Evaluation of Selected Auditory Tests in School-Age Children Suspected of Auditory Processing Disorders

Iyngaram Vanniasegaram, Mazal Cohen, and Stuart Rosen

Objective: **To compare the auditory function of normal-hearing children attending mainstream schools who were referred for an auditory evaluation because of listening/hearing problems (suspected auditory processing disorders [susAPD]) with that of normal-hearing control children.**

Design: **Sixty-five children with a normal standard audiometric evaluation, ages 6–14 yr (32 of whom were referred for susAPD, with the rest age-matched control children), completed a battery of four auditory tests: a dichotic test of competing sentences; a simple discrimination of short tone pairs differing in fundamental frequency at varying interstimulus intervals (TDT); a discrimination task using consonant cluster minimal pairs of real words (CCMP), and an adaptive threshold task for detecting a brief tone presented either simultaneously with a masker (simultaneous masking) or immediately preceding it (backward masking). Regression analyses, including age as a covariate, were performed to determine the extent to which the performance of the two groups differed on each task. Age-corrected *z*-scores were calculated to evaluate the effectiveness of the complete battery in discriminating the groups.**

Results: **The performance of the susAPD group was significantly poorer than the control group on all but the masking tasks, which failed to differentiate the two groups. The CCMP discriminated the groups most effectively, as it yielded the lowest number of control children with abnormal scores, and performance in both groups was independent of age. By contrast, the proportion of control children who performed poorly on the competing sentences test was unacceptably high. Together, the CCMP (verbal) and TDT (nonverbal) tasks detected impaired listening skills in 56% of the children who were referred to the clinic, compared with 6% of the control children. Performance on the two tasks was not correlated.**

Conclusions: **Two of the four tests evaluated, the CCMP and TDT, proved effective in differentiating the two groups of children of this study. The application of both tests increased the proportion of susAPD children who performed poorly compared with the application of each test alone, while reducing the proportion of control subjects who performed poorly. The findings highlight the importance of carrying out a complete auditory evaluation in children referred for medical attention, even if their standard audiometric evaluation is unremarkable.**

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Department of Audiological Medicine (I.V.), St Georges Hospital, Hornchurch, Essex, United Kingdom; and the Academic Unit of Audiological Medicine (M.C.), Institute of Child Health, and Department of Phonetics and Linguistics (S.R.), University College London, London, United Kingdom.

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Auditory processing disorder (APD) is a perceptual dysfunction not caused by peripheral hearing impairment. It has been defined as "an observed deficiency in one or more of the following behaviors: Sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal aspects of audition, including temporal resolution, masking, integration, and ordering, auditory masking with competing acoustic signals, and auditory performance with degraded acoustic signals" (ASHA, 1996). The British Society of Audiology (BSA) APD group has recently put forward an alternative working definition, characterizing APD as "a hearing disorder resulting from impaired brain function and characterized by poor recognition, discrimination, separation, grouping, localization, or ordering of nonspeech sounds" (January 2004, unpublished).

APD is often reflected in school children by difficulties in distinguishing subtle phonetic differences between words and in understanding speech in background noise. There is currently much interest in APD in children, not least because it may be expected to undermine school achievement. Furthermore, although APD may appear in isolation, it is often associated with common developmental deficits including dyslexia, specific language impairment (SLI) and attention deficit hyperactivity disorder (Cestnick & Jerger, 2000; Chermak, Somers & Seikel, 1998; Wright, Lombardino, King, Puranik, Leonard & Merzenich, 1997). Because of the association of language disorders with auditory ones, a common approach in this area has been to study the auditory processing of children with developmental

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language disorders (see Rosen, 2003, for a review of this area). Interestingly, the research on APD from the audiologic standpoint (Musiek, Geurkink & Kietel, 1982) has largely taken a parallel and independent course: most has been focused on diagnosis, but typically with few attempts to dissociate linguistic aspects of the disorder (for example, concerning phonologic processing) from more general nonlinguistic perceptual deficits. An alternative viewpoint has also been proposed that the diagnosis of APD may be either inappropriate or impossible in cases in which APD is comorbid with developmental language problems, due to overlapping phenotype (Grundfast, Berkowitz, Conners & Belman, 1991; Riccio, Hynd, Cohen, Hall & Molt, 1994).

Despite increasing awareness, detecting APD in children is hampered by three main factors: the absence of a gold standard for the disorder, its complex interaction with other developmental conditions, and etiologic and phenotypic heterogeneity. Still, a number of different approaches have been used in attempts to identify APD in children (Demanez & Demanez, 2003; Jerger & Musiek, 2000; Stollman, van Velzen, Simkens, Snik & van den Broek, 2003). Among them, temporal aspects of auditory processing have received much attention, since it was claimed that children with developmental language problems have difficulties in discriminating pairs of complex tones differing only in fundamental frequency when presented in rapid succession (Tallal, 1980; Tallal & Piercy, 1973). These findings formed the basis of the hypothesis that language impairment may be caused by a general nonspeech auditory deficit, specific to the processing of brief or rapidly changing sounds, which is responsible for the degradation of speech perception during critical periods of language development. The discrimination task developed by Tallal and Piercy (1973) proved highly effective in detecting auditory perceptual deficits in children with developmental language problems, although the deficit is no longer accepted to be specific to rapidly presented or changing sounds (Bishop, Bishop, Bright, James, Delaney & Tallal, 1999; Cacace, McFarland, Ouimet, Schreiber & Marro, 2000; Nittrouer, 1999; Rosen, 2003; Waber, Weiler, Wolff, Bellinger, Marcus, Ariel, Forbes & Wypij, 2001).

The causal role of auditory perception in developmental language impairment was explored further by Wright, Lombardino, King, Puranik, Leonard & Merzenich (1997), using brief tones presented in different temporal relationship to noise bursts. Their finding that language-impaired children have difficulties in detecting a brief tone, particularly when it immediately precedes the noise (backward masking), were taken as endorsement of Tallal's premise that temporal processing deficits could underlie impaired language development. However, Hartley and Moore (2002) have recently argued that the backward masking deficit exhibited by language disordered children may in fact arise from poor processing efficiency that is also present but more difficult to detect in simultaneous masking. Other studies of backward masking in normal and language-impaired children have demonstrated significant variability (Neijenhuis, Snik, Priester, Kordenoordt & Broek, 2002). The variability of the findings affects both the interpretation of the findings with regard to normal language development and its clinical use.

Speech perception tests are usually ineffective in detecting auditory perceptual deficits in children, unless the material is degraded in some way. Presenting stimuli in a background of noise is a good way to degrade the stimuli (Bronkhorst & Plomp, 1989) and offers the added benefit that in this form the test reflects the real-world requirements of having to understand speech in other than ideal conditions. Other methods of degrading speech that have been used in APD evaluation include reverberant speech (Halling & Hume, 2000), accelerated speech (Titone, Wingfield, Caplan, Waters, & Prentice, 2001), or filtered speech (Bocca, Calearo, Cassinari & Migliavacca, 1955). An effective alternative to degradation of the stimulus is achieved by increasing the task difficulty. Adlard and Hazan (1998), for example, used minimal pairs of phonologically similar words to test the auditory discrimination abilities of dyslexic children.

The capacity of the central auditory system to process concurrent stimuli in the two ears has also been exploited extensively, most notably by using dichotic tests (Kimura, 1961). Subsequent to Kimura's original study, dichotic tests have been used to localize and lateralize space-occupying lesions in the temporal lobe in adults, using primarily verbal stimuli. Examples of dichotic tests that proved effective in detecting APD in adult neurologic patients are the Dichotic Digits test (Musiek, 1983; Musiek, Gollegly, Kibbe & Verkest-Lenz, 1991) and competing sentences (Bergman, Hirsch, Solzi & Mankowitz, 1987; Brand, Bossema, Ommen, Mv, Moll & Ackerstaff, 2004). Indeed, dichotic tests form part of the recommended audiologic test battery for the evaluation of APD in children in the United States and elsewhere (Demanez & Demanez, 2003; Jerger & Musiek, 2000; Neijenhuis, Stollman, Snik, & Van der Broek, 2001). However, performance on dichotic tasks may be affected by a variety of factors not related to auditory pathology, leading to variable results (Hund-Georgiadis, Lex, Friederici & von Cramon, 2002; Saberi & Antonio, 2003). In children with APD, dichotic tasks may give rise to additional variability because of variation in the maturation of the auditory system (Kraft, Harper & Nickel, 1995; Musiek & Gollegly, 1988; Neijenhuis et al., 2002).

In this study, we selected three auditory tests that have been previously demonstrated to exhibit some promise in distinguishing developmentally language-impaired children with APD from those without. Our aim in this study was to evaluate the effectiveness of these tests and that of a traditional dichotic task in differentiating children suspected of having auditory processing problems from control children. Generally speaking, we tried to use tests that were not closely related to one another, so hoping to sample a range of abilities, using both speech and nonspeech sounds, not least because of important theoretic claims about the extent to which any deficit is speech-specific or not (Rosen, 2003). We therefore used four main tests, based on the kinds of tasks we have detailed above. Two used speech stimuli (discrimination of minimal pairs of words and dichotic competing sentences) and two used nonspeech (discrimination of short tone pairs differing in fundamental frequency at varying interstimulus intervals and simultaneous and backward masking).

METHODS

Subjects

Sixty-five normal-hearing children and adolescents attending mainstream schools participated in the study. Thirty-two of the children (20 boys, 12 girls; mean age, 10.1 ± 2.1 yr; range, 6–14 yr) were referred to the Audiology Clinic because their teacher or parent expressed concerns about their hearing and were suspected of APD (susAPD). The remaining 33 subjects were age-matched control children (18 boys, 15 girls; mean age, 10.2 ± 2.8 yr; range, 6–14 yr). Three (9.4%) of the susAPD children were left-handed compared with one (3.0%) control child. This difference did not reach statistical significance ($p = 0.295$, one-sided Fisher exact test), nor is the incidence of left-handedness in the susAPD children out of line with the incidence reported for the population as a whole.

A clinical history questionnaire was completed for all children who participated in the study in an interview with the child and his or her parent(s) or care giver. This was followed by an otoscopic examination of the ears.

Auditory Evaluation

A standard audiometric evaluation, comprising pure-tone audiometry and tympanometry, was carried out to ensure normal function of the peripheral auditory mechanism. The average hearing thresholds at 0.5, 1, 2, and 4 kHz of all the children who participated in the study did not exceed 20 dB in either ear, and tympanometry was within the normal limits for their age (British Society of Audiology recommended procedures, 1992).

Auditory processing abilities were evaluated using the following tests.

Competing Sentences • This dichotic listening task was based on sentences originally used by Bergman et al. (1987) in Hebrew but translated into English. The test material comprised 40 pairs of sentences, recorded by a male speaker in a soundproof booth on a Sony DAT recorder. All sentences were normalized to the same root-mean-square level. Paired sentences were adjusted in duration to their mean, using a time-domain technique known as the Synchronized Overlap-and-Add method (Roucus & Wilgus, 1985) as implemented in the Speech Filing System software (http://www.phon.ucl.ac.uk/resource/sfs/). Sentence pairs were presented to the two ears dichotically, through TDH 49 headphones, 25 dB above the speech recognition thresholds. The listeners were instructed to repeat the sentences presented to a designated ear and to ignore the competing sentence (CS) in the opposite ear. Twenty pairs of sentences were presented with the left ear as the designated ear and 20 with the right ear as the designated ear. To control for ear bias and sentence list differences, the left ear was designated first in half the subjects and the right ear in the remaining. The first four pairs presented to each ear were practice items. As shown in the example below, each sentence contained three key words (underlined), which could be interchanged with the key words of the competing sentence and still retain a meaningful content:

Designated ear: The <u>mice</u> <u>ate</u> the <u>bread</u>.

Competing ear: The <u>child</u> <u>took</u> the <u>cheese</u>.

Scoring was carried out per key word, yielding 48 (16 × 3 key words) test items per ear.

Tallal Discrimination Task (TDT) • This forced-choice, same/different judgment task was closely modeled on that described by Tallal and Piercy (1973). The test material comprised 20 pairs of complex periodic tones synthesized to have a vowel-like spectrum with two fundamental frequencies: 100 and 305 Hz. Every trial consisted of two 50 msec stimuli presented sequentially at interstimulus intervals (ISI) of 0, 10, 50, 100 or 400 msec. All four possible stimulus orders were presented (low-low, low-high, high-low, high-high) in a random order. The listeners were required to make a "same-different" judgment by clicking on one of two boxes on the computer screen. The boxes had the words "same" and "different" and an appropriate pictorial depiction of the concept on them (two green circles or a red triangle and a yellow circle, respectively).

Consonant Clusters Minimal Pairs in Noise (CCMP) • This, too, was presented in a forced-choice, same/different format, comprising 28 items based on 7 word pairs, 6 of which were found by Adlard and Hazan (1998) to be particularly difficult to discriminate. These consisted of one minimal pair whose initial consonants differed in voice, place, and manner and were therefore deemed "easy" to differentiate (cat/mat); two minimal pairs in which one word was obtained from the other by omitting a single consonant from an initial consonant cluster (bow/blow; fog/frog) and four minimal pairs in which the words differed in a single consonant of an initial s-cluster (skip/slip; smack/snack; scar/star; spill/still). On any given trial, two words were presented (with 1-s ISI), and the listener was required to indicate if the words were "same" or "different" by clicking with a mouse on the relevant graphic on the computer screen, similar to the TDT described above. Each word pair was presented four times, twice in a "same" pair and twice in a "different" pair (smack/snack, snack/smack, smack/smack, snack/snack), in a random order. Four practice trials using the word pair coat/boat preceded the actual test.

The test items were presented binaurally via Sennheiser HD475 headphones from a laptop computer at 60 dB SPL, in a background of speech spectrum noise presented simultaneously at a signal to noise ratio of −2.3 dB. This noise ratio was found from pilot studies of 5- to 12-yr-old control children to lead to a performance level of about 75–80% correct, so avoiding ceiling and floor effects (Walker, 1998). The words were from a recording made digitally in an anechoic chamber by a Southern British phonetically trained female speaker. Each word was recorded twice so that "same" items were not physically the same. The background noise was constructed to approximate the long-term average speech spectrum of combined male and female voices (Table 2 of Byrne, Dillon, Tran, Arlinger, Wilbraham, Cox, et al., 1994).

Simultaneous and Backward Masking • The masking tasks were modeled closely on those described by Wright et al. (1997), with identical stimuli and some minor differences in the adaptive tracking procedure (simultaneous masking [SM] and backward masking [BM]). All aspects of stimulus presentation and response collection were controlled by computer. Stimuli were presented monaurally (as is typical in masking tasks) in the right ear (arbitrarily chosen) over Beyer DT48 headphones. All stimuli were corrected in spectrum to simulate a flat response from the headphones, as measured on a B&K 4157 ear simulator (Brüel & Kjaer, Naerum, Denmark).

Masked thresholds were measured by using a two-interval, two-alternative, forced-choice task implemented as a computer game. A maximum likelihood adaptive procedure was used to track 90% correct, with an 8.6 dB limit on the maximum change in the level of the probe. This adaptive tracking technique is somewhat sensitive to lack of attention, especially during the beginning of the task. To minimize this effect, any incorrect responses on the first two trials were ignored. On each trial, two 300 msec bursts of masking noise were presented sequentially at an ISI of 340 msec. Along with one of the noise bursts occurred the 1 kHz 20 msec long sinusoidal probe tone. On the computer screen were shown two cartoon faces, side by side. Each face opened and closed its mouth in synchrony with the first and second noise burst, respectively. The listener indicated which of the noise bursts was associated with the probe by clicking with the mouse on one of the two faces. Feedback was given by flashing either a smiling or a sad face on the selected face. The masking noise was a bandpass (0.6–1.4 kHz) noise, at a spectrum level of 40 dB SPL. The probe tone was presented either simultaneously with the masking noise (200 msec after masker onset, SM) or immediately preceding the masker (BM). In the latter condition, there was no overlap between the probe and the masker (nonsimultaneous masking). All stimuli were gated on and off with 10 msec cosine-squared envelopes.

The listeners were first acquainted with the experimental situation by being tested with the probe alone (i.e., without the masker). This provided training for the experimental tasks to follow and established the listener's threshold for the tone.

At least two threshold measurements were obtained in each masking condition. Measured thresholds were accepted as long as the two thresholds were within 10 dB for the same condition. When this criterion was not met, a further two thresholds were run until two were within 10 dB. The actual threshold was taken as the median value of all measurements.

Statistical Analyses

For each auditory test, we determined with regression analyses the extent to which the control and susAPD groups differed in auditory performance (treating group as a categoric predictor variable and test score as a response variable), while also accounting for any possible effects of maturation by including age as a covariate. Most of the statistical analyses used logistic regression, analogous to analyses of variance and covariance but appropriate for the three tasks (CS, TDT, CCMP) in which the response variable is binomially distributed (Collett, 2003). For tests with a continuous unbounded response variable (e.g., masked thresholds) standard regression and analysis of variance methods were used.

RESULTS

Auditory Evaluation

Pure-Tone Audiogram • Thresholds were significantly higher for the susAPD group than for the control group ($p < 0.001$, repeated-measures ANOVA). The four frequency averages (0.5, 1, 2, and 4 kHz), reflecting auditory thresholds in the frequencies that are important for speech were also higher in the left and right ears of the susAPD children ($p \leq 0.002$) by about 5 dB (Fig. 1).

Paired-sample t tests show no significant differences between ears either for the population as a whole ($p = 0.208$) or for each group on its own ($p > 0.3$). The correlation across the two ears was high ($r = 0.77$) for the whole group, but there was no correlation with age ($p > 0.19$ for both ears, Pearson and Spearman correlations).

Auditory Processing Tests

Competing Sentences • Logistic regressions were used to assess the effect of group (categoric factor) and age (as a continuous variate) on left and right ear scores of the control and susAPD groups (Fig. 2). Two listeners (one susAPD child and one control child) were excluded from the analysis because they were clear outliers for performance in the right ear (scores of 14 and 15, with other scores in the range 32–48).

There was a significant group × age interaction ($p = 0.0175$) for the left ear scores but not for the right. Both group and age were significant for both ears ($p < 0.005$). It thus appears that the susAPD group is significantly worse, on average, than the control group in both ears. However, as shown in Figure 2, the interaction for the left ear reflects the fact that performance appears to be worse only for the younger susAPD children. This finding is consistent with neuromaturation. By contrast, the deficit in the right ear was stable over age.

Right Ear Advantage • Right ear advantage (REA) was calculated simply by subtracting left ear scores from the right. Most listeners had a positive REA, indicating better performance in the right (Fig. 3). It emerged that the REA was determined predominantly by, and thus correlated more highly with, performance in the left ear, since performance in the right varied considerably less across listeners (−0.919 versus 0.289). As shown in Figure 3, the REA decreased with increasing age ($p = 0.0001$), but the groups did not differ in their REA.

Tallal Discrimination Task • Logistic regression (taking into account a chance performance level of 50%) was used to analyze the effect of group and age on number correct. Analyses were done separately for all ISIs, for "short" ISIs (0 and 10 msec), and for "long" ISIs (100 and 400 msec). In all three analyses,

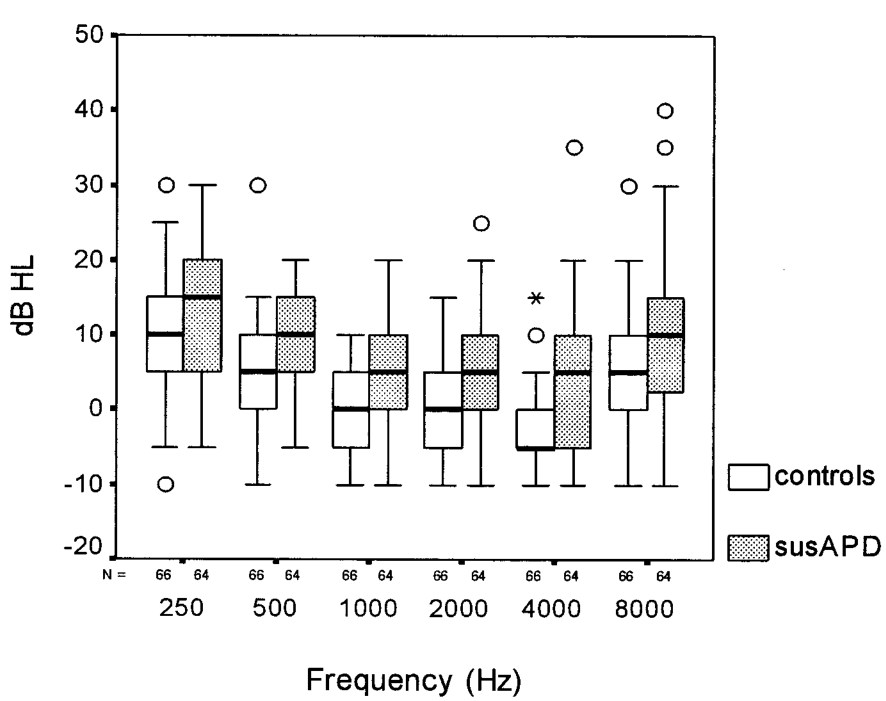

Fig. 1. Boxplots of hearing thresholds at octave frequencies across both ears of control children and children with suspected auditory processing disorders (*susAPD*). Box indicates the interquartile range of values obtained; median is indicated by solid horizontal line. Range of measurements is shown by the whiskers except for points more than one and a half box lengths (indicated by ○) or three box lengths (*) from the upper or lower edge of the box.

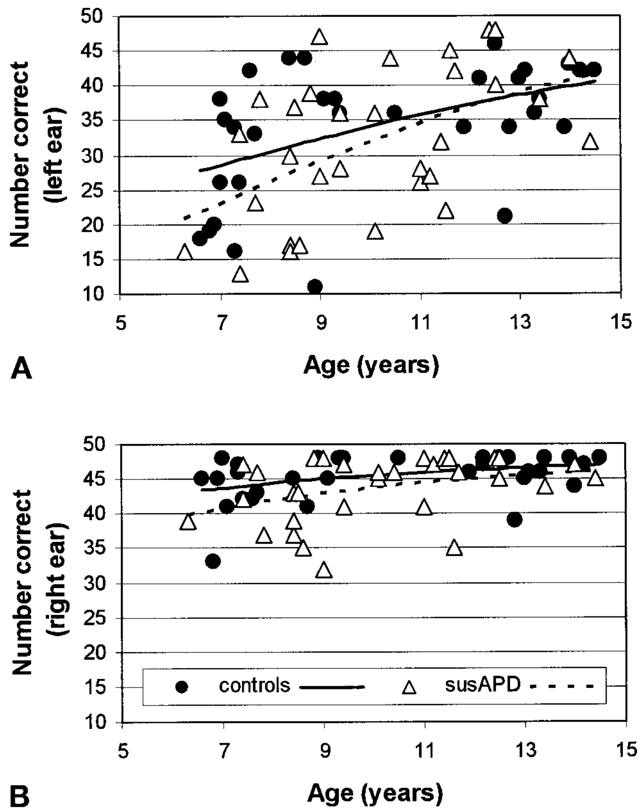

Fig. 2. Competing sentences. Left (A) and right (B) ear scores versus age in the children with suspected auditory processing disorders (*susAPD*) and control children. Lines are fits from appropriate logistic regression models as detailed in the text.

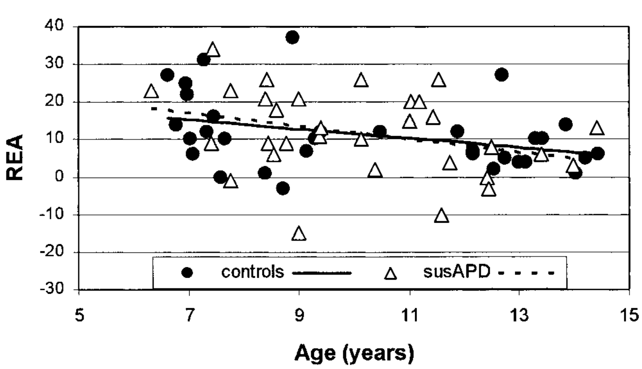

Fig. 3. Right ear advantage (*REA*) in children with suspected auditory processing disorders (*susAPD*) and control groups versus age. Lines are fits from an appropriate linear regression model as detailed in the text.

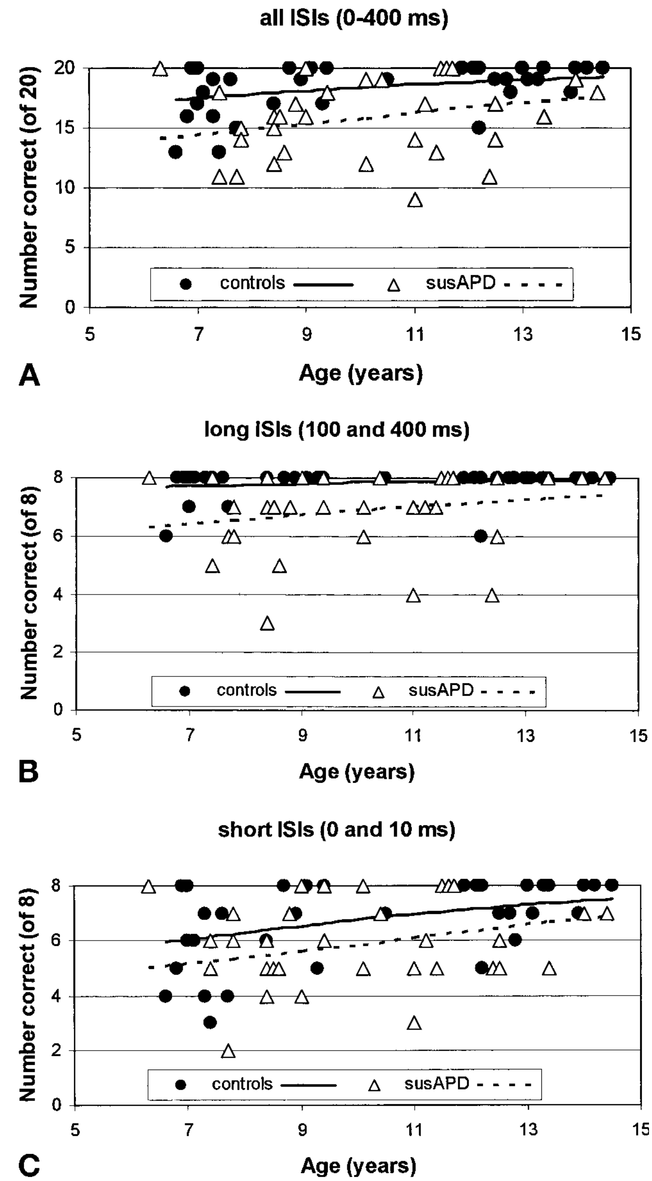

Fig. 4. Tallal Discrimination Task (TDT) scores in the two groups plotted as a function of interstimulus interval (*ISI*) categories. A (top): all ISIs (0, 10, 50, 100, and 400 msec); B (middle): Long ISIs (100 and 400 msec); C (bottom): short ISIs (0 and 10 msec). Lines are fits from appropriate logistic regression models as detailed in the text. *susAPD*, children with suspected auditory processing disorders

age and group were significant predictors of performance, although the effect of age did not reach significance for the long ISIs ($p = 0.0513$). Group emerged as a significant predictor despite a ceiling effect. Figure 4 shows performance as a function of age for the two groups, along with the predictions of the logistic regression in which both age and group are used as predictors. In none of the 3 analyses was the interaction between age and group significant. Therefore, the improvement in performance with age appears to be the same in both susAPD and control children (Fig. 4).

It is interesting to note (with regard to the rapid temporal processing hypothesis) that although all measures clearly distinguish the two groups, there is no indication that the short ISIs separated the groups more effectively than long ISIs. In fact, the statistical evidence is that long ISIs were more effective (Chi-square = 26.8, d.f. = 1, $p < 0.0001$)

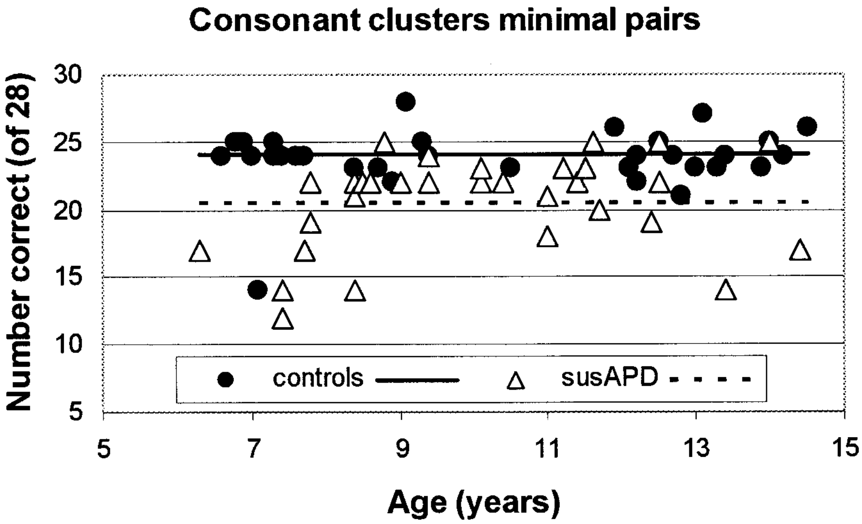

Fig. 5. Consonant clusters minimal pairs (CCMP) performance of the children with suspected auditory processing disorders (*susAPD*) and control groups plotted as a function of age. Lines are fits from an appropriate logistic regression model as detailed in the text.

than short ISIs (Chi-square = 9.0, d.f. = 1, $p <$ 0.0028).

Discrimination of CCMP in Noise • Logistic regression (taking into account a chance performance level of 50%) was used to analyze the effect of group and age on number correct in the 28 test trials. One 7-yr-old control listener performed at chance, far out of line with the other control children, so her data were excluded from the analysis.

The scores achieved by children in the two groups are plotted in Figure 5 as a function of age, along with the predictions of the model, showing no variation in performance with age. The interaction between age and group was not significant, nor was age as a main effect. Group was highly significant ($p < 0.0001$), with the susAPD children worse than control children.

SM and BM • Five susAPD listeners were excluded from this analysis because of abnormally high thresholds in what can be considered the control conditions, which typically have little variability: four had thresholds for simultaneous masking greater than 90 dB SPL, and one 7-yr-old girl exceeded the normal mean thresholds of the unmasked probe tone by more than 2 SD.

Linear regressions of the thresholds obtained by the remaining children in the two groups and in the two masking conditions are shown in Figure 6 in relation to age. It emerged that for both SM and BM, there was a significant effect of age (thresholds improving with increased age, $p < 0.004$) but no differences between the groups otherwise. Performance improved by about 0.5 and 2.7 dB/yr, and age accounted for 13.5% and 19.5% of the variance for SM and BM, respectively. The slopes of the regression lines for SM and BM were significantly different ($p < 0.004$).

Performance in backward and simultaneous masking was also significantly related ($R^2 = 0.23$, $p < 0.001$), again with no differences in the trend between groups. However, this could arise through the relationship of each with age. Multiple linear regression showed, however, that thresholds in SM still accounted for a significant 11.8% of the variance in BM ($p < 0.003$), even when age was taken into account. Age and threshold in SM together accounted for 31.3% of the variance in BM, but neither group nor its interactions with age and SM accounted for significantly more ($p = 0.23$).

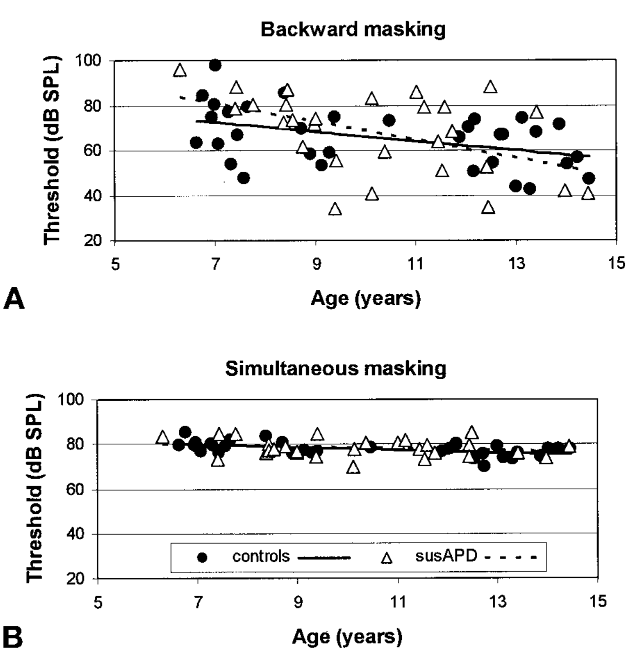

Fig. 6. A and B, Backward and simultaneous masking thresholds plotted as a function of age. Lines are fits from appropriate linear regression models as detailed in the text. *susAPD,* children with suspected auditory processing disorders.

Calculation of *z*-Scores and Determination of Impaired Listeners

Three tasks appeared to discriminate susAPD from control children: CCMP, TDT, and CS. Because the interaction of age and group in determining performance in CS for the left ear indicated that group differences were only evident for younger listeners, only results for the right ear were further analyzed. Using the model estimated from the control data alone, a standardized residual was calculated for the score of each listener. These residuals are independent of age and should (approximately) have a mean of 0 and SD of 1. They are thus directly comparable to *z*-scores calculated from normally distributed data. About 95% of the normal population should have residuals within a range of ± 2.

Table 1 shows the number of listeners in each group with scores worse than -2 (impaired), better than $+2$ (good), and normal (between -2 and $+2$). A relatively high number of control children had poor scores on the CS test, whereas the number of susAPD children with abnormal scores was no higher than the other two measures (TDT and CCMP). Therefore, we have not considered it any further. Of the remaining two measures, the number of control children who performed poorly on the TDT was also a little high (3/33 = 9.1%, when it should be 2.5% or no more than 1 subject). Of the three measures, the CCMP test discriminated the two groups most effectively.

The standardized residuals for the TDT and CCMP tasks for all listeners are shown in Figure 7. Note that although some susAPD listeners performed relatively poorly on both measures (7/32), a number only perform poorly on one measure (11/32). No control listener performed poorly on both tasks, but four did on a single task. Importantly, a significant proportion of the susAPD group had no measurable auditory deficit (14/32 = 44%), at least on the tasks investigated here. Taking the mean of the residuals for the CCMP and TDT tests, two control listeners (6%) and 18 of the susAPD listeners (56%) emerged as "impaired listeners." Notably, within the two groups, no average measure of audiologic threshold (four-frequency average in the ears separately and averaged) correlated significantly with the residuals from either TDT or CCMP.

TABLE 1. Number of listeners in each group and performance category, based on standardized residuals calculated from control listeners only

Test	Group	Impaired	Normal	Good
CCMP	Control	1	31	1
	susAPD	11	21	0
TDT	Control	3	30	0
	susAPD	14	18	0
CS (right ear scores)	Control	5	26	2
	susAPD	11	21	0

CCMP = consonant cluster minimal pairs; TDT = Tallal Discrimination Task; CS = competing sentences; susAPD = suspected auditory processing disorders.

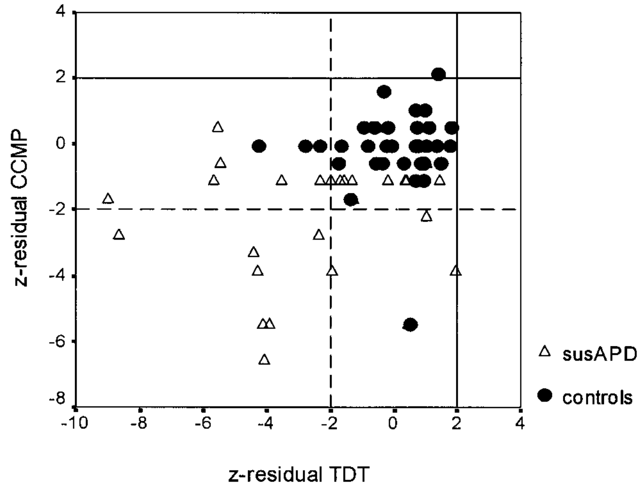

Fig. 7. Consonant clusters minimal pairs (*CCMP*) standardized residual *z*-scores plotted against *TDT* *z*-scores. Dashed lines ($z = -2$) indicate scores below which only about 2.5% of the normal population would be expected to score; solid lines ($z = +2$) indicate scores that only 2.5% of the normal population would be expected to exceed. *susAPD,* children with suspected auditory processing disorders.

DISCUSSION

The main finding to emerge from this study is that 56% of 32 children referred because of concerns about their hearing were found to have auditory perceptual deficits on one or more of our tests, despite having normal or near-normal peripheral hearing. Since APD is associated not only with developmental language problems (Amitay, Ahissar, & Nelken, 2002; Hartley & Moore, 2002; Riccio et al., 1994; Talcott, Witton, Hebb, Stoodley, Westwood, France, Hansen & Stein, 2002) but also with poor academic achievement (Bellis & Ferre, 1999; Cacace & McFarland, 1998; Chermak, Tucker & Seikel, 2002; Oberklaid, Harris & Keir, 1989), our findings highlight the importance of carrying out a thorough audiometric evaluation in such children, even if their standard audiometric evaluation is unremarkable.

The mean auditory thresholds of the susAPD children were poorer than those of the control children across the frequencies. The difference, of approximately 5 dB, was evenly distributed across the frequencies, suggesting that it may arise from inattention in the susAPD group. However, no average measure of thresholds correlated with performance on the CCMP or TDT tasks within groups.

We evaluated four psychoacoustic tests, two verbal and two nonverbal, which have been shown to be effective in unveiling subtle auditory perceptual problems in children. A dichotic test was included, for two reasons. First, these can probe binaural interactions, which are known to occur at the central rather than peripheral level. Second, this allowed the comparison of the effectiveness of a well-established method of evaluating auditory function with some newer tests drawn from the literature. The binaural separation paradigm was used, as it reflects the ability to direct attention in situations that often occur in classrooms or in the playground. The susAPD group performed significantly worse on this task than the control listeners in both ears, although performance in the left ear appeared only to be worse for the younger susAPD children. The performance of listeners in both groups improved with age. Left ear scores varied considerably, particularly in younger listeners. The variability in left ear scores of young listeners has been ascribed to slow maturation of the callosal fibers responsible for the transfer of information across the hemispheres (Kraft, Harper & Nickel, 1995; Musiek & Gollegly, 1988; Salamy, 1978).

The REA is an important measure, reflecting the complex relationship between hand, ear, and hemispheric dominance for various dichotic listening tasks (Fennell, Satz & Morris, 1983). Consistent with expectation, right ear scores were better than left ear scores in most listeners but did not differentiate between the groups. The REA was more or less determined by performance in the left ear, as performance in the right varied considerably less across listeners. The unusually large REA found in some young listeners has been attributed to slow maturation of neural auditory circuits, particularly in dichotic tasks that use “heavily linguistically loaded” stimuli such as sentences (Musiek & Gollegly, 1988).

The performance of the susAPD listeners on the TDT was also significantly worse than that of the control listeners at all ISIs, and at short and long ISIs separately, with no indication that short ISIs were more effective at separating the groups. The latter finding is at odds with Tallal’s rapid processing hypothesis, which predicts poorer performance at short ISIs (Tallal & Piercy, 1973). It may be argued that unlike this study, that hypothesis was based on performance by children with language problems (Tallal & Piercy, 1973; Tallal, Stark, Kallman & Mellits, 1981). However, their findings in children with language problems bear relevance to the children of this study because of the strong association between language development and APD. Furthermore, the dependency of TDT performance on ISI has not been universally upheld, even in studies of auditory processing in language-impaired children: Waber et al. (2001) used a TDT at four ISIs (10, 50, 100, and 400 msec) and varying stimulus durations and reported that the differences between learning-impaired and non–learning-impaired children remained constant across stimulus duration and ISI. Cacace et al. (2000) compared the performance of dyslexic and control children on a number of auditory and visual tasks and found that the deficits found in the dyslexia group were neither modality nor temporally specific. The contradictory findings in the literature with regard to the effect of short ISI on the discrimination ability of some listeners and on the importance of temporal processing to normal language development have been explained by a number of factors, including the reliability and validity of rapid auditory processing tasks, individual differences in the auditory processing abilities of dyslexic and SLI populations, the age of listeners, and the relationship between verbal and nonverbal auditory processing abilities (Bishop et al., 1999; McArthur & Bishop, 2001). These discrepancies challenge the premise of a causative role for impaired rapid temporal processing in language impairments.

Authors are divided in their findings about the effect of age on TDT performance: Waber et al. (2001) reported an improvement with age in children referred for evaluation of learning problems. However, a study using both auditory and visual presentations in SLI children reported that the number of errors made by SLI children in the visual task decreased with age, whereas the number of errors in the auditory task did not change (Tallal, Stark, Kallman & Mellits, 1981). In the current study, the performance of both the control children and the susAPD children improved at a similar rate with age (except for long ISIs, in which the trend was obscured by the fact that the performance of the control group was at ceiling). These findings demonstrate that the gap between the discrimination abilities of the susAPD and control children is maintained through the period of development.

Of the different tests that we used, the CCMP test has perhaps the highest ecologic validity for our susAPD group, reflecting the common symptom of the children in the susAPD group of difficulty understanding speech in noisy background. The susAPD group scores were significantly poorer than the control group on this task, but these deficits did not correlate with performance on the TDT test. One fundamental difference between the two tests, of course, is that one is nonverbal, whereas the other is verbal. The lack of correlation between the tests may thus reflect the predominant involvement of left hemisphere mechanisms for speech as opposed to predominant involvement of right hemisphere mechanisms in tone perception and may be interpreted as challenging Tallal's rapid processing hypothesis. Insofar as the speech stimuli are expected to require an extra level of processing (a linguistic one), it is hard to see how the Tallal theory can account for a failure in discriminating word pairs but not tones (Tallal & Piercy, 1974; Tallal & Piercy, 1975). Clinically, the implication of the effect size combined with the lack of correlation between the TDT and CCMP tests suggests that carrying out both tests will lead to a clearer separation between control and susAPD children, whereas the fact that none of the control children failed both tests will help to reduce the overlap in performance of the two groups.

In contrast to the effectiveness of the TDT and the CCMP tests in discriminating the two groups, SM and BM led to no differences. In both groups, the performance on the masking tasks was characterized by variability and by improved performance with age. Both trends were particularly obvious in relation to performance in backward masking. Similar findings (in normally developing children only) were also reported by Buss et al. (1999) and by Hartley, Wright, Hogan, & Moore, (2000).

The failure of SLI children to separate a brief sound from a rapidly following one (BM), reported by Wright et al. (1997), was interpreted as providing further confirmation of Tallal's claim that language impairment arises from an elementary auditory failure to hear acoustic distinctions of successive brief sounds in speech. Our study focused on children with susAPD, so it may be that our failure to replicate Wright's findings may, at least in part, be due to differences in the populations that were studied. However, studies of BM in SLI children have not always reproduced the findings of Wright et al. (Bishop, Carlyon, Deeks & Bishop, 1999). More specifically, the variability in performance on the masking tasks, coupled with the time taken to administer the test, may preclude its application as a clinical tool to detect subtle auditory perceptual deficits in young children with susAPD.

The evaluation of the test battery as a whole revealed that the combined application of the TDT and CCMP tests was more effective in separating the two groups than each of the tests alone. Neither the masking tasks nor the CS test were used in these calculations, despite the presence of a group effect on the latter test (in fact, including the residual score from the CS test in an overall mean increases by one the number of listeners labeled as "impaired" in each group, so is clearly not desirable). In the absence of a gold standard for APD, it is impossible to appraise the effectiveness of the battery in absolute terms, but it is likely that the inclusion of additional carefully selected and evaluated tests will help to define and characterize APD and may ultimately lead to a better differentiation of the two groups. The battery approach to identifying APD in children is divisive: Domitz and Schow's evaluation of the Multiple Auditory Processing Assessment (MAPA) battery (comprising an auditory attention task, dichotic digits, pitch patterns, and competing sentences) in 81 normal-hearing school children ages 8–9 yr seems to suggest that both the number and type of tests in a battery influence its sensitivity: In their study, the sensitivity of any single test did not exceed 40%, increasing to a maximum of 65% when two tests were applied, and up to 90% for three tests (Domitz & Schow, 2000). By contrast, Singer et al. (1998), in a study similar to the current one, found that the application of just two tests (binaural fusion and masking level differences) out of a battery of seven identified most effectively APD in children with classroom educational deficits and that the application of additional tests increased the overall cost of the evaluation but failed to improve its positive predictive value.

The fact that APD is widely accepted as a heterogeneous disorder may introduce an additional limiting factor in the evaluation of APD. The heterogeneity may provide an explanation as to why some children with suspected APD perform poorly on some tests and not others and emphasizes the need for the inclusion of different types of tests in any battery aimed at assessing APD.

Although we did not set out to evaluate the rapid processing hypothesis, it is interesting to note that some of the findings that have emerged are inconsistent with it. The claim that the difficulty encountered by some children with APD in the discrimination of tones is specific to their presentation in rapid succession (i.e., at short ISIs) was not supported by our findings. The fact that no group effect was found on the BM task eliminated another source of validation for a temporal auditory perceptual deficit; furthermore, the lack of correlation between the TDT and CCMP tests did not bolster the premise of a general auditory perceptual deficit. Insofar as a general auditory deficit is presumed to underlie deficits in speech perception, we would expect any deficit for syllables to also manifest itself as a deficit in discriminating tones.

Nonetheless, 44% of the children of this study referred because of concerns about their hearing exhibited no signs of APD, at least in the tests undertaken. Perhaps surprisingly, this proportion is consistent with studies of individuals with developmental language impairments that indicate that a third to two-thirds of them have no auditory perceptual deficits (Amitay, Ahissar & Nelken, 2002; Ramus, 2003; Ramus, Rosen, Dakin, Day, Castellote, White & Frith, 2003; Riccio, Cohen, Hynd & Keith, 1996; Riccio, Hynd, Cohen, Hall, & Molt, 1994; Tallal, 1980). We might have expected measurable auditory problems to be more apparent in a population recruited on the specific basis of suspected APD than in ones recruited on the basis of a language disorder.

On the other hand, we have found auditory deficits in a majority of children referred for medical attention with hearing difficulty. Perhaps the most significant question is the extent to which this auditory deficit relates to other cognitive skills, including language. It appears likely that the susAPD listeners that we have evaluated will provide a strong test of the extent to which an auditory deficit can cause a language disorder, insofar as one might expect those children with auditory problems also to exhibit problems with language and/or literacy. In fact, we have been able to evaluate a number of cognitive skills in a subset of the children of this study and the results will be reported separately (Rosen et al., in preparation).

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Address for correspondence: Mazal Cohen, Academic Unit of Audiological Medicine, Institute of Child Health, UCL, 30 Guilford Street, London WC1N 1EH, UK.

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