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Nature of Auditory Processing Disorder in Children

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Nature of Auditory Processing Disorder in Children

WHAT'S KNOWN ON THIS SUBJECT: Some children with normal hearing and listening problems are diagnosed as having APD. Their problems are attributed to impaired sound processing in the central auditory nervous system and typically are treated through improved listening strategies, amplification, or auditory training.

WHAT THIS STUDY ADDS: We compared children's cognition and AP skills with caregiver's evaluations of their listening and communication. Impaired AP was unrelated to everyday listening. Reduced general cognitive ability and auditory inattention were better predictors of listening problems.

abstract

OBJECTIVE: We tested the specific hypothesis that the presentation of auditory processing disorder (APD) is related to a sensory processing deficit.

METHODS: Randomly chosen, 6- to 11-year-old children with normal hearing ($N = 1469$) were tested in schools in 4 regional centers across the United Kingdom. Caregivers completed questionnaires regarding their participating children's listening and communication skills. Children completed a battery of audiometric, auditory processing (AP), speech-in-noise, cognitive (IQ, memory, language, and literacy), and attention (auditory and visual) tests. AP measures separated the sensory and nonsensory contributions to spectral and temporal perception.

RESULTS: AP improved with age. Poor-for-age AP was significantly related to poor cognitive, communication, and speech-in-noise performance ($P < .001$). However, sensory elements of perception were only weakly related to those performance measures ($r < 0.1$), and correlations between auditory perception and cognitive scores were generally low ($r = 0.1–0.3$). Multivariate regression analysis showed that response variability in the AP tests, reflecting attention, and cognitive scores were the best predictors of listening, communication, and speech-in-noise skills.

CONCLUSIONS: Presenting symptoms of APD were largely unrelated to auditory sensory processing. Response variability and cognitive performance were the best predictors of poor communication and listening. We suggest that APD is primarily an attention problem and that clinical diagnosis and management, as well as further research, should be based on that premise. *Pediatrics* 2010;126:e382–e390

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KEY WORDS

hearing, listening, communication, language impairment, learning disorder, spectral resolution, temporal resolution

ABBREVIATIONS

AP—auditory processing
APD—auditory processing disorder
CHAPPS—Children's Auditory Processing Performance Scale
CCC-2—Children's Communication Checklist 2
GCC—general communication composite
VCV—vowel-consonant-vowel speech-in-noise test
BM0—backward masking with 0-millisecond gap
BM50—backward masking with 50-millisecond gap
FD—frequency discrimination
FR—frequency resolution
TR—temporal resolution
SPL—sound pressure level
SM—simultaneous masking
SMN—simultaneous masking with spectral notch
IHR—Institute of Hearing Research
IMD—index of multiple deprivation

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At least 5% of children referred to audiology services are found not to have hearing loss.[1] Many report listening difficulties, usually involving speech perception, and receive a diagnosis of auditory processing disorder (APD), despite the lack of international consensus regarding what APD is.[2] Professional societies on both sides of the Atlantic Ocean have proposed definitions,[3,4] suggesting that APD involves listening difficulties caused by impaired bottom-up processing of sounds by the brain, in the central auditory system. To test this hypothesis, we surveyed auditory processing (AP) among children with normal hearing from the general population. We also assessed speech perception, cognition, and communication and listening skills, to test an alternative hypothesis that poor performance on these measures (APD) occurs because of impaired top-down processing, which is known to affect lower levels of the auditory system.[5–7]

The term APD was first used at the 1974 meeting of the American Speech, Language, and Hearing Association (R. W. Keith, PhD, personal written communication, 2009), and a conference to explore "central auditory dysfunction" was held in Cincinnati, Ohio, in 1977. However, a debate concerning the contribution of auditory perception to language disorders was already raging.[8] Previously, studies of central lesions and the information-handling capacity of hearing[9] provided evidence for defects and limits of hearing imposed by brain function. Today, concepts of APD range from brain lesion deficits through auditory contributions to learning difficulties in otherwise healthy children.[10] Although many researchers think that APD is too poorly specified for scientific study, there is a huge appetite for improved diagnosis and management among caregivers and professionals dealing with children with poor listening.[11]

A key question is whether APD is attributable to reduced ability to encode sounds as needed for speech perception. Although testing of speech perception seems the obvious way to address this issue, speech includes language-specific features that require processing beyond the auditory system, including coarticulation, semantic factors, and syntax.[12] Therefore, it is impossible to determine whether impaired speech perception without hearing loss is attributable to APD or to language impairments.[4] Tests of perception also involve considerable nonsensory processing.[12] A listener typically must attend to and remember the ordering of sequentially presented sounds and then indicate which of the sounds had a distinguishing feature (eg, pitch). In the studies reported here, sensory and nonsensory contributions to 2 basic elements of auditory perception, namely, time and frequency, were distinguished through comparisons of performance on nearly identical tests to obtain derived measures of AP. This method assumes that systematic variability attributable to the procedural demands of the tests for an individual would be canceled out (for further discussion, see Supplemental Appendix, published as supplemental information at www.pediatrics.org/cgi/content/full/peds.2009-2826/DC1 Supplemental Appendix).

Because APD is so poorly understood, clinical diagnosis is not presently a reliable way to recruit research participants. Our alternative, the population approach, tested a sample large enough to provide a high likelihood of including participants who have APD, powered with the assumption that the 5% of referred children without hearing loss[1] all have APD. The specific aims were (1) to examine AP among children 6 to 11 years of age, (2) to relate AP to the clinical presentation measures of speech perception, cognition, communication, and listening, (3) to use those relationships to inform a new definition of APD, and (4) to provide a new diagnostic measure of APD.

METHODS

Population

A total of 1469 of 1638 children from 44 mainstream primary schools in Cardiff, Exeter, Glasgow, and Nottingham, England, tested in a 1-hour session, had normal hearing (≤25-dB hearing level at 1 and 4 kHz) and used English as the main home language. Cases were stratified according to age ($6\frac{9}{12}$ to $11\frac{11}{12}$ years), gender, and socioeconomic status (IMD). Written consent and questionnaire results (on audiologic testing, education, and medical history) were obtained from caregivers after invitation packs were sent to 8044 homes. Approval was received from research and development departments of host National Health Service trusts at the 4 sites and from local educational authorities.

Data Collection

Additional details of the rationale, methods, results, and interpretation are available in the Supplemental Appendix. Children were tested in quiet locations in their schools by using laptop computers running customized software (Institute of Hearing Research [IHR] STAR)[13] and calibrated to measure tone thresholds, AP, and cognition. In a follow-up letter, caregivers were asked to complete the Children's Communication Checklist 2 (CCC-2)[14] and the Children's Auditory Processing Performance Scale (CHAPPS)[15] questionnaires; 856 (60%) completed both.

AP testing consisted of 5 individual measures (Fig 1) that were chosen on the basis of relevance to hearing, retest reliability, wide threshold distri-

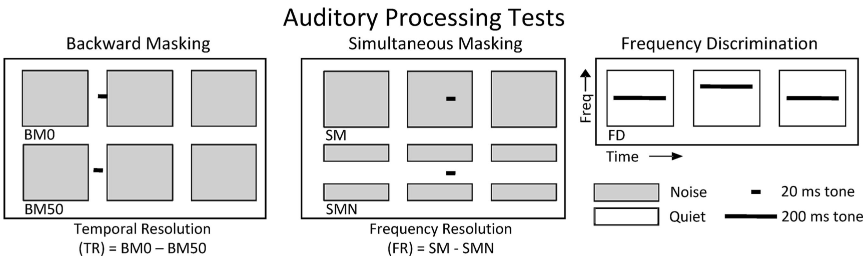

FIGURE 1

Schematic diagrams of individual (BM0, BM50, SM, SMN, and FD) and derived (TR and FR) AP tests. Each set of 3 boxes designates successive sound presentation intervals of noise or quiet. Lines are target tones. The "odd one out" is shown in the middle interval but could occur (randomly) in any interval.

bution among individuals, and appropriateness for distinguishing sensory and nonsensory aspects of hearing. AP tests consisted of 2 tracks, each of 20 trials. Trials involved 3 sequential stimuli, that is, 2 identical, standard tones (1 kHz) and a different, randomly ordered, target tone. The child's task was to report (by using a 3-button box) the "odd one out" (ie, serial order of target). Successive trials varied the difference between the standard and target tones by using a 3-down/1-up adaptive staircase.[16,17] For frequency discrimination (FD), the 200-millisecond target tone had a higher frequency than the standard tones. In 2 measures of backward masking, a 20-millisecond pulse tone target occurred immediately (backward masking with a 0-millisecond gap [BM0]) or 50 milliseconds (backward masking with a 50-millisecond gap [BM50]) before a longer block of noise. In SM, the noise was continuous, whereas the other (SMN) target had a quiet, spectral notch surrounding the tone. A speech-in-noise test (vowel-consonant-vowel [VCV] nonwords in speech-modulated noise[18]) used matched procedures. The task was to repeat verbally the VCV target as its level varied adaptively.

Variable AP thresholds may be attributed to many factors, including attention, memory, and learning. We assumed that neither learning nor long-term memory was significant, because the children had not experienced the tests previously. Within tests, however, attention was required to achieve reproducible data. Other factors (eg, motivation, emotion, and fatigue) may be subsumed under a broad concept of attention, because changes in an individual's engagement with a task produce performance inconsistencies. Attention was assessed first through performance variability on the AP tests (intrinsic attention) and then through a novel extrinsic test (the IHR Cued Attention Test),[19] similar to the Test of Attentional Performance.[20] These tests measure phasic alertness through comparison, separately for hearing and vision, of the effect on reaction time induced by a cue occurring before a target stimulus. Cognitive tests were standardized measures of nonverbal reasoning (nonverbal IQ; matrices reasoning, Wechsler Abbreviated Scale of Intelligence[21]), working memory (digit span, Wechsler Intelligence Scale for Children[22]), phonologic processing and memory (repetition of nonsense words, Developmental Neuropsychological Assessment[23]), and reading accuracy and fluency (word and nonword, Test of Word Reading Efficiency[24]).

Analysis

Derived AP measures of temporal resolution (TR)[5,25,26] and frequency resolution (FR)[27] were obtained by subtracting the BM50 threshold from the BM0 threshold, and the SMN threshold from the SM threshold, respectively (Fig 1). This subtraction eliminated memory-related and other order- and task-related modulations of nonsensory performance from the derived measures. Thresholds for all AP tests were grand means of the last 3 trials in each track. Multivariate regression analysis used a univariate general linear model; 96 variables were input into the model, including demographic characteristics (age, gender, Index of Multiple Deprivation score, and test center), audiometric findings (ear and frequency), cognition results (the 5 test scores), and multiple measures of AP threshold and individual response variability. Intrinsic attention was also indexed by deriving, for each child, one variability composite score for each individual AP test and another score based on all 5 tests.

RESULTS

AP in Children

Almost all children (92%) performed the entire test battery. For each individual AP test, performance was variable both within and between children (Fig 2A). Median thresholds decreased significantly with age ($P < .001$ for all tests), achieving maturity between 7 and 9 years, as reported previously.[28] Although the threshold range for the derived measures (TR and FR) decreased with age, median thresholds did not change significantly (Fig 2B).

Audibility did not influence individual or derived AP (Table 1). Modest but significant correlations were seen between the cognitive test results and between cognitive test results and individual AP test results (Table 2). However, derived AP measures (TR and FR) generally were not related to cognitive performance. Also, AP generally was not related to caregiver-rated communication and listening (Table 3). Speech-in-noise (VCV) findings were related significantly but weakly to al-

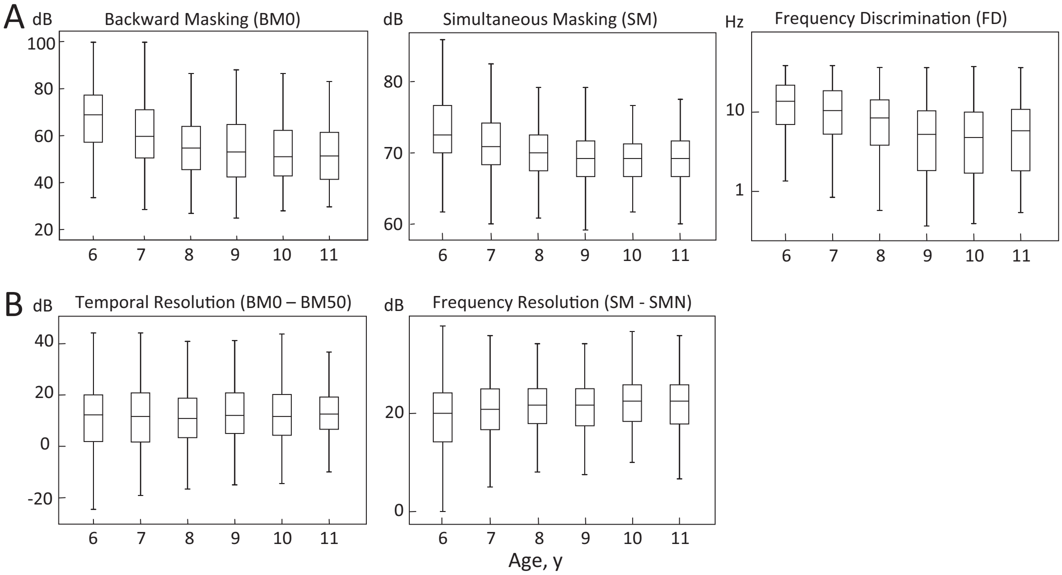

FIGURE 2
Box plot distributions of AP thresholds among children 6 to 11 years of age for 3 individual tests of AP (A) and derived tests of AP (B), demonstrating variations in AP with age and across tests. Box plots show the median (horizontal line, the inter-quartile range (25%–75%, box) and the minimum and maximum values (whiskers).

TABLE 1 Correlations Between Hearing Thresholds (Left ear, Right ear), Age-Standardized AP Thresholds, and Speech-in-Noise Thresholds (VCV) for All 6- to 11-Year-Old Children With Normal Hearing

	r						
	Right Ear	BM0	SM	FD	TR	FR	VCV
Left ear	0.56[a]	0.07[c]	0.06[c]	0.04[d]	−0.01[d]	0.03[d]	0.07[c]
Right ear		0.08[b]	0.04[d]	0.04[d]	0.01[d]	−0.02[d]	0.07[c]
BM0			0.30[a]	0.42[a]	0.61[a]	−0.22[a]	0.13[a]
SM				0.23[a]	0.01[d]	0.32[a]	0.06[c]
FD					0.11[a]	−0.17[a]	0.12[a]
TR						−0.02[d]	0.02[d]
FR							−0.08[a]

[a] $P < .001$.
[b] $P < .01$.
[c] $P < .05$.
[d] Not significant.

most all measures of audibility, cognition, and caregiver ratings.

In summary, performance on individual tests improved with age, but sensory processing did not change. Individual AP measures were correlated significantly but weakly with cognitive and listening measures. Derived AP measures generally were not correlated with these measures, which suggests that sensory processing does not predict which children will present with APD.

Children With Poorer AP

It is possible there is a small minority of poorer AP performers for whom, unlike the whole population, the sensation of sound does predict cognitive and listening skills. Figures 3 and 4 show performance for typical (upper 95%) and poorer (lower 5%) AP performers. Typical AP performers produced highly consistent mean scores across the cognitive tests (Fig 3). Poorer performers on the derived AP tests (TR and FR) generally did no worse on the cognitive tests than typical performers (Table 4). In contrast, poorer performers on individual tests achieved significantly lower scores on each of the cognitive tests, compared with typical AP performers (Table 4). Poorer speech-in-noise (VCV) results also were associated with lower cognitive scores.

Clinical presentation measures yielded more-complex findings; scores for communication (CCC-2 general communication composite [GCC] score) and listening (CHAPPS total score) were not normally distributed (Fig 4A). In comparisons of typical and poorer AP performers (Fig 4B), VCV and GCC results followed those of the cognitive tests (Table 4). No consistent association was found between CHAPPS results and separate AP test results, although FR and a composite AP measure reached significance.

Children with poor AP performance tended to have cognitive rather than sensory problems. Procedural demands of individual tests were related to communication and listening difficulties, rather than sensory chal-

TABLE 2 Correlations Between Age-Standardized AP Thresholds and Cognitive Test Scores for All Children

	r									
	Digit Span	NEPSY Nonword Repetition	TOWRE Words	TOWRE Nonwords	BM0	SM	FD	TR	FR	VCV
Nonverbal IQ	0.36[a]	0.25[a]	0.33[a]	0.27[a]	−0.18[a]	−0.15[a]	−0.31[a]	−0.02[b]	−0.10[a]	−0.12[a]
Digit span		0.36[a]	0.37[a]	0.35[a]	−0.13[a]	−0.11[a]	−0.21[a]	<0.01[b]	0.05[b]	−0.10[a]
Nonword repetition			0.31[a]	0.32[a]	−0.14[a]	−0.11[a]	−0.20[a]	0.01[b]	0.03[b]	−0.29[a]
Words				0.82[a]	−0.19[a]	−0.16[a]	−0.25[a]	−0.05[b]	0.04[b]	−0.15[a]
Nonwords					−0.17[a]	−0.15[a]	−0.25[a]	−0.04[b]	0.03[b]	−0.14[a]

NEPSY indicates Developmental Neuropsychological Assessment. TOWRE is the Test of Word Reading Efficiency.

[a] $P < .001$.

[b] Not significant.

TABLE 3 Correlations Between Age-Standardized AP Thresholds and Caregiver Ratings for All Children

	r						
	CHAPPS	BM0	SM	FD	TR	FR	VCV
CCC-2 GCC	0.48[a]	−0.06[d]	−0.04[d]	−0.19[a]	0.01[d]	0.10[b]	−0.09[b]
CHAPPS		−0.01[d]	−0.01[d]	−0.11[b]	0.02[d]	0.07[c]	−0.06[d]

It should be noted that only ~60% of children had caregivers who completed both communication questionnaires.

[a] $P < .001$.

[b] $P < .01$.

[c] $P < .05$.

[d] Not significant.

lenges. However, these demands do not contribute greatly to clinical presentation (Fig 4A, arrows), and their measurement would not, by itself, make a sensitive diagnostic APD test.

Contributions to Clinical Presentation

A potentially large number of variables might contribute to the clinical presentation measures (GCC and CHAPPS scores) and VCV results. Multivariate regression analysis for each measure showed that only ~20% of the variance (R^2) was attributable to all 96 variables examined (Table 5). However, a consistent pattern was seen across the 3 measures. The AP threshold accounted for only 1% to 2% of the variance. Demographic factors[29,30] accounted for 2% to 3%. The largest contributions came from cognitive test scores (6%–8%) and variable individual performance on the AP tests (5%–9%).

Attention

Data presented above suggested that inattention may make a major contribution to the clinical presentation of APD. In a measure of extrinsic attention (different reaction times with cued and uncued stimuli), we found that AP performance was unrelated to auditory attention but, for 2 AP tests, children with poorer listening skills had reduced visual alertness ($P < .01$) (Supplemental Figure 5, published as supplemental information at www.pediatrics.org/cgi/content/full/peds.2009-2826/DC1 Supplemental Figure 5). For intrinsic auditory attention (variable AP performance), we found that poorer AP performers had significantly more-variable composite profiles than did typical performers (Table 5). Poorer VCV performers did not show greater response variability. In summary, we found a close, predictable relationship between AP performance and intrinsic attention.

DISCUSSION

Overall Findings

Sensory processing, represented by TR and FR, bore little relationship to measures of speech perception or to cognitive, communication, and listening skills that are considered the hallmarks of APD in children. This finding provides little support for the hypothesis that APD involves impaired processing of basic sounds by the brain, as currently embodied in definitions of APD. However, threshold performance on individual auditory tests (eg, FD) had significant but modest links with measures indicative of the clinical pre-

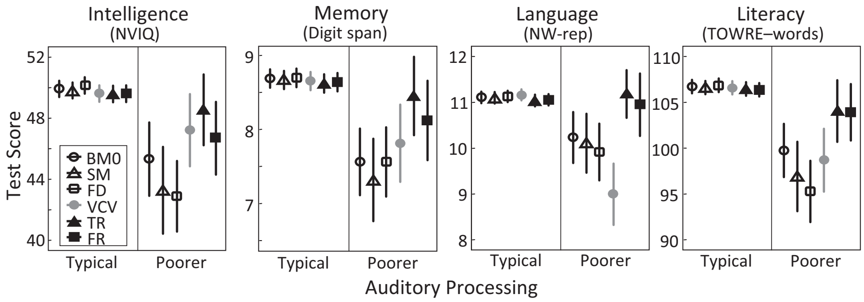

FIGURE 3

Reduced cognitive performance for children with poorer AP. Mean standard scores and 95% confidence intervals for each cognitive test for children in the upper 95% (typical) or lower 5% (poorer) of performance (threshold) on each AP test are shown. NVIQ indicates nonverbal IQ; NW-rep, nonword repetition test; TOWRE, Test of Word Reading Efficiency.

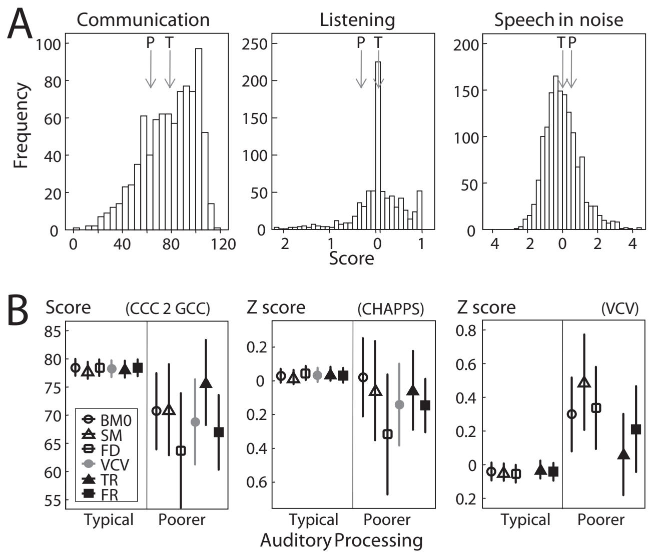

FIGURE 4

Reduced communication, listening, and speech-in-noise skills for children with poorer AP. A, Histograms of standardized, whole-population scores for each presentation test. B, Mean scores (or median CHAPPS scores) and 95% confidence intervals for each test. Arrows in A mark the mean scores for the tests in B with the greatest difference between typical (T) and poorer (P) performers.

sentation of APD. Variable auditory performance and poor cognitive skills contributed most in a factor analysis of each measure of clinical presentation. These results suggest that, in the absence of hearing loss, poor performance on auditory tasks is attributable much more to the cognitive demands of the tasks (specifically, the attentional demands) than to their sensory challenge. Consequently, we suggest that what is currently called APD, for individuals without known neurologic lesions, should be redefined as primarily a cognitive disorder, rather than a sensory disorder.

Relationships Between AP, Speech Perception, and Listening

The specific hypothesis that childhood APD is connected to AP through the central auditory system has not been scrutinized in detail previously. A lack of association has been found between AP, speech-in-noise perception, and the development of language, reading, and academic skills.[31,32] This might be because speech, as used previously, is highly redundant, which enables individuals with even severely degraded cues to perceive well.[33] We found significant but weak ($r \approx 0.1$) correlations of AP and speech-in-noise thresholds with nonverbal IQ, language, and reading. Together, this evidence suggests relative dissociation between AP, speech perception, and language and academic skills for listeners with normal hearing.

APD and Auditory Attention

An alternative hypothesis is that symptoms currently labeled APD represent a problem of attention or working memory. We showed that relatively little of the variance in 3 clinical presentations (communication, speech-in-noise perception, and listening) was captured by the many variables examined. Although we simply might have missed $\geq$1 crucial variable, it seems more likely that the poor capture was attributable to lack of reliability of the measures. The reliability of the VCV test and CHAPPS is not known but the reliability of the CCC-2 is high,[14] and the close correspondence in the multivariate regression analysis of these 3 measures, together with their different nature, suggests that they are not the main source of the low reliability. Previous research showed that most measures of AP in children are not very replicable.[17,34,35] We suggest that this poor retest reliability may be attributable primarily to fluctuating attention. The finding that some children do perform as reliably and as sensitively as adults[34] gives further credence to the likely influence of attention fluctuations both in the maturation of hearing in 6- to 11-year-old children and in the poor (for age) performance of some children. Of the variance in the multivariate regression analysis that was explicable from the variables, approximately two-thirds was attributable to the cognitive measures and to AP response variability. Therefore, we suggest that fluctuating attention of the children was a major contributor to both the unexplained and explained components of the presentation measures. Our measure of working memory suggested an association with poor AP and a contribution to presentation. This association is an issue for further research.

Attention is a multifaceted construct that, in most models, includes both multimodal and unimodal sensory processing elements.[36,37] Recent comparisons of auditory and visual processing in children examined their relative ability to perform tasks that were closely matched procedurally in each sensory mode,[17,35] testing the notion that AP may involve a unique or predominant element of specifically auditory attention. The overall results showed a degree of dissociation between response thresholds and variability in the 2 modes. Another study found that response thresholds and variability for unconnected auditory and visual tests in individual children had no or low-level correlation.[38] Further research is required to establish

TABLE 4 Comparisons Between Typical and Poorer AP Performers on Each AP Test and Derived Measures for Scores on Cognitive and Clinical Presentation Measures

	P							
	Nonverbal IQ	Digit Span	Nonword Repetition	Words	Nonwords	CCC-2 GCC	CHAPPS	VCV
AP composite	<.001	<.001	<.001	<.001	<.001	.001	.019	.001
BM0	<.001	<.001	.003	<.001	<.001	.028	NS	.001
SM	<.001	<.001	.003	<.001	<.001	NS	NS	<.001
FD	<.001	<.001	<.001	<.001	<.001	.007	NS	.003
VCV	NS	.004	<.001	<.001	<.001	.020	NS	
TR	NS	NS	NS	NS	NS	NS	NS	NS
FR	.006	.031	NS	NS	NS	<.001	.010	.038

Data show probability levels (*P*) from F tests (AP composite; mean of all age-standardized individual AP thresholds) and posthoc *t* tests (individual AP tests), except for the CHAPPS (Kruskal-Wallis χ^2 test). NS indicates not significant.

TABLE 5 Summary of Multivariate Regression Analysis

	Proportion of Variance, %		
	Communication (CCC-2 GCC)	Speech-in-Noise Perception (VCV)	Listening (CHAPPS Total)
R^2	24	20	19
η^2, Cognitive	8	8	6
AP variability	9	5	8
AP threshold	2	1	1
Demographic factors	5	4	3

Data show proportions of variance for each clinical presentation measure accounted for by all variables studied (R^2) and by each main (supervariable) factor (η^2).

the modality specificity and other characteristics of attention and memory deficits associated with poor listening in some children. One idea is that people normally form perceptual anchors on the basis of repetitive stimuli and children with learning problems, including poor listening, have difficulty forming these anchors.[39] These issues are of considerable professional interest because APD and, it may be argued, auditory attention problems are rightly the domain of audiologists. A multimodal problem is a symptom of an attention disorder, which generally would be managed by a psychologist or psychiatrist.

Comorbidity of APD

APD has been closely connected with language-based learning impairments (dyslexia and specific language impairment) and attention-deficit disorders.[40] We found previously that children with clinical diagnoses of APD or specific language impairment had virtually identical profiles of poor scores for many of the same parent-based assessments, cognitive measures, and AP tests as examined here.[18] Other authors demonstrated poor AP in a subset of children with diagnosed dyslexia.[41,42] A temporal processing theory proposes that an inability to resolve rapidly presented sounds is the root cause of language impairment in children.[43] This theory has been questioned on several grounds.[44,45] Although a disproportionate number of children with language impairments do perform poorly on tests of auditory temporal processing, many do not. Poor temporal performers also tend to perform poorly on tests of spectral processing and on almost every sort of listening test.[41] The results presented here suggest that the poor performance of those children may be attributable more to a general inability to perform the tests than to specifically temporal, or even specifically auditory, impairments. Our analysis of APD also suggests that the understanding of other, language-based, learning problems may benefit from reassessment of their links with attention.

Diagnosis of APD

Our final aim in this study was to derive a new clinical diagnostic method for measurement of APD. Such a method is badly needed, because the clinical management of APD has developed because of genuine need and appropriate concern but without a clear theoretical framework or well-validated, agreed-upon, diagnostic or management strategies. This chaos was exemplified in a recent case-control study by Dawes et al.[46] The authors reported on 2 well-matched groups of children referred to a specialist APD clinic because of listening problems. One group was diagnosed as having APD on the basis of a commonly used, speech/sound-based, test battery[47] and failure on $\geq$1 of 4 tests of nonverbal AP. However, this group could not be distinguished, on the basis of presenting symptoms or cause, from the group of children diagnosed as not having APD on the same basis.

To move forward with APD definition, diagnosis, and management, several issues need to be recognized and addressed. First, the symptoms currently labeled APD may not be attributable to a primary, bottom-up, sensory processing problem but may have their origins in higher-level, top-down, control of listening. We must acknowledge, however, that even large, population-based studies such as this one may fail to identify a small proportion of children (<1%) with alternative conditions, including sensory processing deficits (eg, auditory neuropathy[48,49]). Second, for people with normal hearing (ie, pure-tone sensitivity), tests of AP and speech perception (whether in quiet or in noise) are poor predictors of language, literacy, and academic skills. Third, scientific principles must be applied to assessment of the validity, sensitivity, and specificity of diagnostic tests for what is currently termed APD. This means developing new forms of diagnosis on the basis of further research, starting with the hypothesis that listening problems in children are symptoms of reduced auditory attention.

CONCLUSIONS

Current understanding of and clinical practices for childhood APD have grown out of real need. However, diagnosis and management largely lack a scientific basis, which leads to much confusion. Our research suggests that APD in children is primarily a result of poor engagement with sounds, rather than impaired hearing. Further research and clinical practices should be directed toward exploring and improving auditory attention in children with impaired listening. Practical recommendations for managing APD/listening problems are available in a British Society of Audiology-sponsored brochure (available at www.ihr.mrc.ac.uk/index.php/research/apd.index).

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Nature of Auditory Processing Disorder in Children

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Supplemental Information

SUPPLEMENTAL APPENDIX

Population

Participating sites were chosen on the basis of national and regional diversity within the United Kingdom and the presence of major, willing, audiology services at each site. Schools and children were chosen from each site on the basis of postal codes, in an attempt to obtain a representative sample, according to socioeconomic status, across the United Kingdom as a whole. Children were chosen within each school only on the basis of their and their parents' willingness to participate, their home language being English, and, for this study, passage of the screening hearing test. Data for the 169 children who did not pass the hearing screen will be reported separately. It should be noted that children were not excluded on the basis of any diagnosed learning problems, although 52 had a statement of special educational needs. Our rationale was that, given the predicted prevalence of APD in our population and the high level of comorbidity between APD and language-based learning problems,[18] exclusion of such children would remove many of the very children we were searching for in the population.

Data Collection and Analysis

One of the greatest challenges we identified in characterizing APD was the disconnect between the symptoms with which children present initially to caregivers and subsequently to primary and specialist referral services and the tests used for diagnosis. Current approaches sometimes advocate taking a clinical history to bridge that disconnect but, without detailed knowledge of the possible contributions to listening difficulties and a formally validated series of questions, the reliability of diagnoses and assessments of interventions is likely to remain poor. Formal caregiver assessments of children's relevant skills in communication and listening and an objective measure of speech-in-noise listening were introduced to capture clinical presentation. The CCC-2 is a very well-constructed and well-validated questionnaire, with abundant documentation and cross-references to other measures of language difficulties. In contrast, the CHAPPS is largely lacking in the usual validation measures. However, it is currently the most widely used instrument for the specific assessment of listening difficulties in children. Elsewhere, we provided a detailed discussion of these issues and advocated the development of a new, well-validated questionnaire to assess listening problems.[18] Measures of speech perception and intelligibility are widely used in studies of hearing difficulties. Because we wanted to assess speech perception rather than analysis (intelligibility) and because speech-in-noise difficulties often are regarded clinically as a hallmark of APD,[18] we chose the low-redundancy VCV stimulus in speech-modulated noise. The relevance of such a stimulus to clinical presentation is currently unclear; therefore, an aim of this study was to determine whether the listening problems we encountered might be related to early stages of speech processing. It should be noted that, although this is a simple stimulus without higher-level linguistic content, it provided results similar to those of a sentence-in-noise test in another of our studies of pediatric APD.[18]

Selection of the 5 individual AP tests was based on the fact that the timing and frequency of sound are, together with level, phase, and location, the fundamental physical properties of sound. Both timing and frequency were implicated in previous work that showed that many children (approximately one-half) with various forms of learning difficulties had AP deficits.[40] The results of an earlier study, to be reported elsewhere, showed that backward masking and FD were reliable measures in children, with wide variation between individuals and a relatively long period of maturation, both of which suggested that the measures might be sensitive to individual differences in AP. The derived AP tests represented an attempt to separate sensory from nonsensory aspects of perception by assuming that the constituent individual tests (BM0 and BM50 tests for TR, and SM and SMN for FR) would make essentially identical cognitive demands on the listener and that subtracting the thresholds derived from each test would yield a relatively pure index of sensory processing. Therefore, the cognitive load of performing the task, including memorizing the order of the stimuli before responding, paying attention to each stimulus, and selecting the correct response button, could be largely eliminated by subtracting the results from such carefully matched, constituent tests. It is acknowledged, however, that random fluctuations in attention and other sources of internal noise for the listener would change between stimulus trials, and those factors could not be totally eliminated.

After successful completion of a 5-trial demonstration, each individual AP test consisted of 2 tracks, each with 20 trials. Each trial consisted of 3 sequential stimuli, 2 of which were identical, standard stimuli, with the other being a different, randomly ordered target. The child's task was to report (by using a 3-button box) the "odd one out" (ie, serial order of target). Successive trials varied the difference between the standard and target stimuli by using a

3-down/1-up adaptive staircase procedure incorporating 3 diminishing step sizes, to obtain the minimal detectable threshold for the test. The use of 2 tracks refined measures of threshold and response variability, and the child-friendly test design facilitated compliance. A FD test presented 3 successive, 200-millisecond tones in each trial. The standards were always 1 kHz and the initial target was 1.5 kHz. Two measures of auditory backward masking were obtained. In one (BM0), the target was a variable-level (initially 90-dB sound pressure level [SPL]), 20-millisecond tone followed immediately by a fixed-spectrum level (30 dB/Hz), 300-millisecond, bandpass noise (600–1400 Hz) masker. The other measure (BM50) was identical except that a 50-millisecond silent gap occurred between the tone and the masker and the initial target level was 75-dB SPL. Two measures of simultaneous, tone-in-noise masking consisted of the same, variable-level, 20-millisecond tone target (initially either 95- or 80-dB SPL) presented during the masker (30 dB/Hz), which was delivered either without or with a spectral notch (800–1200 Hz) centered on the target frequency. Standard stimuli for these 4 measures consisted of the maskers without the tones. All stimuli incorporated 10-millisecond, raised cosine ramps. Errors made during the first 2 trials of the staircase or on >1 of the demonstration trials resulted in repetition of the track. Children who were unable to complete the demonstration track successfully were exempt from that AP task. A speech-in-noise test (VCV syllables in 3-band, single-male talker–weighted, idealized speech-modulated noise [International Collegium of Rehabilitative Audiology, Amsterdam, Netherlands]) used closely matched procedures. The target (VCV) level varied adaptively (from 80 dBA), and the noise level was fixed at 60 dBA. Other parameters were the same as those for the AP tests. The child repeated verbally what was heard, and results were scored regarding the accuracy of the consonant report.

Derived sensory processing measures of TR and FR[27] were obtained by subtracting the BM50 threshold from the BM0 threshold and the notch SMN threshold from the no-notch SM threshold, respectively. Modeling of TR from source data[25,26] produced, for the 74% of our data (with positive TR) that fitted the model, very strong correlation ($r = 0.97$) between the simple subtraction method used here and the threshold constant of the model. Detection and discrimination thresholds for individual and derived AP tests were calculated primarily from the mean values of the last 3 trials in each track, and the overall test threshold was the mean of the 2 track thresholds. Additional measures of AP threshold and variability for the multivariate regression analysis were calculated from the number and level of trials in each adaptive step, from the number and width of adaptive staircase reversals, and from intertrack difference measures.

Extrinsic and Intrinsic Measures of Attention

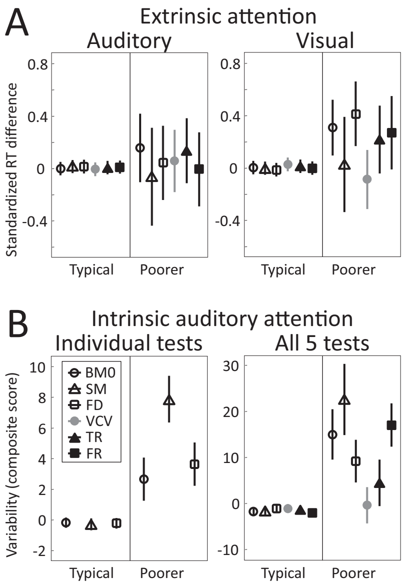
Our previous observations of the variability that some 6- to 11-year-old children display when responding to standard psychoacoustic tests, such as pure-tone FD, suggested that such variability was a major and informative component of individual differences in auditory perception.[17] We assumed that this response variability was caused by variable attention, or a related, top-down process, which led to our notion of intrinsic attention (see below). In support of this assumption, there is strong evidence from both human and animal studies that bottom-up sensory processing in the central auditory system is mature at a very early age, probably within the first year for humans.[50]

Another question that could not be addressed from any other data was whether children who performed poorly on AP tasks had a more-global attention problem. If they did, was that problem specific, in whole or in part, to the auditory modality, or was it a multimodal problem? Therefore, we developed an extrinsic test that (1) was quick and easy and thus was usable by children in a clinical setting, (2) distinguished between auditory and visual attention, and (3) captured the time course of the findings we had observed anecdotally in our psychophysical work,[17] that is, performance (attention) seemed to fluctuate in ~10- to 40-second cycles during tests. The resulting test (IHR Cued Attention Test) was called extrinsic because it was performed separately from the AP tests.

The premise of the IHR Cued Attention Test is that sustained attention (more precisely, phasic alertness [T. Manly, PhD, personal communication, 2007]) may be the main problem children face when performing repetitive auditory tasks.[51] The test rationale is that the reaction time for response to a simple auditory or visual stimulus would be decreased through pairing with a preceding cue stimulus, to a degree related inversely to the level of attention. An inattentive observer should derive greater benefit from the cue than an alert observer, with a correspondingly larger difference between the cued and uncued reaction times.

Separate tests of auditory and visual reaction times were presented with IHR STAR software. During the visual test, the participant fixated on a cartoon character and was asked to press a button as soon as the target (character lifting its arms) occurred. Some trials (20 of 36 trials) were cued by a change in the color of the character's shirt. The auditory test was designed to be as similar as possible, procedurally, to the visual task. The participant fixated on the same (unchanging) cartoon character. The target was a 1-kHz tone (200 milliseconds, 80-dB SPL), and the cue was a frequency-modulated tone (carrier frequency: 4.0–0.6 kHz; modulating frequency: 32 Hz; duration: 125 milliseconds; intensity: 75-dB SPL). For each test, trials were presented at random intervals (1000–4000 milliseconds) after the previous response. The interval between the cue and target also varied randomly (500–1000 milliseconds). Reaction times that were too short (<70 milliseconds) or too long (timed out at 2000 milliseconds) were not analyzed.

Summary reaction time differences are shown in Supplemental Figure 5A in relation to AP performance thresholds. Auditory phasic alertness was not related to any individual AP task threshold, but visual alertness was significantly related generally to AP thresholds ($P < .01$) and specifically to backward masking and FD but not to SM, speech-in-noise (VCV) discrimination, or derived measure thresholds. In summary, children with poorer listening skills had reduced visual alertness.



SUPPLEMENTAL FIGURE 5

Reduced attention of children with poorer AP thresholds. A, Extrinsic, reaction time measures of auditory and visual alertness (IHR Cued Attention Test) for children with typical or poorer performance on each AP test. B, Intrinsic, composite, response variability measures for children with typical or poorer AP thresholds.

For the intrinsic auditory attention measures, we found that poorer performers on the individual AP tests had significantly more variable response profiles than did typical performers on the same individual tests (all $P < .001$) (Supplemental Figure 5B, left). When we combined variability across all 5 individual AP tests, we found that poorer AP performers (at threshold) on each test again showed significantly more-variable response profiles than did their typically performing peers (all $P < .001$) (Supplemental Figure 5B, right). For this composite, intrinsic measure, we also found significantly greater response variability for the poorer AP performers for both TR ($t_{69.6} = -2.27$; $P < .03$) and FR ($t_{73.3} = -7.90$; $P < .001$). However, poorer performers on the VCV speech-in-noise test did not show an overall higher level of response variability. In summary, we found a close, largely predictable relationship between performance thresholds and variability for the various individual listening tests, but it is noteworthy that sensory deficits (represented by TR and FR performance) were related to response variability for the individual AP tests and speech-in-noise deficits were not.

Sensation and Cognition

The terminology here can be confusing, even for (perhaps particularly for) experts. Formally, both sensation and attention are aspects of cognition, but sensation is usually distinguished from perception, with the latter being recognized as including higher-order cognitive elements such as attention, memory, motivation, and emotion.[52] In this article, we attempted to separate the sensation of sounds, consisting of more-peripheral, bottom-up processing, from cognition, which is cortically generated in a top-down manner. This distinction is particularly important for APD (often called central APD), because APD is defined as referring to central (ie, neural) processing. We argued elsewhere that this distinction is itself debatable,[10] but the specific hypothesis addressed in this article was that APD involves listening difficulties caused by impaired sensory processing, as the name of the disorder implies. Our alternative hypothesis, suggested by the data, was that APD involves listening difficulties caused by impaired cognition.

In the multivariate regression analysis, we tested a large number of variables generated by the unreliable responding of the children on the AP tasks, and these were collected together into the AP variability factor (Table 5). Measures of individual variability are referred to elsewhere in the article as intrinsic attention, which means that the variability was attributed primarily to fluctuations in attention on the task itself. Performance on the cognitive tasks (intelligence, memory, language, and literacy) did not test specifically for attention, but fluctuations in attention undoubtedly contributed to performance on those tasks, just as they did to performance on the AP tasks. The extrinsic measure of attention (see above) was separated, in time and nature, from the actual AP tasks and, in that respect, could be regarded as more like the other cognitive tests. In short, we think that cognitive factors, of which attention was the main one studied, made the major contribution to the clinical presentation measures. We acknowledge, however, that other cognitive factors, particularly working memory, which is impossible to dissociate from attention, also likely played a role.