The Impact of Auditory Processing and Cognitive Abilities in Children

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Objectives: To examine the links between auditory processing (AP) test results, functional deficits, and cognitive abilities.

Design: One hundred and fifty-five children, ages 7–12 years, comprising 50 control children and 105 children referred for AP assessment, all with normal peripheral hearing, completed an AP and cognitive (sustained attention, auditory working memory, and nonverbal intelligence) test battery. Functional outcome measures of listening ability (developed using questionnaires from parent, teacher, and child respondents) and reading fluency were also collected.

Results: AP scores for dichotic digits, frequency pattern, and listening in spatialized noise-sentences test baseline scores showed significant intertask correlations, and significant correlations with functional outcomes. The gaps in noise task showed correlation with reading fluency only. The AP tasks of masking level differences and spatial advantage showed no correlation with listening ability or reading fluency. Results showed significantly poorer cognitive abilities overall in the children referred for AP assessment compared with the control group. Within the referred group, children diagnosed with an auditory processing disorder had significantly poorer cognitive abilities than those passing the test battery. Correlation and regression studies showed significant associations between AP and cognitive scores. The results of multilinear regression analyses showed that the associations of AP scores with listening and academic results were no longer significant when cognitive scores were also included as predictors.

Conclusions: A complex interaction of cognitive abilities and AP scores is evident. For many children with listening difficulties, who perform poorly on AP tasks, cognitive deficits are also in place. Although the direction of causality is unclear, it is likely that these cognitive deficits are causing the perceived difficulty and/or are having a significant effect on the test results. Interpretation of AP tests requires consideration of how cognitive abilities may have impacted on not only task results but also the functional difficulties experienced by the child.

Key Words: Auditory processing disorders, Cognition.

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INTRODUCTION

Auditory processing (AP) disorder (APD) is defined by the American Academy of Audiology (AAA 2010) as “difficulties in the perceptual processing of auditory information in the central nervous system and the neurobiological activity that underlies that processing.” AP is the link between sound detection and the extraction of meaning from the signal (Bamiou et al. 2006) and inefficient AP is assumed to result in compromised listening ability (Moore et al. 2011).

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A diagnosis of APD is an umbrella term, reflecting a child’s pass/fail performance across a selection of AP behavioral tasks. The current recommended criterion for a diagnosis of APD is for scores falling two or more standard deviations (SDs) below the mean for at least one ear on any two different AP tests (AAA 2010). Earlier recommendations of the American Speech and Hearing Association (ASHA) have included an alternative criterion of falling below three SD on a single task (ASHA 2005), however. A criterion of 2 (or 3) SDs below the mean, on any task, as the criterion for a diagnosis of APD is not an evidence-based decision, and appears to have been chosen with the aim of failing only a few percent of children, assuming a normal distribution of scores. There is no evidence of the real-life consequences when scores on different AP tests are below normal. There is also no consideration of how real-life consequence, or impact, alters with differing scores on the same AP task.

The behaviors reported in children who meet a diagnostic criterion for an APD are well documented. Concerns include difficulties with skills, such as hearing and concentrating in the presence of background noise; following complex instructions; memory and literacy development, in the absence of any peripheral hearing dysfunction (Kraus et al. 1996; Chermak et al. 2002; Moncrieff & Musiek 2002; Wible et al. 2005; Sharma et al. 2007; Dawes et al. 2008; Sharma et al. 2009; AAA 2010; Ferguson et al. 2011). The causal link between behaviors and AP task performance is unclear, however. Presenting concerns, when compared with the diagnostic outcomes of an AP test battery, did not predict which children passed or failed the battery (Dawes et al. 2008), and therefore provide no better understanding of the consequences of poor AP ability. Furthermore, the presence or absence of a behavior does not quantify the degree of difficulty experienced by the child.

Behavioral questionnaires while unable to “predict” which child will be diagnosed with an APD (Dawes et al. 2008; Ferguson et al. 2011; Wilson et al. 2011) may provide a measure of impact in the quantified measures of functional listening ability. AP questionnaires were designed to characterize auditory difficulty, or listening ability, not diagnose APD (Smoski et al. 1998; Purdy et al. 2002a). Children who perform poorly on AP test batteries have been judged by teacher- and parent-completed questionnaire to have poorer listening performance than their peers (Smoski et al. 1992; Moore et al. 2010). Wilson et al. (2011) showed that questionnaire results correlated with diagnostic AP test scores (dichotic digits and frequency pattern tasks) in a clinical population. This demonstrated a link between a subjective report of behavior and AP task performance, and therefore a potential outcome measure.

Academic performance may also provide a functional outcome measure when examining the effect of APD. Children showing poor academic performance are often suspected of having an APD, presumed to be due to poor listening skills (Smoski

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TABLE 1. Examples of studies investigating the links of cognitive processes with APD

Authors	Subjects	APD Test Battery	Cognitive Assessments	Conclusions
Gyldenkærne et al. (2014)	119 children Age: 7–12 years (101 susAPD and 18 control)	FPT, DDT, GIN, and MLD	Attention: IVA-CPT NV-IQ TONI-4	Significant correlations of AP score with: NV-IQ and attention High comorbidity of attention deficit and APD; but two separate conditions
Ferguson et al. (2011)	SLI (n = 22) APD (n = 19) Controls (n = 47) Age: 6–13 years	Presence of accepted symptoms for diagnosis	Attention: questionnaire NV-IQ: WASI AWM: WISC (digit span)	Significantly reduced NV-IQ was seen in the APD (and SLI) group in comparison to mainstream groups. No group differences seen with attention or memory APD and SLI share similar profiles
Wilson et al. (2011)	104 children, susAPD Age: 6–14 years	Low pass filtered speech, competing sentences, DDT, and FPT	AWM: TAPS-R	Weak to moderate correlations between AWM and AP scores Significant deficits in memory could influence a subject's performance in AP tasks
Moore et al. (2010)	1469 (population study) Age: 6–11 years	Frequency discrimination Backward masking Simultaneous masking Speech in noise test	Attention: variability on AP tasks & IHR cued attention test. NV-IQ: WASI AWM: WISC (digit span)	Correlations of cognitive scores with AP Strongest relation was intrinsic attention and AP score APD is primarily an attention problem
Rosen et al. (2010)	20 susAPD 28 age matched controls Age: 6–14 years	Consonant cluster minimal pairs Tallal discrimination task Backwards and simultaneous masking	NV IQ: (WISC) ADHD: ADGDT questionnaire.	The presence or absence of auditory deficit does not predict cognitive skills
Sharma et al. (2009)	68 children susAPD Age: 7–12 years	FPT, DDT, RGDT, and MLD	Attention: IVA-CPT NV IQ TONI-4 AWM: CELF-4 (forward digits)	Attention and memory explain only a small amount of variance in AP scores
Keller et al. (2006)	18 children with NVLD Age: 6–18 years	SSW, phonemic synthesis and speech-in-noise tests	WISC Neuropsychological measures	The children also diagnosed with APD (n = 11) had significantly lower scores on memory function tasks
Riccio et al. (2005)	36 children referred for neuropsychological assessment Mean age of 7.78 years	SSW SCAN	AWM: CAVLT & CELF-4 Attention: TOVA (72% of children were diagnosed with ADHD)	Significant correlation between memory and AP tasks. No significant correlation between attention and AP scores. But poor attention as a group overall AP assesses attention and memory but also other processes

(*Continued*)

TABLE 1. Continued.

Authors	Subjects	APD Test Battery	Cognitive Assessments	Conclusions
Tillery et al. (2000)	32 school-age children diagnosed ADHD	SSW, phonemic synthesis speech-in-noise test	Psychologist diagnosed ADHD, receiving medication	No improvement in AP task performance in the medicated versus placebo conditions APD and ADHD are independent, but comorbid
Riccio et al. (1994)	30 children previously diagnosed with APD	SSW, low pass filtered speech Pitch pattern test seashore rhythm test	Presence of behaviors meeting criteria for ADHD 50% of children also met diagnostic criteria of ADHD	No significant differences were seen on cognitive measures between the children who passed and failed the APD battery High incidence of ADHD in this sample, but two separate disorders occurring
Cook et al. (1993)	Children with ADD (n = 15) Control group (n = 10) Age: 6–10 years	Speech reception, SSW, competing sentences, filtered speech, and rapidly alternating speech tests	Pediatrician diagnosis of ADD 12 of the 15 ADD boys met criteria for CAPD	Drug treatment in the ADD group resulted in improvement in AP test scores Sustained attention is a critical feature of AP performance. The two disorders are difficult to separate

ADD, attention deficit disorder; ADHD, attention deficit hyperactivity disorder; AWM, auditory working memory; CAVT, children's auditory verbal learning test; CELF-4, clinical evaluation of language fundamentals; DDT, dichotic digits test; FPT, frequency pattern test; GIN, gaps in noise; IHR, institute of hearing research; IVA-CPT, integrated visual and auditory continuous performance test; MLD, masking level differences; NV-IQ, nonverbal intelligence quotient; NV-LD, nonverbal learning disability; RGDT, random gap detection test; SCAN, screening test for auditory processing disorders; SusAPD, suspected of having an APD; SLI, specific language impairment; SSW, staggered spondaic words; TAPS-R, test of auditory perceptual skills, revised; TOVA, tests of variable attention; WASI, Wechsler abbreviated scale of intelligence; WISC, Wechsler intelligence scale for children; APD, auditory processing disorder.

et al. 1992). Although a study by Watson et al. (2003) found no significant link between AP ability and academic outcomes, other studies have demonstrated comorbidity between reading deficits and APD diagnosis (Ramus 2003; Bishop & Snowling 2004; Sharma et al. 2009). Reading ability may therefore provide a second quantified measure of real-life difficulty the child experiences, although it may have many causes other than AP deficits.

An important caveat to any discussion of the effect of poor AP skills is the contribution of a child's cognitive, or top–down processing skills. The underlying nature of APD and the role of top–down processes in listening ability has long been debated (Cacace & McFarland 1998; Moore et al. 2010).

The definition of APD, and consequently the way that cognitive abilities are thought of in relation to AP ability, can be seen to vary greatly between professional bodies (ASHA 2005; AAA 2010; BSA 2011). In 2005, ASHA stated that higher order cognitive abilities were specifically excluded from their definition of AP. APD was defined as "a deficit in neural processing of auditory stimuli that is not due to higher order language, cognitive, or related factors." The AAA, in 2010, built on the ASHA (2005) definition of APD, but reported that cognition may have a greater contribution; AP being a complex event, with not just parallel and serial processing occurring in the central auditory nervous system, but also shared processing with higher order brain structures. It was noted that the behaviors in APD often overlap with cognitive disorders, and a multi-disciplinary approach to the diagnosis of APD was recommended. The following year, the British Society of Audiology (BSA 2011) defined APD as a neurodevelopmental disorder with a significant, dominant cognitive influence. A range of symptom(s), including impaired language and perception of sounds (speech and nonspeech) were included in the definition, with all being closely associated with impaired top–down, cognitive functioning.

Similarly studies can be found that conclude that cognitive disorders and APD exist independently (Tillery et al. 2000; Sharma et al. 2009; Rosen et al. 2010); others conclude that APD is in itself a cognitive disorder (Cook et al. 1993; Moore et al. 2010; Ferguson et al. 2011). A large population study by Moore et al. (2010) of 1469 randomly selected children with normal hearing concluded that APD represents a problem of auditory attention, with poor task performance highlighting children who have problems with "control of listening." Close relationships between attention deficit disorder (ADD) and auditory processing have been shown, with stimulant drug treatment for ADD resulting in significant improvements in AP test performance (Keith & Engineer 1991; Cook et al. 1993; Freyaldenhoven et al. 2005; Sutcliffe et al. 2006). Tillery et al. however found that children diagnosed with ADD showed no improvement in performance on the tasks selected to measure AP ability.

More specific discussions of the extent to which the results of the individual tests commonly used to diagnose APD are affected by cognitive abilities can also be seen (Cacace & McFarland 1998; Sharma et al. 2009; Moore et al. 2010; Rosen et al. 2010). Frequently, it is the degree of influence of not only sustained attention but also auditory working memory (AWM) and nonverbal intelligence (NV-IQ) on AP task performance that is discussed under the heading of cognition and AP. The question of the degree to which cognitive abilities influence AP ability (meaning the child's performance on tests designed to measure AP) has not been definitively answered. Examples of these studies, and their conclusions, are shown in Table 1. Studies can be found demonstrating strong links between cognitive and AP scores (Cook et al. 1993; Riccio et al. 2005; Moore et al. 2010). Moderate links, demonstrating contributory relations between cognition and AP ability are found (Riccio et al. 1994; Wilson et al. 2011; Gyldenkærne et al. 2014) alongside studies reporting weak interactions between cognitive and AP task ability (Tillery et al. 2000; Sharma et al. 2009; Rosen et al. 2010).

Few consistencies are found in the design, and conclusions of studies examining AP ability, as measured by task performance, and the cognitive abilities of attention, memory, and/or NV-IQ as evidenced in Table 1. Studies vary in composition of test battery (although some commonalities exist, rarely do two studies utilize the same test battery), and the tools used for cognitive assessment. Participant characteristics also vary between studies, for example whether a child is suspected of APD on the basis of symptoms present or has been diagnosed by a behavioral test battery. Small sample sizes are often reported and many do not include a control group. A further factor confounding comparisons between studies is whether results were considered as correlations in performance across continuums, or as group differences between those diagnosed and those not (and again how this definition was reached).

This study explores the influence of cognitive abilities on performance on AP tasks commonly used clinically, and the joint relation of both cognitive and AP abilities to a child's real-life listening ability and academic performance. The hypotheses are threefold. First, that the scores on the different tasks within the AP test battery will show little correlation with each other as they measure different listening skills. Second, that across the various AP tasks, different relations with the real-life difficulties the child experiences will be shown. Finally, that the influence of the cognitive measures will be evident not only on AP tasks but also on the relation between AP scores and functional outcomes. The aim of this research is to better understand the link between functional listening ability and AP skill deficit as measured with commonly used tests of AP.

METHODS

This study carries approval from the Ethics Committees of the Royal Victorian Eye and Ear Hospital (10/941H) and the Department of Education (2010_000789). All testing conformed to the tenets of the Declaration of Helsinki and informed consent was obtained for all children after explanation of the nature, purpose and expected outcomes of the study.

Participants

One hundred and fifty-five children between 7 and 12 years of age at the time of testing were enrolled in this study. All children completed the same test battery (summarized in Table 2). Children demonstrated normal peripheral hearing (≤15 dB HL) at the octave frequencies from 250 Hz to 8 kHz, bilaterally, and were shown to have middle ear immittance values consistent with normal middle ear function (Jerger Type A tympanograms; Jerger 1970), defined as a peak compliance within 0.2 to 1.6 mmhos, and peak pressure within −100 to +20 daPa, at the time of assessment. All children were enrolled in mainstream metropolitan primary schools.

Two separate recruitment streams were used. The first enrolment pathway, the "clinical group," consisted of a total of 105

TABLE 2. Summary of test battery components across the measures of auditory processing, cognition, academic progress, and listening ability

Measure	Domain	Test	Task
Auditory processing	Temporal sequencing	FPT (DVA recording)	State the sequence of pitch in a series of three high (1122 Hz) or low (880 Hz) pitched tones
	Binaural integration	DDT (ASL recording)	Free recall of the four numbers in the two ears (two pairs, with the members of each pair presented simultaneously to each ear)
	Temporal resolution	GIN (ASL recording)	Detect gaps in a noise burst between 2 and 20 msec in duration.
	Binaural integration	LiSN-S	Spatial listening ability determined by speech reception thresholds to sentences in various signal to noise presentations
		MLD (ASL recording)	Detect a tone in noise with and without an inter-ear phase difference
Cognition	Nonverbal IQ	TONI-4	State which figure (out of a choice of 6) completes a pattern
	Auditory working memory	CELF-4	
	Sustained attention	Digit span forward	Repeat number sequence
		Digit span reverse	Repeat number sequence in reverse order
		IVA CPT	Mouse click when the number "1" is seen or heard, but ignoring the number "2"
Outcome measures	Reading fluency	WARP	Word correct per minute score from passage of text read aloud
	Listening ability	Questionnaire	Composite measure based on questionnaire results completed by child, parent, and teacher

DVA, Department of Veterans Affairs; Tonal & Speech Material for Auditory Perceptual Assessment, Noffsinger et al. (1994). ASL, Auditec of St Louis recording; TONI 4, test of nonverbal intelligence (version 4), Pro-Ed; CELF-4, Clinical Evaluation of Language Fundamentals (version 4), Pearson; IVA CPT, Integrated Visual and Auditory Continuous Performance Test, BrainTrain; FPT, frequency pattern test; DDT, dichotic digits test; GIN, gaps in noise; LiSN-S, listening in spatialized noise-sentences test; MLD, masking level differences; WARP, Wheldall assessment of reading passages.

children (70 boys, 35 girls) with a mean age of 8.9 ± 1.5 SD years (range of 7.0–12.9 years) referred to the University of Melbourne Audiology Clinic for a clinical APD assessment. The second group, the "control" group, comprised a total of 50 children (31 girls and 19 boys) with a mean age of 9.3 ± 1.4 SD years (range of 7.0–12.2 years). Control children were recruited through their primary schools. Inclusion criteria were no parental-reported concerns regarding hearing, listening, academic progress, and/or learning ability.

No significant between group age differences were seen using a two-sample t test ($t = -0.20$, df = 107; $p = 0.84$). A gender bias was evident between the two groups (χ^2 test of association; $\chi^2 = 11.84$, df = 1; $p = 0.001$) and is addressed further in the results section.

Socioeconomic Status

For children in both control and clinical groups, the index of relative socioeconomic advantage and disadvantage (IRSAD) was recorded. Based on residential postcode this summarizes information about the economic and social conditions within the postcode area, including both relative advantage and disadvantage measures (Australian-Bureau-of-Statistics 2013). Postcode determination of socioeconomic status (SES) potentially lacks the precision that measures, such as parental education may provide, but is an inexpensive, nonintrusive method of aggregate imbalances (Centre for the Study of Higher Education 2008). Mean scores of 1033 (39.5 SD) for the control group and 1041 (47 SD) for the clinical group (higher score greater advantage) were not shown to be significantly different using a Mann–Whitney test of difference ($w = 3494$; $p = 0.12$). SES was found to have no significant correlation with any component of the test battery (Table 5).

Test Battery

AP Tasks • An AP test battery was chosen to reflect not only the current literature but also to contain tasks currently in clinical use (Jerger & Musiek 2000; Emanuel 2002; Chermak & Lee 2005; Sharma et al. 2009). The test set was also chosen to meet the recommendations of ASHA (2005) and AAA (2010) to assess the domains of AP as it is defined: sound localization and lateralization; dichotic listening, auditory discrimination; auditory temporal processing, and auditory performance with competing or degraded acoustic signals.

The five behavioral tests selected to assess AP ability were the frequency pattern test (FPT), dichotic digits test (DDT), gaps in noise (GIN), masking level differences (MLD), and the listening in spatialized noise-sentences test (LiSN-S). Moderate to strong test–retest reliability have been demonstrated for all five tasks (Musiek et al. 1991; Musiek et al. 2005; Cameron et al. 2009; Moore et al. 2011; Sharma et al. 2012). The domain of temporal sequencing was assessed using the FPT (Musiek 1994), in which the listener states the sequence of pitch in a series of three high (1122 Hz) or low (880 Hz) pitched tones, heard under headphones, monaurally. Percentage correct scores (reversals were counted as incorrect) were determined for each ear, for 15 presentations per ear, after three to five practice trials. The second domain was assessed by the DDT (Musiek 1983), which requires the listener to repeat four numbers heard (two pairs, with the members of each pair presented simultaneously to each ear). Percentage correct scores for each ear were collected, after 20 trials, and three initial practice trials. Temporal resolution was assessed using the GIN task (Musiek et al. 2005). Broadband noise segments of 6 seconds in duration are presented monaurally, containing up to three silent gaps, which vary in duration from 2 to 20 ms, with the listener responding when a gap is perceived. Threshold scores (the shortest gap correctly identified for a minimum of four of six presentations) for each ear are obtained over approximately 30 trials per ear, after completion of a practice test. Binaural interaction was assessed using the MLD (Wilson et al. 2003) and LiSN-S (Cameron & Dillon 2007) tasks. The MLD is a binaural listening task that determines the signal (500 Hz tone) to noise (500 Hz narrow band noise) ratio required for tone detection, for interleaved homophasic and antiphasic tone conditions presented with decreasing signal to noise ratios, with a "yes" response used for tone detection. The resulting score (dB) is the difference in scores between the thresholds in the two conditions. The LiSN-S (Cameron & Dillon) determines two speech reception thresholds in conditions that vary in terms of the location of the masker source and vocal quality of the speaker. Also reported is the spatial advantage score of the LiSN-S being the dB improvement afforded by the provision of spatial cues when the target and distractor speech are spoken by the same talker.

This test battery is summarized in Table 2. Test materials (excluding the LiSN-S) were delivered under headphones, at 50 dB HL. Test and ear order were randomized.

Expression of AP Results • DDT, FPT, and LiSN-S scores were converted to z scores using age-specific normative data from published sources (Cameron & Dillon 2007; Tomlin et al. 2014), expressing performance as the difference from the mean of their age peers, in SD units of that population. z scores were generated for the GIN and MLD results from the normative data provided by the control group.

Cognitive Tasks • AWM was assessed using the Digit Span subset of The Clinical Evaluation of Language Fundamentals, 4th edition (CELF-4; Semel et al. 2003). The task requires correct repetition of a series of numbers, in increasing length, in both a forward and reverse order. Evidence of good reliability is reported in the CELF-4 manual (Semel et al. 2003). Raw scores are converted to age-matched scaled scores. The forward condition is thought to be indicative of auditory short-term memory, affecting phonological processing and retention of verbal information for a brief period, with the reverse score being more specific to AWM, involving higher level executive function and attention control (Rosen & Engle 1997; St Clair-Thompson 2010). Both measures were collected and converted to z scores (the CELF-4 provides age-specific results that express a child's result as a scaled score, with a mean of 10 and SD of 1.5). A Pearson r correlation of 0.47 ($p < 0.001$) was demonstrated between the forward and reverse digit span scores. For the majority of analyses, a mean score (termed the AWM score) was used (generated by averaging the two z scores). In addition, the forward and reverse scores are included in the correlation matrix (Table 5).

The test of NV-IQ (4th edition; TONI-4; Brown et al. 2010) was used to obtain NV-IQ scores; a score of reasoning ability and intelligence with minimum influence of language. The task requires the child to complete a pattern using multiple-choice options, with increasing complexity. This task has been demonstrated to be culturally robust for Australian populations (Jenkinson et al. 1996; Kamieniecki & Lynd-Stevenson 2002;

Mathias et al. 2007), with high test–retest reliability demonstrated (McGhee & Lieberman 1991).

Sustained attention was assessed using the integrated visual and auditory continuous performance task (IVA-CPT; Sandford & Turner 1995), a normed testing tool demonstrated to be effective in the diagnosis of attention deficit hyperactivity disorder (Losier et al. 1996; Quinn 2003). The quotient scores are automatically generated by the reporting component of the IVA-CPT software, and represent age- and gender-matched population norms (Sandford & Turner). Moderate to strong test–retest reliability measures are reported in the IVA-CPT interpretation manual (Sandford & Turner 2009). The test lasts approximately 13 minutes, presenting trials of 500 “1”s and “2”s in a pseudorandom pattern to assess sustained visual and auditory attention ability. The child is instructed to respond only when they see or hear a “1.” Alternating segments are presented with either the “1”s or “2”s being commonly presented. Response scores (both raw and quotient) are provided. The full-scale Attention quotient incorporates measures of inattention, loss of focus, and slow processing speed (as measured by reaction time) and is derived from separate auditory and visual attention quotients. Also utilized in this study were the visual and auditory sustained attention IVA-CPT scores; global measures of the ability to respond accurately under low demand conditions and to sustain attention under high demand conditions. Strong correlations were observed between the sustained auditory and visual attention measures ($r = 0.68$; $p < 0.001$), and both also showed equally strong correlation with the overall full-scale attention score ($r = 0.86$; $p < 0.001$). Therefore, the full-scale score (termed the attention score) has been utilized in the analyses for this study.

For all three cognitive measures, raw scores were converted to age-specific quotient scores using the provided norm references. The resulting quotient scores (having a mean of 100 and SD of 15) were converted to z scores, referred to as the NV-IQ score, the AWM score, and the attention score, expressing the child’s performance in line with the other measures in the battery.

Functional Outcome Measures

Listening Ability • A measure of the child’s listening ability was obtained using questionnaires. To increase the reliability of the measure, a three-way approach was taken with the child, parent, and teacher each completing a different questionnaire. Three questionnaires were selected that explored the child’s listening ability and the results of these were used to generate a composite listening ability score.

The parent completed the Fisher’s Auditory Problem Checklist (Fisher 1976). This is a 25-point behavioral checklist, on which the parent indicates if certain specific behaviors have been observed. The classroom teacher completed the teacher evaluation of auditory performance (TEAP; Purdy et al. 2002b), which rates seven of the child’s listening and classroom behaviors in comparison to peers on a seven-point scale of degree of difficulty. The child completed the listening inventory for education (LIFE; Anderson & Smaldino 1996), which quantifies a child’s level of listening difficulty. A shortened version of this was used, with the child rating ease of listening in seven classroom listening scenarios (questions 2, 5, 7, 9, 10, 11, and 13 from the LIFE-UK questionnaire) on a five-point scale (Purdy et al. 2009).

TABLE 3. Correlations (Pearson *r* correlation; *p* ≤ 0.01) among the three questionnaires

Questionnaire	Fisher	LIFE
Fisher (parent)	—	—
LIFE (child)	−0.40	—
TEAP (teacher)	0.63	−0.49

LIFE, listening inventory for education; TEAP, teacher evaluation of auditory performance.

Questionnaire Internal Consistency • Each set of questionnaire results underwent an item-total correlation analysis, performed for all children and two random (even and odd identifier) groups. Questions were removed from the final total score of that questionnaire where the individual item-total correlation for the question was weak (<0.3) in all three analyses. A Cronbach’s α analysis was then used to confirm that removing these items improved the internal consistency of the question set for that questionnaire (Dillon 2012). This process resulted in six items being removed from the Fisher checklist, with a resulting improved Cronbach’s α of 0.88. One item was removed from the LIFE, with a resulting improved Cronbach’s α of 0.74. No items of the TEAP were removed, with a Cronbach’s α of 0.95 recorded. A maximum Cronbach’s α of 0.9 is recommended, with values exceeding this (as is seen with the TEAP results) suggesting redundancies may be present in the question set (Tavakol & Dennick 2011). This suggests that some of the items in the TEAP questionnaire were interpreted as asking about similar scenarios, rather than seven different listening situations.

Intrasubject Reliability • The three questionnaire results were then analyzed to ensure correlations were present between the three reporters before combining the results. Moderate to strong ($p < 0.01$) correlations were found, with Pearson correlation coefficients as shown in Table 3. Note the negative correlations are a result of poorer TEAP and Fisher scores suggesting more difficulty, and the converse in the LIFE.

Factor Analysis to Generate the Listening Ability Score • To produce the final listening ability score, a maximum likelihood factor analysis of the correlation matrix was carried out on the results of the 95 children for whom all three questionnaires were available. The analysis returned a one-factor model with an Eigenvalue of 1.8. No further factors with an Eigenvalue > 0.5 were identified. The one-factor model, with the unrotated factor loadings and standardized coefficients shown in Table 4, was found to explain 53% of the variance in the three individual questionnaire scores.

The proportion of individual questionnaire variance that is error variance (i.e., variance that is not associated with scores on the other two questionnaires) equals one minus the factor loading squared. This error variance varied from 23% for the TEAP up to 69% for the LIFE questionnaire. The variance in the factor scores can be partitioned into a component that is

TABLE 4. Factor analysis results of questionnaires

Questionnaire	Factor Loading	Factor Coefficient
Fisher (parent)	0.71	0.24
LIFE (child)	−0.56	−0.14
TEAP (teacher)	0.88	0.66

LIFE, listening inventory for education; TEAP, teacher evaluation of auditory performance.

related to the variance common to the individual questionnaire scores and an error component. The error component is estimated to be 17%, reflecting the ability of factor scores to more accurately represent the underlying ability than any one of the indicator scores (Harman 1976).The remaining 83% of the variance in the factor scores represents the upper proportion of variance that could be explained by, or that could explain, any other variable, given the error component in the listening ability factor scores.

Scores were standardized and then combined according to the factor coefficients shown in Table 4 to generate a listening ability measure. The teacher-completed TEAP shows the highest correlation with the other two measures and therefore has the highest contribution to the overall score. The negative contribution of the LIFE is consistent with a lower score in this questionnaire indicating less difficulty; the opposite to the scoring applied to the Fisher and TEAP (where a lower score describes greater difficulty).

Missing Questionnaire Data Points • Sixty of the 155 children had missing teacher-completed TEAP scores. Based on their reading proficiency scores, the mean reading fluency scores of the group with TEAP scores was 0.03 (SD 1.03), and for those without a TEAP score was −0.25 (SD 1.08). This difference of 0.28 (confidence interval: −0.14 to 0.69) was not significant (two sample t test, $t = 1.62$, df = 153; $p = 0.11$) and Levene's test for equal variances also returned a nonsignificant result ($p = 0.62$). These statistics suggest that there was no systematic relation between reading ability and the likelihood of the TEAP scores being missing. Consequently, a multiple regression was then used to generate an equation (from the 95 children with all three questionnaire results and therefore a listening ability score) to estimate listening ability score based on the standardized LIFE and Fisher scores only (LIFE: $T = -6.01$, $p < 0.001$; Fisher: $T = 10.4$, $p < 0.001$; R^2 adjusted: 0.72). The regression equation was applied to the standardized LIFE and Fisher results of the 60 children without TEAP scores to provide an estimated listening ability score. The process was repeated for the children with the TEAP scores to compare the estimated score to the actual score. The estimated score showed a significant correlation (Pearson correlation $r = 0.85$; $p < 0.001$). This process produces an unbiased estimate of listening ability, but has lower reliability than when all three scores are available.

Reading Fluency Score • Reading fluency for all children was determined using the Wheldall Assessment of Reading Passages (WARP) as outlined by Madelaine & Wheldall (2002), providing a correct word per minute score as the child read aloud from a specified passage of text.

A subset of children (67) also had National Assessment Program of Literacy and Numeracy (NAPLAN; ACARA 2012) results available (completed within 12 months of the AP assessment). These provide an independent assessment of reading, along with writing, spelling, grammar, and numeracy. Significant correlations were seen between the WARP score and each of the NAPLAN measures, with the highest correlation being seen with the reading score ($r = 0.65$; $p < 0.001$). For all other NAPLAN measures, the Pearson r correlation ranged from 0.53 (numeracy) to 0.59 ($p < 0.001$). This supported the use of the WARP reading fluency score across the cohort both as a direct measure of literacy and as an indirect estimator of overall academic progress.

RESULTS

Gender Effects

To explore effects of gender biases present in both the clinical and control group (toward boys in the clinical group, and girls in the control group), a three-way ANOVA was performed, with gender and group as categorical variables and test scores (all measures across the AP and cognition test battery) as repeated measure (within group) variables. A significant effect of group was seen ($F(1,93) = 20.7$; $p < 0.001$), but not of gender overall ($F(1,93) = 1.60$; $p = 0.29$). No interaction of group by gender ($F(1,93) = 0.02$; $p = 0.88$) or three-way interaction among test, gender, and group was seen ($F(11,1023) = 0.49$; $p = 0.91$). An interaction of gender with test was found ($F(11,1023) = 2.35$; $p < 0.01$). ANOVA results therefore demonstrate gender having the same effect in both groups, but a significant interaction with test scores. Consequently, in multiple regression analyses, gender (dummy coded as 0/1) has been added as a predictor.

Table 5 shows the resulting correlation matrix, using z scores on all tasks, across the cohort (i.e., clinical and control group combined). In this analysis, no diagnosis is being made, but rather scores are considered along a continuum.

Many significant correlations are seen across the matrix, demonstrating significant relations among AP, functional outcomes, and cognitive scores. The following sections explore these relations in greater detail. A significant correlation ($r = 0.54$; $p < 0.001$) was observed between the child's listening ability score and reading score, demonstrating the links between the questionnaire results and the quantified functional performance score of reading fluency which had been independently verified (by the significant correlation of the WARP score with NAPLAN data).

Correlations Between AP Scores

Significant and high correlations were found between the right and left ear FPT (Pearson r correlation = 0.91; $p < 0.001$) and GIN (Pearson r correlation = 0.80; $p < 0.001$) scores. Consequently, the results of these tests are reported as the mean of the bilateral scores.

Within the AP test battery, significant correlations were seen among the FPT, DDT, and baseline measures of the LiSN-S (high cue and low cue). GIN, MLD, and the spatial advantage measure of the LiSN-S showed no significant correlation with other AP scores.

Functional Outcomes and AP Scores

Individual AP Tasks • Weak to moderate significant correlations were observed between a child's listening ability and the DDT, FPT, and LiSN-S low-cue and high-cue scores. No significant relation with listening ability was seen for the AP tests of GIN, MLD, and LiSN-S spatial advantage scores (Fig. 1 and Table 5).

Weak to moderate significant correlations were also observed between a child's academic progress as measured by reading fluency in a similar set of AP tasks: DDT, FPT, GIN, and LiSN-S low-cue and high-cue scores. Again, no significant relation with reading fluency was seen for the AP tests of MLD and LiSN-S spatial advantage scores (Fig. 2 and Table 5).

It is evident from the plots in Figures 1 and 2 that the significant correlations between the AP scores and the outcome measures occur because the two groups have different mean

TABLE 5. Pearson correlation results across the test battery

Score	Listening Ability	Reading Fluency	Left DDT	Right DDT	Mean FPT	MLD	Mean GIN	LiSN-S Low Cue	LiSN-S High Cue	LiSN-S Spatial Advantage	Digit Span Forward	Digit Span Reverse	AWM	Attention Score	NV-IQ
Listening ability	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Reading fluency	0.54†	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Left DDT	0.21*	0.35†	—	—	—	—	—	—	—	—	—	—	—	—	—
Right DDT	0.34†	0.32†	0.38†	—	—	—	—	—	—	—	—	—	—	—	—
Mean FPT	0.20*	0.34†	0.30†	0.29†	—	—	—	—	—	—	—	—	—	—	—
MLD	−0.09	0.00	−0.07	−0.10	0.00	—	—	—	—	—	—	—	—	—	—
Mean GIN	0.10	0.26†	0.09	0.09	0.18	0.03	—	—	—	—	—	—	—	—	—
LiSN-S low cue	0.27†	0.21†	0.24†	0.21†	0.13	−0.05	0.04	—	—	—	—	—	—	—	—
LiSN-S high cue	0.20*	0.34†	0.18*	0.10	0.11	−0.08	0.13	0.24†	—	—	—	—	—	—	—
LiSN-S spatial Advantage	0.07	0.12	0.06	0.11	0.11	0.02	0.18	−0.08	0.47†	—	—	—	—	—	—
Digit span forward	0.25	0.45†	0.43†	0.36†	0.26†	0.09	0.11	0.27†	0.12	0.00	—	—	—	—	—
Digit span reverse	0.37	0.53†	0.39†	0.34†	0.36†	−0.06	0.06	0.18*	0.11	0.03	0.47†	—	—	—	—
AWM	0.36†	0.56†	0.48†	0.41†	0.35†	0.06	0.10	0.27†	0.14	0.02	0.87†	0.84†	—	—	—
Attention	0.31†	0.38†	0.22†	0.22*	0.27†	0.02	−0.04	0.02	0.09	0.09	0.16	0.36†	0.31†	—	—
NV-IQ	0.40†	0.51†	0.38†	0.28†	0.43†	0.05	0.14	0.28†	0.22†	0.08	0.32†	0.32†	0.37†	0.26*	—
Socioeconomic status	−0.05	0.08	−0.10	0.01	−0.01	0.07	0.06	−0.04	−0.07	0.05	0.04	0.06	−0.06	−0.02	0.04

*Asterisks denote significant relations (*p ≤ 0.05; †p ≤ 0.01).*
DDT, dichotic digits; FPT, frequency pattern test; MLD, masking level differences; GIN, gaps in noise; AWM, mean auditory working memory score; NV-IQ, nonverbal intelligence; LiSN-S, listening in spatialized noise-sentences test.

values for both the AP score and the outcome measure. The correlations are less evident when viewed within each group. Correlation analyses between the two functional outcome measures and the AP test battery was repeated separately for the clinical and control groups. Only the mean FPT and reading fluency scores showed a significant correlation in both the control group (r = 0.35; p = 0.01) and clinical group (r = 0.28; p = 0.01). None of the remaining comparisons showed significant results in either group. This suggests that the correlations seen for the total group are being caused by a difference between the two groups rather than an intrinsic relation between the two variables plotted.

Cognition and AP Scores

Group Differences • Thirty-six of 105 (34%) of the clinical group met conventional diagnostic criteria for APD of failing two AP tasks by two SD or one task by three SD (ASHA 2005). This subgroup has been termed "APD+." The remaining 69 children of the clinical group are termed "APD−" (representing the children from the clinical group who passed all AP tasks). The cognitive scores for these groups are shown in Figure 3, alongside the scores of the control group.

An ANOVA was performed with the cognition scores as the dependent variables. Cognition type (AWM, attention, and NV-IQ) was the within-subjects factor and subgroup (control, APD+, and APD−) was the between-subjects factor. The ANOVA showed a highly significant effect of subgroup (F(2,114) = 32.24; p < 0.001), and a (just) nonsignificant interaction between cognition type and subgroup (F(4,228) = 2.32; p = 0.058). Posthoc comparisons showed that the average of the two clinical subgroups (APD− and APD+) had poorer cognitive ability (averaged across the three cognition scores; difference score 95% confidence interval [0.73, 1.24]; p < 0.001) than the control group, and that the APD+ group was poorer than the APD− group (95% confidence interval [0.13, 0.73]; p = 0.006).

Posthoc tests showed that the three groups differed from each other in terms of overall cognitive scores (p < 0.001) but not in terms of any one cognitive test when taken one at a time.

This demonstrates that, on average, children in the clinical group had poorer cognitive ability than those in the control group. Within the clinical group, those diagnosed with APD had poorer cognitive ability overall than those not diagnosed.

Interaction of Individual AP Scores and Cognitive Measures

Correlations • The results in Table 5 demonstrate the correlation results seen across tasks. The AP tasks showing significant correlation with cognitive skills are the same group of tasks that were found to show a relation with a child's functional difficulties: the DDT, FPT, and speech reception threshold measures of the LiSN-S. These relations are shown in Figure 4. The DDT scores show the highest significant correlation with AWM (r = 0.48 and 0.41 for left and right scores, respectively; p <0 .001), however, they also show a moderate significant correlation with NV-IQ (left ear: r = 0.38; right ear r = 0.28; p<0.001) and attention score (left and right ears r=0.22; right ear r = 0.22; p < 0.001). The mean FPT score correlates similarly across cognitive scores, but has the highest significant correlation with NV-IQ (r = 0.43; p < 0.001). The mean FPT

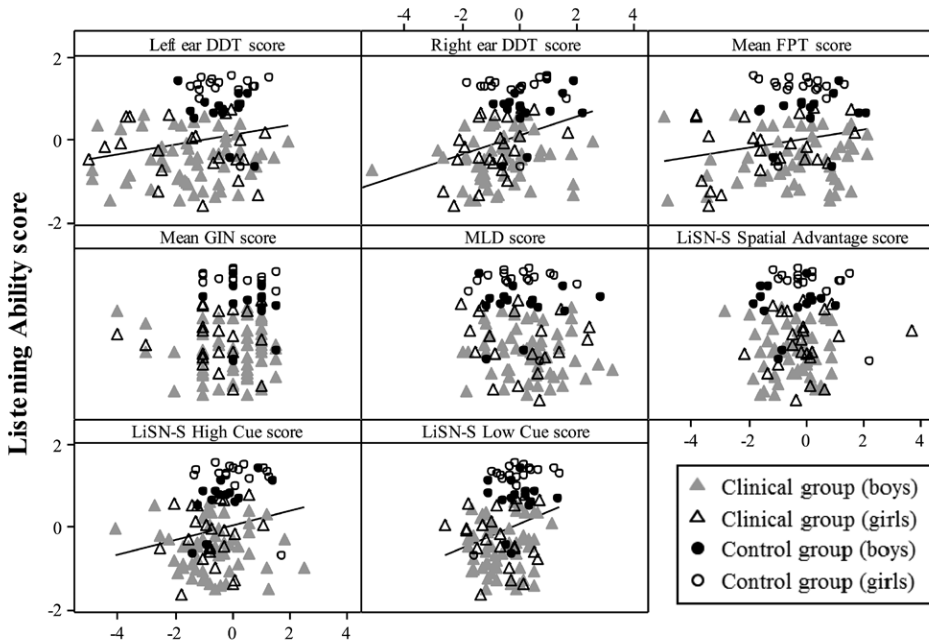

Fig. 1. Plots of auditory processing task scores (DDT, FPT, GIN, MLD, and LiSN-S) against the measure of listening ability, with all measures expressed as *z* scores. Correlation coefficients are shown in Table 5. DDT, dichotic digits; FPT, frequency pattern test; GIN, gaps in noise; MLD, masking level differences; LiSN-S, listening in spatialized noise-sentences test.

score also correlates with AWM ($r = 0.35$; $p < 0.001$). The LiSN-S low cue score shows significant correlation with the AWM ($r = 0.27$; $p < 0.01$) and NV-IQ measure ($r = 0.28$; $p < 0.01$). Comparison of the forward and reverse digit span score correlations with the AP scores show similar strength correlations are present for the digit span scores with Pearson *r* correlation differences of *less than* 0.1 that are well represented by the analyses utilizing the AWM mean score (Table 5).

It is evident from the plots in Figure 4 that the significant correlations between the AP and cognitive scores are still present when viewed within each group. When the clinical group is considered separately, similar significant correlations are still seen. The DDT scores again show the highest correlation with AWM ($r = 0.39$ and 0.41 for left and right scores, respectively; $p < 0.001$), and a weak correlation with NV-IQ (left ear $r = 0.26$; right ear $r = 0.33$; $p < 0.001$). The mean FPT score has the highest significant

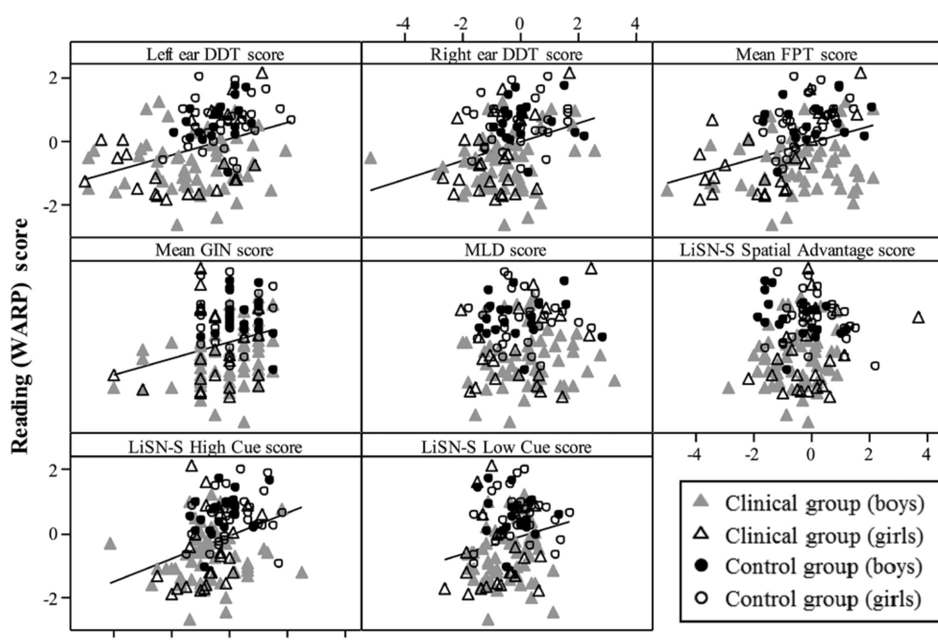

Fig. 2. Plots of auditory processing task scores (DDT, FPT, GIN, MLD, and LiSN-S) against the measure of reading fluency, with all measures expressed as *z* scores. Correlation coefficients are shown in Table 5. DDT, dichotic digits; FPT, frequency pattern test; GIN, gaps in noise; MLD, masking level differences; LiSN-S, listening in spatialized noise-sentences test.

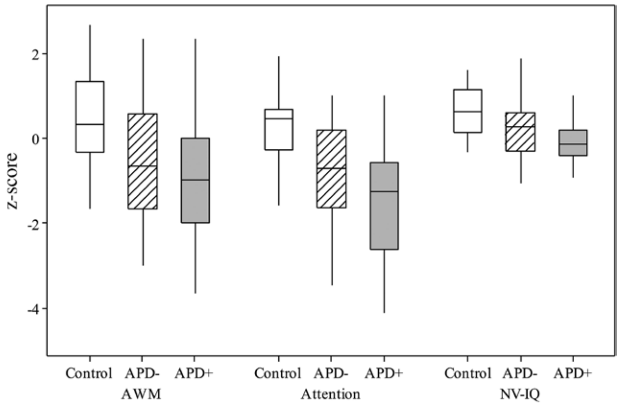

Fig. 3. Box and whisker plots showing the median, interquartile range, and overall range of the cognitive *z* scores of AWM, attention and NV-IQ for the control, APD−, and APD+ groups. AWM, auditory working memory; NV-IQ, nonverbal intelligence; APD, auditory processing disorder.

correlation with NV-IQ ($r = 0.38$; $p < 0.001$) and also a significant correlation with AWM ($r = 0.30$; $p < 0.001$). The LiSN-S low cue score shows significant correlation with the AWM ($r = 0.21$; $p < 0.01$) and NV-IQ measure ($r = 0.33$; $p < 0.01$). The control group in isolation is also able to demonstrate some significant correlations are still present between AP and cognitive scores. The left ear DDT scores show similar significant correlation with AWM ($r = 0.40$; $p < 0.001$) as with NV-IQ ($r = 0.39$; $p < 0.001$). The mean FPT score has a significant correlation with NV-IQ ($r = 0.42$; $p < 0.001$). This finding of significant correlations being present between AP and cognitive scores in the clinical and control groups separately supports that the correlations seen for the total group are being caused by an intrinsic relation between the variables plotted.

Multiple Regression Prediction of AP Ability

Multiple regression analysis was performed to explore the extent to which the three cognitive measures act as predictors of each AP task, as significant correlations were seen between each of the cognitive scores individually and the AP scores. Gender was also included as a predictor as the earlier ANOVA indicated an interaction between gender and AP test.

Results are summarized in Table 6, demonstrating that AWM and NV-IQ are the significant predictors ($p < 0.01$) of DDT (left ear; $r = 0.5$) and FPT ($r = 0.48$). The right DDT score was significantly predicted by AWM ($r = 0.36$). For the remaining tasks, LiSN-S, MLD, and GIN, no significant cognitive predictor in the model was identified.

Interaction of AP, Cognitive, Listening Ability, and Academic Score

AP scores of DDT, FPT, and LiSN-S (and GIN in the case of academic score) correlated with the functional real-life difficulties the child is experiencing. Multiple linear regression analysis was used to predict each of listening ability and reading score with the predictors comprising the AP scores, cognitive scores, and gender.

The significant ($p < 0.01$) predictors of listening ability were the NV-IQ score and gender ($r = 0.62$). Sustained attention, AWM, and AP scores were not significant predictors (Table 7).

The only significant ($p < 0.01$) predictor of reading fluency score was the AWM score ($r = 0.65$). Sustained attention, NV-IQ, and AP scores were not significant predictors (Table 7).

DISCUSSION

This research examined the link between real-life functional difficulty and AP skill deficits. Subjectively reported listening ability and academic progress (as measured by reading fluency) scores were collected as outcome measures, along with clinical AP and cognitive behavioral battery results.

The first hypothesis was that different tasks within the AP test battery would show little or no correlation in score, measuring different listening skills. Excluding within-task correlations, this was found to be true for the MLD, GIN, and the difference scores of the LiSN-S, supporting that these tasks are measuring different skills. Significant correlations were observed, however, between DDT and FPT scores and the baseline measures of the LiSN-S scores. This would suggest that there is a degree of commonality to these three tasks.

The second hypothesis was that AP tasks would show differing relations with the real-life difficulties the child experiences, and was supported by the results. Three of five components of the AP test battery demonstrated significant correlations with both academic and listening ability: DDT, FPT, and baseline measures of the LiSN-S (the same subset of tests that showed intertask correlations). DDT and FPT are the same tests demonstrated by Wilson et al. (2011) to correlate with functional scores from questionnaires. The GIN task demonstrated a correlation with academic performance, but not listening ability, and the MLD and difference measure of the LiSN-S showed no correlation with listening ability or reading fluency in this population. It was the tasks where intertask correlation was seen that also demonstrated links with the functional outcome for the child. The associations between AP scores and functional outcomes were less evident when the clinical and control groups were considered separately, suggesting that the correlations for the total group may have been caused by some other difference between the two groups rather than an intrinsic relation between the two variables plotted. Rosen (2003), when examining the links between AP and dyslexia, similarly demonstrated that due to group differences between control and clinical groups, such as increased variability, suggests that the analysis of group effects needs to also be considered separately.

A caveat, and the third hypothesis, was that the influence of cognition may be significant enough to be responsible for the associations observed between AP tasks, and associations observed between AP and the functional outcomes of listening ability and reading fluency (Rosen 2003; Ferguson & Moore 2014). A significant association of the top–down cognitive processes was found with a subset of AP tasks and the functional outcomes. This association, however, does not necessarily demonstrate the "influence" of cognition; that would be an assumption of the direction of causality; there also exists the possibility of a sensory deficit creating the impression of a cognitive impairment (Ferguson & Moore).

Between-group results (Fig. 4) showed that the clinical group had poorer cognitive ability than the control group, as was demonstrated by Rosen et al. (2010). Also similarly to Rosen et al. within the clinical group, the APD+ group (children meeting the diagnostic criteria of APD) showed similar cognitive ability

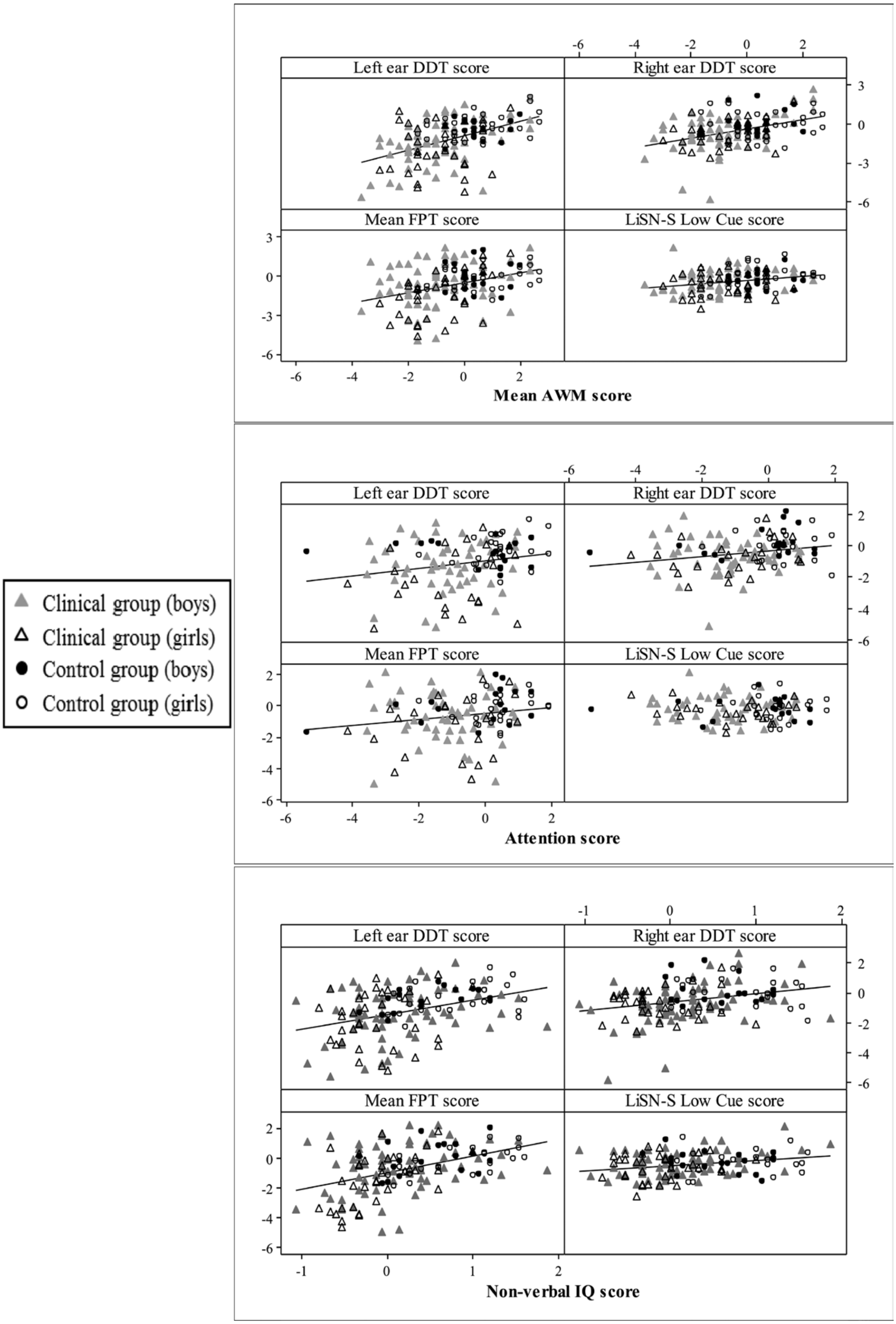

Fig. 4. Plots of attention, AWM and NV-IQ *z* scores against auditory processing (AP) *z* scores (DDT, FPT, and LiSN-S [low cue]). Correlation coefficients are shown in Table 5. AWM, auditory working memory; NV-IQ, nonverbal intelligence; DDT, dichotic digits; FPT, frequency pattern test; LiSN-S, listening in spatialized noise-sentences test.

TABLE 6. Multiple regression results (regression coefficient β) and 95% confidence intervals of the coefficient (in brackets)

Score	Nonverbal IQ	Attention	Mean AWM	Gender	r
Left DDT	**β = 0.58 (0.10–1.02); p = 0.01**	β = 0.10 (−0.09 to 0.30) ; p = 0.30	**β = 0.42 (0.21–0.63); p < 0.001**	β = −0.47 (−1.01 to 0.06); p = 0.08	0.50
Right DDT	β = 0.15 (−0.19 to 0.49); p = 0.38	β = 0.09 (−0.05 to 0.25); p = 0.20	**β = 0.24 (0.08–0.40); p < 0.01**	β = −0.04 (−0.45 to 0.36); p = 0.84	0.36
Mean FPT	**β = 0.81 (0.37–1.24); p < 0.001**	β = 0.05 (−0.14 to 0.24); p = 0.63	**β = 0.29 (0.09–0.49); p < 0.01**	β = −0.41 (−0.92 to 0.11); p = 0.12	0.48
MLD	β = 0.20 (−0.19 to 0.59); p = 0.30	β = −0.01 (−0.18 to 0.17); p = 0.92	β = 0.10 (−0.07 to 0.28); p = 0.25	β = −0.20 (−0.60 to 0.26); p = 0.39	0.17
Mean GIN	β = 0.07 (−0.26 to 0.42); p = 0.66	β = 0.04 (−0.10 to 0.19); p = 0.56	β = −0.03 (−0.19 to 0.13); p = 0.68	β = −0.20 (−0.67 to 0.20); p = 0.33	0.10
LiSN-S low cue	β = 0.14 (−0.10 to 0.39); p = 0.26	β = −0.03 (−0.13 to 0.08); p = 0.62	β = 0.09 (−0.02 to 0.21); p = 0.11	β = −0.06 (−0.06 to 0.65); p = 0.68	0.20
LiSN-S high cue	β = 0.25 (−0.05 to 0.55); p = 0.11	β = −0.00 (−0.13 to 0.13); p = 0.99	β = 0.05 (−0.09 to 0.19); p = 0.53	β = 0.29 (−0.67 to 0.20); p = 0.10	0.25
LiSN-S spatial advantage	β = 0.09 (−0.21 to 0.40); p = 0.55	β = 0.02 (−0.11 to 0.15); p = 0.76	β = −0.01 (−0.16 to 0.12); p = 0.79	**β = 0.48 (0.12–0.39); p = 0.01**	0.27

Probability values are also shown, for the three cognitive measures, and gender, as predictors of Auditory processing scores in multiple regression models. Significant predictors (p < 0.05) are shown in bold.

DDT, dichotic digits; FPT, frequency pattern test; MLD, masking level differences; GIN, gaps in noise; AWM, mean auditory working memory score; NV-IQ, nonverbal intelligence; LiSN-S, listening in spatialized noise-sentences test.

to the APD− group (children "passing" an AP test battery) when each cognitive task was considered separately. Significant differences in overall cognitive ability were found, however, between the APD+ and APD− groups. By including all three cognitive measures in the battery, the possible overall influence of cognition on a diagnosis of APD using this test battery becomes evident. Group differences, however, do not reveal the degree of influence.

Correlations across abilities may reflect the significant association of top–down processes with AP task performance. The same three AP tasks that showed intertask and functional outcomes links were the tasks showing significant links with cognition; the DDT and FPT showed correlation with all three cognitive scores, and the LiSN-S base measures showed weak correlations with NV-IQ (and the low cue also with AWM). The same degree of correlation each AP task had with functional outcomes was also seen in the correlation with cognitive scores; moderate correlations for the DDT and FPT, weak correlations with the LiSN-S baseline scores, and none with the GIN score or the derived scores of LiSN-S and MLD. Similar correlations were still evident when the clinical and control groups were considered separately.

Of the three cognitive processes, AWM and NV-IQ, but not attention, were found to be the significant predictors of the AP scores of FPT and DDT when multiple regressions were used to examine these interactions. Cognitive processes accounted for over 20% of the variance in the AP scores, supporting the possibility that significant contributory links exist between these AP tests and cognitive processes, and indicating that children with cognitive deficits are more likely to fall outside the normal range of these "AP" tasks. This finding of a link between AWM with FPT and DDT scores has been shown previously (Sharma et al. 2009; Wilson et al. 2011).

No AP score was found to be a significant predictor of reported listening ability once the three cognitive processes were included in the regression as predictors. A child's NV-IQ was found to be a significant predictor of subjectively measured listening ability. Interestingly, NV-IQ is a measure of reasoning ability and intelligence with minimum influence from language, and is essentially a pattern-solving task, as complex listening

TABLE 7. Multiple regression results for the three cognitive measures, auditory processing scores and gender in models of the predictors of listening ability and reading fluency scores

Score	Listening Ability	Reading Fluency
NV-IQ	**β = 0.41 (0.09–0.73); p < 0.01**	β = 0.33 (−0.02 to 0.68); p = 0.07
Attention	β = 0.41 (−0.08 to 0.17); p = 0.48	β = 0.09 (−0.04 to 0.22); p = 0.18
Mean AWM	β = 0.09 (−0.06 to 0.25); p = 0.24	**β = 0.28 (0.16–0.45); p < 0.001**
Mean DDT	β = 0.10 (−0.08 to 0.28); p = 0.26	β = 0.04 (−0.17 to 0.24); p = 0.72
Mean FPT	β = −0.06 (−0.19 to 0.07); p = 0.37	β = 0.06 (−0.08 to 0.21); p = 0.39
MLD	β = −0.08 (−0.22 to 0.06); p = 0.25	β = −0.03 (−0.16 to 0.15); p = 0.97
Mean GIN	β = 0.08 (−0.08 to 0.24); p = 0.35	β = 0.09 (−0.08 to 0.26); p = 0.29
Mean LiSN-S low/high cue	β = 0.17 (−0.09 to 0.43); p = 0.19	β = −0.02 (−0.31 to 0.27); p = 0.89
Gender	**β = 0.51 (0.16–0.86); p < 0.01**	β = 0.32 (−0.06 to 0.69); p = 0.10
r	0.62	0.65

Significant predictors (p < 0.05) are shown in bold.

DDT, dichotic digits; FPT, frequency pattern test; MLD, masking level differences; GIN, gaps in noise; AWM, mean auditory working memory score; NV-IQ, nonverbal intelligence; LiSN-S, listening in spatialized noise-sentences test.

can also be. Gender was also shown to be a predictor of listening ability, suggesting that there is an underlying factor that results in boys having a poorer perceived listening ability than girls. This is in line with what has been termed the referral bias. Although the phenotype and prevalence of disorders, such as attention and reading delays show no gender bias in population-based studies, boys are thought more likely to demonstrate the behaviors that will trigger a referral, whereas the girls are underidentified, being likely to "tolerate their deficits more easily" and display less disruptive behaviors (Shaywitz et al. 1990; Biederman et al. 1999).

The second functional outcome measure, reading fluency, was also not significantly predicted by AP skills. The only significantly predictor was AWM. Links between working memory and reading are well documented (Kibby et al. 2004; Swanson & Jerman 2007; Kibby & Cohen 2008). The associations reported in previous studies between academic progress and AP scores (Ramus 2003; Bishop & Snowling 2004; Sharma et al. 2009) may simply be a reflection of the effects of cognition on both measures. For both real-life measures, cognition explained 40% of the variance in scores. Ferguson & Moore (2014) demonstrated a similar effect of partialling NV-IQ from AP tests scores; children with language impairments and APD showed no significant differences in the majority of AP group scores compared with typically developing children, once NV-IQ was accounted for. These findings support the conclusions of Rosen (2003) that NV-IQ must be accounted for when considering psychoacoustic skills.

It may be more prudent to consider the three cognitive skills examined as being interleaved contributory components of top–down cognitive processing. Considerable overlap has been demonstrated between the three cognitive skills of intelligence, AWM, and attention (Musiek & Baran 1987; LaBar et al. 1999; Engle & Kane 2004; Schweizer & Moosbrugger 2004). Here, moderate correlations are also seen between the three measures. The finding that one cognitive process, NV-IQ, appears to dominate in this population as a predictor of a child's listening ability does not necessarily imply that there is no contribution from AWM and attention. Sustained attention and AWM have been shown to predict more than half of the variance in intelligence (Schweizer & Moosbrugger). The interaction of attention and memory "is the elementary determinant of broad cognitive ability" (Engle & Kane 2004, p. 147). It is therefore likely that sustained attention is under-represented in the results of these analyses, having contributed to the AWM and NV-IQ measure. Outcome measures show significant correlations of similar degree with attention, AWM, and NV-IQ. There are also other aspects of attention that we did not measure; for example measures of divided attention, or measures of attention switching that may also have demonstrated a stronger contribution from attention to the AP tasks (Dhamani et al. 2013). Similarly, there are also other forms of working memory that have not been assessed, such as working memory updating or inhibition that may have shown a different contribution of working memory to the AP tasks (St Clair-Thompson & Gathercole 2006). Although the forward and reverse digit scores demonstrated similar results in the correlation matrix, subtle differences were present, but not in a consistent pattern that allows for discussion of a more significant influence of short term or working memory. For the dichotic digit correlations, the mean AWM score demonstrated a marginally higher correlation than either the forward or reverse score, suggesting that a combined effect of these two memory skill components best predicts a child's score.

The theory of resource allocation is in line with these findings and proposes a limited pool of cognitive and AP resources, both of which are required for effective interpretation of a degraded speech signal (Norman & Bobrow 1975). Resources are flexibly allocated to an activity depending on the demands of the task. When these resources are insufficient, or channeled elsewhere, task failure begins to occur. Resources may be inadequate because of the complexity of the task or may be due to a weak ability placing a greater demand on resources to perform the task. The process of attention is theorized to be the gatekeeper for the allocation of resources (Murray et al. 1997; Schweizer & Moosbrugger 2004). Therefore if, as these results show, AP tasks require a significant cognitive contribution, and any of the three cognitive resources are weak or insufficient, reduced task performance will eventuate.

Of interest is that the correlations seen in the speech reception scores of the LiSN-S (high cue and low cue scores) with cognitive processes were not seen in the derived spatial advantage measure. Similarly MLD, also a difference score, shows no correlation with any of the cognitive measures. This demonstrates the ability of derived scores, as also found by Moore et al. (2010), to control for confounding intrinsic factors, as they are held constant between conditions generating the difference score (Cameron & Dillon 2007). Although this lack of correlation could also be explained by poor reliability of the derived score, as two sources of measurement error are present, good test–retest reliability has been demonstrated for the derived scores of the LiSN-S (Cameron et al. 2011), and the MLD (Moore et al. 2011). Development of new AP tests should consider this approach as a tool to restrict the influence of cognitive processes.

With cognitive ability demonstrating a significant influence on test results this should influence remediation strategy. For example if dichotic listening and AWM scores are poor, remediation may be most effective if focused on strengthening AWM. This highlights a second future research direction: for children with cognitive and apparent APD deficits, is it cognitive training or AP training that will better improve each of AP scores, cognitive scores, real-life listening ability, and more importantly in the longer term, academic progress? Cognitive abilities also predict the perceived listening and reading difficulties of children referred for AP assessments, which further promotes the inclusion of assessments of cognitive skills. A complex relation clearly exists between cognitive processes and AP test results and effective clinical assessment and management of AP must acknowledge the implications of this interaction.

Limitations

These results are specific to the clinical population employed. Different selection criteria for the clinical group may have provided different results, in particular for the binaural interaction tasks. The MLD and LiSN-S spatial advantage measures show a relatively narrow distribution of results, with few children falling below the −2 SD mark, and no correlation with functional outcomes is seen. A clinical group targeting children with a history of otitis media would be predicted to produce a wider range with poorer scores (Moore et al. 2003; Tomlin & Rance

2014; Cameron et al. in press) and potentially allow relations with functional outcomes to emerge.

The subjective nature of the listening ability measure is also a limitation of this study. It is not evident, however, what an objective measure of listening ability would be and subjective impressions remain the best estimate available of a child's listening ability. As a subjective measure, listening ability may well be influenced by the academic progress of the child. Therefore, no conclusions are drawn from the correlation between listening ability and academic progress. Instead, two functional outcome measures are described, both with significant cognitive predictors. Measures of speech and language ability of the children were also not available, which may have provided an additional piece in the puzzle of the definition of this disorder. Although no socioeconomic differences were identified between groups based on postcode, future research should also consider including more specific data regarding SES and background influences of the children.

CONCLUSIONS

The results show that top–down cognitive processes significantly influence, or are at least correlated with, a subgroup of AP scores. Cognitive abilities significantly predict a child's reported listening ability and reading fluency, while AP ability, as measured with the current test battery, does not, once cognitive abilities are allowed for.

These findings suggest that for many children in the population assessed, cognitive deficits may be both responsible for the perceived listening and academic difficulties and have a significant effect on the AP test results. Given the associations between the scores on some AP tests and cognitive abilities, and the much greater effect of cognitive abilities than AP scores on functional outcomes, it is very likely that many children currently diagnosed with APD are actually experiencing real-life difficulties as a result of their cognitive deficit, not as a consequence of having a pure APD. Hence, measures of cognition should be standard inclusions in an APD test battery, to best determine the cause of the listening difficulties being experienced by the child and the appropriate management pathway. It is hoped that these results will influence test battery selection, the interpretation of these test results by clinicians, and clinical practice guidelines. By better understanding the difficulties faced by children who perform poorly on AP tasks, future research can explore how best to ameliorate these deficits.

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