward poor performance for both clinical groups on 2 Hz and 40 Hz, and for the APD group on 240 Hz, remembering that scores were standardized to have a minimum of 70. In terms of the number of auditory tests on which children performed poorly ($< -1 sd$), for the normative group, 85% scored poorly on 1-2 tasks with 15% scoring poorly on 3-4 tasks, compared to 66.6% and 33.3% for the dyslexia group and 58% and 42% for the APD group.

A MANOVA was carried out for standardised threshold scores by group. Performance on psychophysical tasks was significantly different between normative, dyslexia and APD groups ($F(12) = 4.38, p < 0.01$). Group performance differed significantly for every task. Pairwise comparisons revealed significant differences between normative and dyslexia groups on 2 Hz and 240 Hz FM, between normative and APD groups on all tasks, and between APD and dyslexia groups on 240 Hz FM. A discriminant function analysis with all six psychophysical tasks was performed to confirm the relation between groups and task performance. A single factor was able to explain 94% of variation in group performance ($\chi^2(12) = 52.2, p < 0.01$). 40 Hz FM and 240 Hz FM were the strongest contributors to this factor. 2 Hz FM and the two visual tasks did not strongly contribute to discriminating between groups. Standardized discriminant function coefficients are ranked in order of the strength of contribution to the discriminating function and displayed in Table 1

Insert Table 1 here

66% of participants could be classified correctly according to their function score.

However, this classification was more effective in discriminating between normative and clinical cases (dyslexia/APD) than between dyslexia and APD cases. Table 2 shows unstandardized canonical discriminant function scores at the mean for each group. The opposite signs for the normative (positive) and the two clinical groups (negative) suggests good discrimination between normative and clinical groups, but not between clinical groups.

Insert Table 1 here

Factors affecting performance of auditory psychophysical tasks

A discriminant function analysis was run with only the four auditory psychophysical tests. One function was able to explain 99% of the variance in scores ($\chi^2(8) = 48.7, p < 0.01$), and 40 Hz and 240 Hz FM again contributed most strongly to this factor. Factor scores were saved as a variable, and correlations with total SCAN score, performance IQ, composite literacy score (average of TOWRE word and non-word reading and spelling) and SDQ raw score for 'hyperactivity/inattention' scale calculated, as displayed in Table 3. There was no association between SDQ hyperactivity category or the literacy composite and the auditory factor score. There were small correlations with SCAN-C score and performance IQ.

Hypothesised 'APD performance'

One hypothesis regarding the cause of APD is a problem with temporal coding of sound. The test battery was therefore designed to assess sensitivity to variations in sound at different rates; 2 Hz FM, 40 Hz FM and IRN. A control task – 240 Hz FM, which can be done without reliance on central mechanisms - was included in the battery. The hypothesis was that if children with APD have a problem with temporal coding of sound, they will have a deficit in performance on one or more of the tasks 2 Hz, 40 Hz and/or IRN with normal performance on the 240 Hz task. A pattern of hypothesised 'APD performance' was then defined as a standard score poorer than -1sd on 2 Hz, 40 Hz and/or IRN and better than -1sd on 240Hz. Non-APD performance was either scores within the normal range on all auditory tests or a poor score on 240 Hz FM with or without poor scores on the remaining auditory tests. In the case of a poor score on the 240 Hz FM task, poor performance is hypothesised to be due to non-central auditory factors such as attentional or memory problems. Participants were not included in this analysis if they were missing any auditory test thresholds. 21% (21/98) of the normative group, 33% (6/18) of the dyslexia group and 32% (7/32) displayed the 'APD performance' profile.

Discussion

Is there evidence for specific problems with temporal auditory processing in children diagnosed with APD?

We hypothesized that if APD children had an auditory temporal deficit, they would display a pattern of good performance on the 240 Hz control task (which draws on spectral processes), with poor performance on one or more of the three temporal auditory tasks (2

Hz, 40 Hz or IRN). In fact, a similar sized minority (20-30%) of children in the APD, dyslexia and normative groups showed this pattern. This proportion may simply reflect the statistical likelihood of a child doing poorly on at least one of three tasks (ie 2 Hz, 40 Hz or IRN). In terms of group comparisons on individual auditory tasks, children with a diagnosis of APD did do more poorly on average than normative children on all auditory psychophysical tasks, including the control 240 Hz FM task. 240 Hz and 40 Hz were the two strongest contributors to discriminating auditory performance between normative and clinical groups. 240 Hz is thought to draw mainly on spectral processes while 40 Hz is thought to draw on both spectral and temporal processes. 2 Hz and IRN (the two tests that did not discriminate strongly between groups) are thought to draw mainly on temporal processes (B. J. C. Moore, 2004). It seems that peripheral, spectral auditory processes may actually be the auditory variable upon which children differed. Peripheral hearing was tested using a basic audiometric screening and only children who had thresholds better than 20 dB included in testing. In addition, APD is a diagnosis in which peripheral hearing abnormalities are specifically excluded; APD participants had undergone comprehensive peripheral hearing examinations at the auditory clinics from which they were recruited. If there were such a deficit in peripheral hearing, it must be one that is not detectable by normal audiogram. One possibility is that some children may have a deficit in spectral frequency resolution, perhaps due to broadened auditory filters. This is a peripheral hearing problem that would not be detectable using audiometry, but which could impact upon both speech discrimination in noise and psychophysical task performance. One could test this possibility by testing children's thresholds for signal detection in notched noise. Children with deficits in spectral frequency resolution would perform poorly on this task.

Insofar as there is a sensory processing deficit, is this deficit modality specific?

With regard to visual test performance and the hypothesis of modality specificity, there were significant between-group differences between the normative and the APD group on both coherent visual form and motion detection, with the APD group having poorer average performance. The fact that poor performance by children was not specific to the auditory modality is in line with the assertion that processing deficits are likely to be multi-modal (Bellis & Ferre, 1999).

Do attentional problems impact significantly on auditory test performance to the extent that some children's poor performance might be attributed to an attentional deficit?

We found a high proportion (46% versus an expected population rate of 10%) of children diagnosed with APD scored in the 'abnormal' range on the inattention/hyperactivity subscale of the parent completed SDQ. However, there was no correlation between auditory test performance and SDQ inattention/hyperactivity rating.

Given that many children with APD have poor reading, and conversely, auditory temporal problems have been described in dyslexia, are comparable problems seen in the two groups? More generally, are auditory problems more closely related to a child's literacy status or APD status?

A similar proportion of the dyslexia and the APD group scored poorly on the SCAN while ~50% of the APD group would also fit a diagnosis of dyslexia. Both children with dyslexia and children with an APD diagnosis did significantly more poorly on average than normative children on two auditory psychophysical tasks; 240 Hz and 40 Hz FM detection. Performance tended to be worse for the APD group across tasks, though except for 240 Hz FM, between-group comparisons were non-significant. The APD and dyslexia groups

could not be discriminated according to a general auditory performance factor. Although auditory and literacy problems were a feature of both clinical groups, there was no correlation between literacy skill and auditory performance. In the introduction to this article we identified a major issue in APD research and in learning disabilities research in general as being the relation between auditory impairments and language or literacy problems. The results in this study support the view that auditory impairments co-occur with literacy problems though they are not themselves directly related.

In summary, the auditory deficit seen in this study was not one that was specific to children with an APD diagnosis. The auditory deficit was one of spectral rather than temporal processing. There was also no evidence for a specific auditory deficit, as patterns of group performance on the visual tasks were similar to the auditory ones.

APD diagnosed children performed similarly to dyslexia children on all psychophysical tasks, though there was a non-significant trend for the APD group to be poorer than the dyslexia group. The difference between APD and dyslexia groups, then, is more one of quantity than quality. Note that two APD children were excluded from analysis due to low performance IQ, whereas no dyslexia cases were excluded on this basis. One possibility is that APD children may have more severe learning problems and have thus gone on to receive a diagnosis of APD because they have had more thorough clinical investigations – including auditory testing - than their peers with a dyslexia diagnosis. These results support Friel-Patti's (1999) suggestion that there may be more similarities than differences between children with APD and dyslexia or similar diagnoses and that the diagnostic label a child receives is partly dependent on the profession of the clinician they consult.

Auditory perceptual deficits may be better seen as part of a multi-factorial description of learning problems rather than as part of a diagnostic category in their own right. In both research and clinical settings, any distinction between children on the basis of categories such as 'Dyslexia' or 'APD' may actually be unhelpful, as it may focus attention on a single aspect of a child's difficulties –reading or auditory – when it may be more appropriate to view each case as involving contributions from multiple areas.

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Figure

Figure 1 Screen shots of the visual form and motion tests

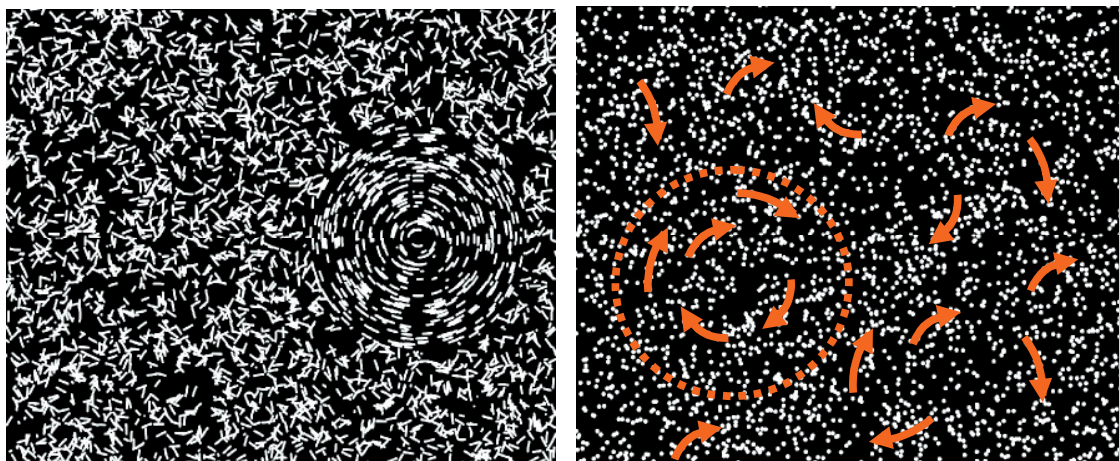


Figure 1 Group performance for auditory psychophysical tasks: Boxplots

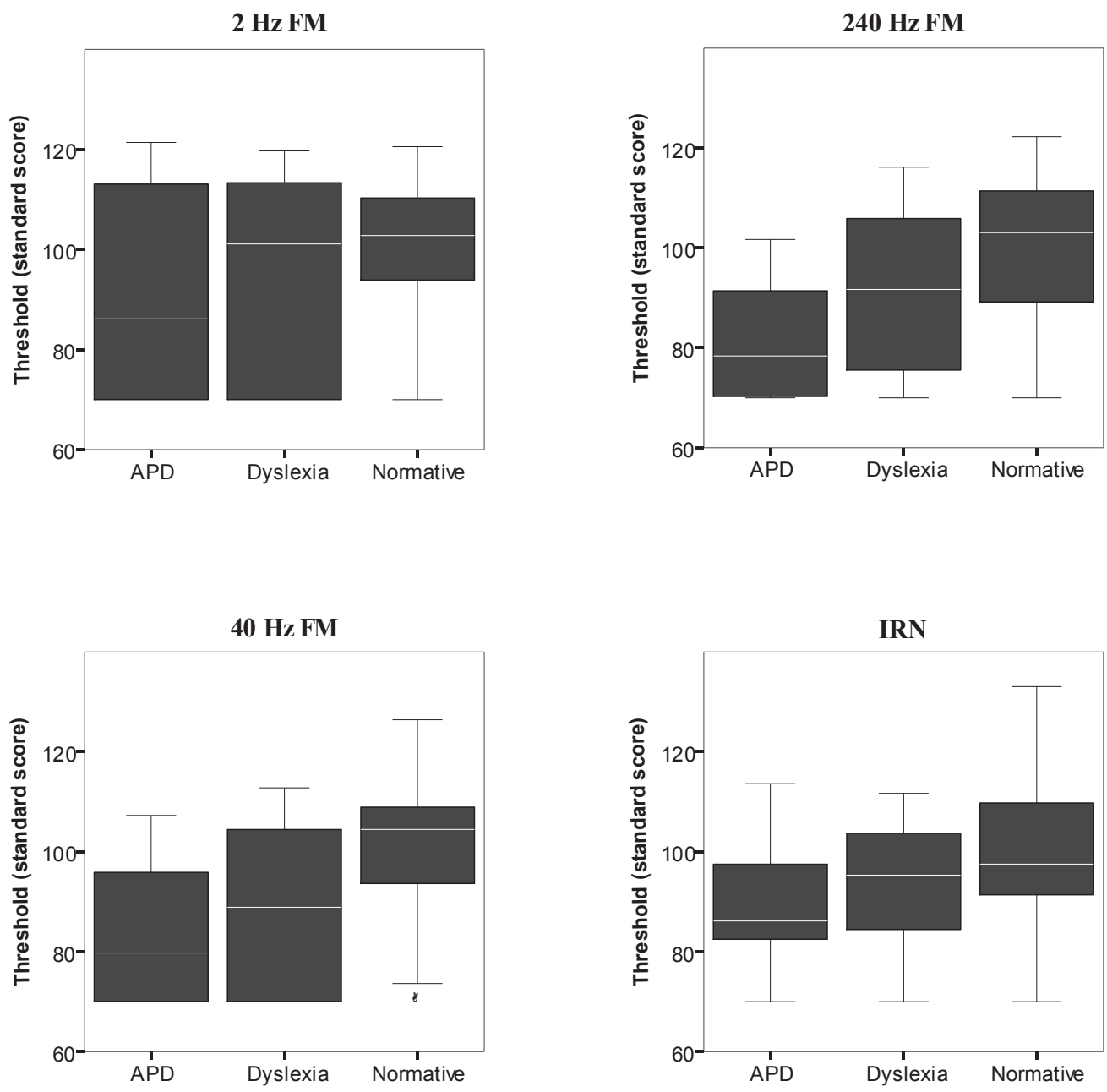
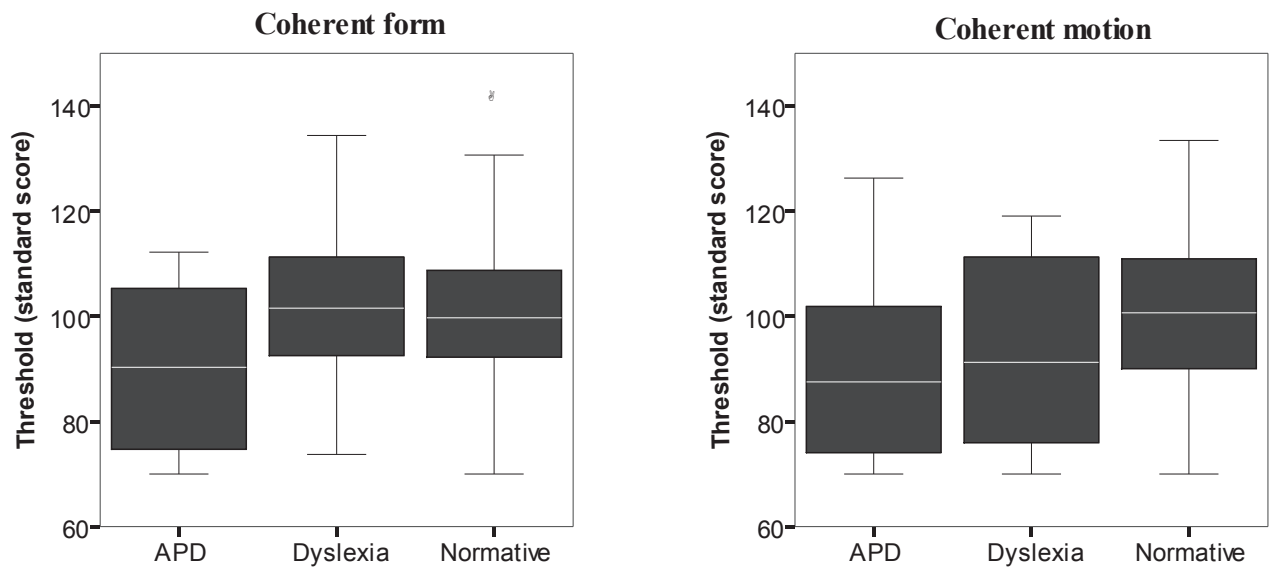


Figure 1 Group performance for visual psychophysical tasks: Boxplots



Table

Table 1 Standardized canonical discriminant function coefficients for each psychophysical task.

Task	Function 1
40 Hz FM	.54
240 Hz FM	.53
IRN	.30
Visual Form	.06
2 Hz FM	-.01
Visual Motion	-.02

Table

Table 1 Unstandardized canonical discriminant function scores at group centroids

Group	Function 1 score*
Controls	.43
Dyslexia	-.60
APD	-1.40

*Function 1 score is derived from discriminant function analysis including all six auditory and visual psychophysical tasks

Table

Table 1 Correlations between hyperactivity, performance IQ, literacy and auditory psychophysical performance

	Correlation with auditory factor score
SCAN-C	.41(**)
WASI IQ	.35(*)
Literacy composite	.10
SDQ	-.03
Hyperactivity	

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Pearson correlations, except for SDQ hyperactivity, Spearman correlation