Auditory Temporal Processing in Children With Specific Reading Disability With and Without Attention Deficit/Hyperactivity Disorder

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The auditory temporal deficit hypothesis predicts that children with specific reading disability (RD) will exhibit a deficit in the perception of auditory temporal cues in nonspeech stimuli. Tasks assessing perception of auditory temporal and nontemporal cues were administered to children with (a) RD without attention-deficit/hyperactivity disorder (RD/no-ADHD, $n = 40$), (b) ADHD alone (ADHD/no-RD, $n = 33$), (c) RD and ADHD (RD/ADHD, $n = 36$), and (d) no impairment (NI, $n = 41$). The presence of RD was associated with a specific deficit in detection of a tone onset time asynchrony, but no reduction in performance on other tasks assessing perception of temporal or nontemporal acoustic cues. The presence of ADHD was associated with a general reduction in performance across tasks. The pattern of results did not indicate a pervasive deficit in auditory temporal function in children with RD, but did suggest a possible sensitivity to backward masking in this group. Results also indicated that the comorbid presence of ADHD is a significant factor in the performance of children with RD on psychoacoustic tasks.

KEY WORDS: specific reading disability, attention deficit/hyperactivity disorder, auditory perception, psychoacoustics

Dyslexia, or specific reading disability (RD), is a developmental disorder that affects approximately 5–17% of the school-age population, depending on the sample and how it is defined (Lyon, 1995; B. A. Shaywitz & Shaywitz, 1994). RD is characterized by difficulty in single word decoding that is not the result of general developmental disability or sensory impairment (B. A. Shaywitz, Fletcher, & Shaywitz, 1995). In addition to difficulty in decoding print, children with RD exhibit deficits on a variety of tasks requiring the processing of auditory verbal stimuli, including phonemic awareness, rapid automatized naming, and immediate phonological memory (Blachman, 2000; Fletcher et al., 1994; Shakweiler & Crain, 1986; Stanovich, 1988). Children with RD also exhibit deficits in phoneme perception (Brandt & Rosen, 1980; de Weirdt, 1988; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Manis et al., 1997; Mody, Studdert-Kennedy, & Brady, 1997; Reed, 1989), which may also play a role in the difficulty these children have in acquiring phonological processing skills (McBride-Chang, 1995).

Although some researchers suggest that deficits in phoneme perception in children with RD are specific to speech stimuli (Bishop, Carlyon, Deeks, & Bishop, 1999; Brady, Shankweiler, & Mann, 1983; Mody et al., 1997), others hypothesize that at least a subgroup of children with RD have a deficit at the perceptual level that affects processing of both speech and nonspeech stimuli (Tallal, Merzenich, Miller, & Jenkins, 1998; Tallal, Miller, & Fitch, 1993; Wright, Bowen, & Zecker, 2000; Wright et al., 1997). The auditory temporal deficit hypothesis posits that this deficit is specific to auditory temporal cues, affecting the perception of brief portions of the speech stimulus, such as formant transitions, that provide important cues for some phonemic contrasts (Tallal et al., 1993, 1998). The present study was undertaken to test the auditory temporal deficit hypothesis as it applies to nonspeech stimuli.

The initial formulation of the auditory temporal deficit hypothesis was based on observations in children with specific language impairment (SLI), who have more general receptive and expressive language deficits than most children with RD (Tomblin & Zhang, 1999). Tallal and Piercy (1973a, 1973b) found that performance by children with SLI on discrimination and temporal order judgment (TOJ) tasks utilizing nonspeech stimuli (steady-state complex tones) deteriorated relative to controls as the interval between stimuli decreased, which they interpreted as suggestive of a deficit in the rate of processing of auditory stimuli. These findings were replicated in children with RD (Reed, 1989; Tallal, 1980). Although subsequent research has not always found deficits on TOJ tasks utilizing nonspeech stimuli in children with RD (e.g., Heath, Hogben, & Clark, 1999; Mody et al., 1997; Nittrouer, 1999), a number of studies have sought to evaluate auditory perception in general, and auditory temporal processing in particular, in children with RD or SLI (for detailed reviews see Farmer & Klein, 1995; Wright et al., 2000).

Auditory temporal processing is not a unitary construct, and temporal phenomena present in acoustic stimuli manifest themselves in different ways depending on the task (Green, 1984). Auditory temporal resolution, or acuity, represents the ability of the auditory system to respond to rapid changes in the envelope of sound over time, and is measured by gap, tone onset time asynchrony, and amplitude modulation detection thresholds (Viemeister & Plack, 1993). Although detection of a gap in a pure tone is reported to be deficient for children with RD (McCroskey & Kidder, 1980), other studies find no deficit for gap detection in broad-band noise (McAnally & Stein, 1996; Schulte-Korne, Deimel, Bartling, & Remschmidt, 1999). Both children (Hari, Saaskilahti, Helenius, & Uutela, 1999; Lorenzi, Dumont, & Füllgrabe, 2000) and adults (Menell, McAnally, & Stein, 1999) with RD have been found to be less sensitive to amplitude modulation than normal reading controls, although not all studies have replicated this finding (e.g., Helzer, Champlin, & Gillam, 1996). Temporal integration, another distinct aspect of auditory temporal behavior, refers to the ability of the auditory system to accumulate acoustic energy, over durations up to approximately 300 ms, to improve performance (Eddins & Green, 1995). Children with SLI (Hochman, Thal, & Maxon, 1977), but not children with RD (Cacace, McFarland, Ouimet, Schrieber, & Marro, 2000; Tobey & Cullen, 1984), have been found to have abnormal temporal integration functions. Binaural temporal phenomena include detection of interaural differences in time of arrival and phase (Grantham, 1995; Noble, Byrne, & Ter-Horst, 1997). In some studies (McAnally & Stein, 1996), but not others (Hill, Bailey, Griffiths, & Snowling, 1999), children with RD have been found to have reduced sensitivity to interaural phase difference as evidenced by less unmasking of a sinusoid in noise.

Children with RD have also been found to perform more poorly than controls on nontemporal tasks, including frequency discrimination (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Hari et al., 1999; McAnally & Stein, 1996), frequency resolution (Wright et al., 2000), and detection of frequency modulation (Talcott et al., 1999, 2000; Witton et al., 1998). Not all studies, however, support such deficits (e.g., Bishop et al., 1999; Hill et al., 1999; Mody et al., 1997).

In sum, the evidence for a nonspeech auditory processing deficit in children with RD is mixed, as is the evidence for the specificity of the deficit to auditory temporal cues. Therefore, the presence of an auditory temporal processing deficit in children with RD that extends to nonspeech stimuli, as well as its role in phoneme perception deficits, remain a matter of controversy. An alternative hypothesis suggests that deficits in phoneme perception are a result of deficient phonological coding and are, therefore, specific to speech stimuli (Brady et al., 1983; Libermann & Mattingly, 1989; Lieberman, Meskill, Chatillon, & Schupack, 1985; Mody et al., 1997). This "speech specific" hypothesis is supported by those studies that fail to find evidence for a general auditory temporal processing deficit in children with RD (Bishop et al., 1999; Helzer et al., 1996; Mody et al., 1997; Schulte-Korne, Deimel, Bartling, & Remschmidt, 1998), as well as those that find a deficit for speech, but not nonspeech stimuli (Adlard & Hazan, 1998; Brady et al., 1983; Mody et al., 1997; Nittrouer, 1999).

The current study was designed to test the auditory temporal deficit hypothesis using a range of psychoacoustic tasks assessing auditory temporal and nontemporal function. Most studies use a limited number of tasks, and differences in criteria for participant selection make comparisons across studies difficult. The current study used a low achievement definition of RD similar to that used in previous studies by our group (Fletcher et al., 1994; Foorman, Francis, Fletcher, & Lynn, 1996) and others (Joanisse, Manis, Keating, & Seidenberg, 2000; Manis et al., 1997; Post, Swank, Hiscock, & Fowler, 1999; Stanovich & Siegel, 1994). Multiple measures, including phonological and single word decoding, reading fluency, and spelling ability, were used to identify children with RD in order to avoid placement of children who have a history of RD and have had intervention into one of the comparison groups not disabled in reading. Children with RD who have had intervention often show improvement in single word and nonword decoding skills but continue to exhibit significant deficits in decoding speed and spelling (Torgesen & Wagner, 1999). Aggregating scores by averaging across tests also attenuates the error of measurement, improving the reliability of estimates of whether a child is above or below a particular cutpoint. Children with SLI were identified and excluded from the study. In addition, as reading ability is a continuous variable that is normally distributed in the population (Rodgers, 1983; S. E. Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992), all analyses were repeated treating reading ability as a continuous rather than as a categorical variable in order to examine the generalizability of results across reading disability definitions.

Attention deficit/hyperactivity disorder (ADHD) was also included as a factor. The rate of comorbidity of RD and ADHD is substantially greater than predicted by chance, with estimates ranging from 15% to 45% (Purvis & Tannock, 2000). Most studies of perception in children with RD, however, do not take the potential presence of ADHD into account in a systematic fashion. Behavioral deficits associated with ADHD include an inability to sustain focused attention (Barkley, Grodzinsky, & DuPaul, 1992), an impulsive response bias (Barkley, 1997a, 1997b), and reduced working memory (Barkley, 1997b), all of which potentially affect performance on perceptual tasks.

For the current study we chose psychoacoustic tasks that measure auditory temporal acuity and binaural temporal function, as well as frequency resolution and absolute threshold. The auditory temporal deficit hypothesis predicts that children with RD will exhibit deficits on psychoacoustic tasks assessing auditory temporal function only. Although we expected a general lowering of ability for children with ADHD across experimental factors, we were particularly interested in the possibility of a synergistic interaction between RD and ADHD.

Method

Participants

One hundred fifty children, ranging in age from 7;5 (years;months) to 14;5 (M = 10;4, SD = 1;6), served as participants. This age range was chosen because the measures used in this study can be reliably employed in this age range, and the classification of RD can be made with temporal stability (S. E. Shaywitz et al., 1992). The Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) was administered to estimate intellectual abilities. In order to eliminate children with below average intelligence, a Full Scale IQ above 79 was required for participation in the study. In addition, as IQ scores of children with RD tend to be somewhat lower than those obtained for children without RD, children with IQ scores above 130 were excluded from the study to avoid creating groups with large IQ discrepancies. The Hollingshead two-factor index of social position (Hollingshead, 1965), which is based on the parents' occupation and highest achieved grade level, was used to assess socioeconomic status (SES).

All children had hearing sensitivities of 20 dB or better in each ear by pure-tone audiometric screening at 500, 1000, 2000, and 4000 Hz (American Speech-Language-Hearing Association [ASHA], 1997); normal middle ear function by tympanogram; English as their primary language; and no history of neurological disorder. Audiometric screening and tympanogram were performed the same day as psychoacoustic testing. The protocol used in this study received full approval from the Institutional Review Board of the University of Texas Medical School at Houston. Parents with potential interest in having their children participate in the study were identified through contacts maintained by the authors with parents, advocacy groups, and professionals who work with the local school districts and private agencies. Parents initiated contact with the authors, and children were tested after parents had given informed consent and children had given informed assent.

Children were identified as having RD by administering several achievement measures, including (a) the Basic Reading Cluster of the Woodcock Reading Mastery Test–Revised (Woodcock, 1998), which consists of the Word Attack (decoding of pseudowords) and Word Identification (decoding of real words) subtests; (b) the Spelling subtest of the Wechsler Individual Achievement Test (Wechsler, 1992); and (c) the Test of Word Reading Efficiency (Torgesen & Wagner, 1999), a test of word decoding speed. Standard scores on these three measures were averaged to form a composite, and children were placed into the RD group on the basis of having a composite score at or below 90, with at least two of the three tests being at or below this cutoff (Breier et al., 2001). This criterion is similar to that used in other studies (Fletcher et al., 1994; Foorman et al., 1996; Joanisse et al., 2000; Manis et al., 1997; Post et al., 1999; B. A. Shaywitz & Shaywitz, 1994; Stanovich & Siegel, 1994). Children were also identified as having SLI by using the Concepts and Directions and Recalling Sentences subtests of the Clinical Evaluation of Language Function–3 (Semel, Wiig, & Secord, 1995), as well as the Vocabulary subtest of the WASI. Children with a scaled score below 7 on all three tests were identified as SLI (n = 9) (Joanisse et al., 2000). As this study focuses on RD, and only 9 children were identified as having SLI, these children were not included in the study.

Licensed psychologists (authors JIB and JMF) made the diagnosis of ADHD based on (a) a semistructured clinical interview of the caretaker during the evaluation, (b) clinical observation, and (c) caretaker and teacher (when available) responses on the Swanson, Nolan, Achenbach, and Pelham–IV (SNAP-IV) rating scale (Swanson, 1992). The semistructured clinical interview was modeled on the *Diagnostic and Statistical Manual of Mental Disorders* (4th ed. [*DSM-IV*]; American Psychiatric Association, 1994) criteria for the diagnosis of ADHD. The interview documented specific behavioral symptoms of inattention and hyperactivity-impulsivity that have persisted for more than 6 months with associated impairment in social and/or academic functioning in two or more settings, including home, school, and other activities such as scouting organizations and church. It also documented the presence of such behaviors prior to age 7 with associated impairment. The examiner filled out a checklist of behavioral symptoms modeled after the *DSM-IV* criteria for symptoms of inattention, impulsivity, and hyperactivity. The initial diagnosis of ADHD was made by one rater, and then checked independently by the second. In the event of disagreement the case was discussed and a decision reached on the basis of all available data.

SNAP–IV responses were obtained from at least one parent or guardian in all cases, and from at least one current teacher for 99 participants. All but 5 of the participants who were subsequently placed in the ADHD group either had a teacher SNAP–IV form returned or had been placed on psychostimulants for ADHD and/or had a previous diagnosis of ADHD by a pediatrician. The 5 participants placed into the ADHD group without a history of ADHD or SNAP–IV teacher responses met all *DSM-IV* criteria for ADHD as determined by clinical interview. Of the 27 children placed in the no-ADHD group who did not have teacher SNAP–IV responses, none had a history of ADHD or met the *DSM-IV* criteria for ADHD, nor were behavioral symptoms of ADHD observed during testing in these children.

Only children with ADHD/combined type were included in the current study, in order to maintain group homogeneity. Children with the predominantly inattentive type have different cognitive deficits than those with the combined type (Barkley, 1997a, 1997b). Children who exhibited evidence of psychiatric disorders (e.g., anxiety disorders, conduct disorder, obsessive–compulsive disorder, depression, and Tourette's syndrome) that would interfere with performance on perceptual tests were excluded from the study (n = 9). In order to assess the effects of ADHD on phoneme perception independently of the effects of medication, we had children with ADHD who were medicated with stimulants (n = 30) discontinue their medication 24 hr prior to testing (Purvis & Tannock, 2000). These procedures resulted in the formation of four groups: (a) specific reading disability without ADHD (RD/no-ADHD; n = 40), (b) ADHD without RD (ADHD/no-RD; n = 33), (c) RD with ADHD (RD/ADHD; n = 36), and (d) not impaired (NI; n = 41).

Demographic data for each group are presented in Table 1, and scores on IQ and academic achievement tests used to form the groups are presented in Table 2. Group comparisons for continuous variables were performed using analysis of variance (ANOVA) with RD and ADHD group membership as independent variables. Chi square was used to test for differences in distributions between RD groups and ADHD groups for categorical variables.

As shown in Table 1, there were no significant group differences in age, ethnicity, SES, or gender ($p > .05$). Table 2 shows that although all groups had mean Full Scale IQ scores within the average range, children with RD had lower Full Scale IQ, $F(1, 146) = 11.86, p < .0007$, and Verbal IQ, $F(1, 146) = 11.95, p < .0007$, scores. These findings are not surprising, as lowering of language functions is expected in children with RD (B. A. Shaywitz et

Table 1. Demographic data by group.

Measure	NI (n = 41)	ADHD/ no-RD (n = 33)	RD/ no-ADHD (n = 40)	ADHD/ RD (n = 36)
Age (Years)				
M	10;3	9;9	10;9	10;4
SD	1;8	1;7	1;6	1;5
SES (Hollingshead Social Class)				
I	4	5	5	4
II	15	10	12	10
III	18	14	18	15
IV	4	4	5	7
Race				
White	32	27	33	25
Black	4	5	5	10
Hispanic	1	0	2	1
Asian	4	0	0	0
Indian	0	1	0	0
Gender				
Male	26	22	28	31
Female	15	11	12	5

Note. NI = no impairment; ADHD = attention deficit/hyperactivity disorder; RD = reading disability; SES = socioeconomic status.

al., 1995). There were no group effects for Performance IQ ($p > .05$). As expected, children with RD performed significantly below those without RD on academic achievement tests used for group placement, and children with ADHD scored significantly higher on the SNAP–IV inattention and hyperactivity/impulsivity scales than did children without ADHD. (SNAP–IV scores represent the mean of parent and teacher scores, when both were available. It should be noted that the large number of children with ADHD who were medicated at the time of evaluation likely artificially lowers the ADHD group means on this instrument.)

General Psychoacoustic Testing Methods

Children were tested in a double-walled, double-floored, sound-attenuating chamber (IAC Model 1200-A) with a single examiner present. Stimuli were created with a Tucker-Davis Technologies (TDT) digital sound system (AP2 array processor with fiber optic interface to DD1 2-channel 16-bit digital-to-analog converter running at a 50 kHz sampling rate), filtered (TDT FT5-9 Dual 9-pole antialiasing filter set at 20 kHz), amplified (TDT HB5 stereo headphone driver), and presented over phase-matched TDH-49 stereo headphones. Stimuli were calibrated with a Bruel & Kjaer 4152 artificial ear, B&K 2235 sound level meter, and HP 3561A dynamic signal analyzer. Order of presentation of tests was randomized across participants.

Table 2. Test data by group.

Measure	NI	ADHD/ no-RD	RD/ no-ADHD	ADHD/ RD
WASI Full Scale IQ (Standard Score)				
M	109.6	104.8	101.7	100.4
SD	9.5	11.5	11.2	11.4
WASI Verbal IQ (Standard Score)				
M	108.5	108.8	100.8	100.9
SD	18.9	12.4	10.5	11.6
WASI Performance IQ (Standard Score)				
M	105.9	99.9	101.9	100.5
SD	11.3	14.2	13.0	12.9
WRMT-R Basic Reading Cluster				
M	104.9	99.8	86.2	86.8
SD	8.6	7.0	6.5	7.2
WRMT-R Word Reading Efficiency				
M	94.6	89.4	68.1	70.5
SD	7.3	8.6	13.5	12.9
Spelling				
M	104.6	96.3	80.9	82.7
SD	12.1	7.4	7.7	8.4
SNAP-IV Inattention Scale				
M	0.63	1.92	0.78	2.02
SD	0.46	0.45	0.44	0.51
SNAP-IV Hyperactivity/Impulsivity Scale				
M	0.35	1.48	0.42	1.14
SD	0.42	0.58	0.43	0.71

Note. NI = no impairment; ADHD = attention deficit/hyperactivity disorder; RD = reading disability; WASI = Wechsler Abbreviated Scale of Intelligence; WRMT-R = Woodcock Reading Mastery Tests–Revised; SNAP-IV = the Swanson, Nolan, Achenbach, and Pelham–IV rating scale.

All tests were estimates of thresholds that used the same bias-free, four-interval two-alternative forced-choice (4I2AFC) adaptive procedure or "staircase" (Trahiotis, Bernstein, Buell, & Spektor, 1990). Multiple-interval forced-choice requires only that the participant identify the odd (different) interval, reducing and equating tasks for cognitive load. As each of four stimuli was played, the numbers 1, 2, 3, and 4 were displayed consecutively from top to bottom on a computer screen. There were 17 ms of silence between intervals. Participants were instructed that only one of these intervals, either number 2 or 3, would be different from the other three. That is, the first and fourth intervals were a standard and never contained the target. The participant pressed a brightly labeled button on a computer keyboard to indicate which interval was different from the others and received immediate feedback ("yes" or "no" on the computer screen).

Three automated practice opportunities assured that participants learned and understood each task. For the first practice opportunity the stimulus repeated with an easily detected difference that was always in the same interval. Participants were able to listen repeatedly before they indicated which interval contained the target. Immediate feedback was given. The same stimulus continued after incorrect responses, so participants could listen knowing which interval contained the stimulus. This initial practice was repeated until the participant understood the task and had made two correct responses in a row. In the second practice opportunity, the stimulus repeated as before, but only until a response was made. Feedback was given, but the target interval was randomized after each response. Five correct responses in a row were required to move on ($p < .05$). The third practice was an abbreviated adaptive procedure for only 20 trials or five changes of direction.

In the third and final practice opportunity, and in the estimate of threshold that followed, the four intervals were presented only once before the participant decided which one was different. The amount of difference in the target interval was determined by the two-down, one-up staircase procedure (Levitt, 1971). The task is made more difficult after each two sequential correct responses and made easier after each incorrect response. This algorithm converges, after several changes of direction, on a level that elicits 71% correct responses, which is used as the estimated threshold. Staircases were started with clearly detectable targets, and became more difficult as the participant responded correctly. Step sizes, or how much the task is made easier or harder, were decreased after each change of direction in the adaptive procedure. Participants were told that the computer would try to make them get half the items wrong and were asked to listen carefully, but not to be discouraged if they were guessing about the interval that contains the target. In all cases, eight changes of direction were obtained and the average of the peak of the last six changes was used to estimate threshold.

Psychoacoustic Tests

Binaural Temporal Cues

Binaural masking level differences (BMLD): Children were required to detect a 200-ms 500-Hz tone in a 70 dB (SPL) octave-band masker (354–708 Hz at 45 dB spectrum level). In the homophasic condition the tone and noise were presented identically to both ears. In the antiphasic condition the tone was reversed in phase at the two ears ($180^\circ = \pi$ radians), although the masker remained the same. Initial signal intensity was 80 dB. Stepsize was 4 dB for the first two reversals and 2 dB thereafter. The normal auditory system is able to take advantage of the antiphasic tone to better hear the signal in noise.

Monaural Temporal Cues

1. Gap detection threshold: Each interval contained three 80-ms bursts of white noise presented diotically at 80 dB (A) with 300 ms between bursts. In the target interval, an instantaneous gap was introduced in the middle of the noise bursts. The staircase began with a 10-ms gap. The initial step size was 2 ms and step sizes decreased by half after every other change of direction.

2. Tone onset time asynchrony detection threshold (TOT): Stimuli were diotically presented complex tones produced by the addition of 500 Hz and 1500 Hz pure tones (Pisoni, 1977). The 500-Hz tone was always 12 dB louder. The 1500-Hz tone was always on for 230 ms, and the tones went off simultaneously. In the target interval, the 500 Hz tone always lagged, and participants were asked to identify the interval where the "different" (stimulus with a lag) sound occurred. For the test, the staircase began at a 40 ms lag, with an initial stepsize of 8 ms with a change of 2 ms for every change of direction afterwards.

Frequency Resolution. The homophasic condition of the BMLD, or the ability to detect a diotically presented tone in noise with no interaural phase reversal for the tone, is also a simple measure of the width of the auditory filter or frequency resolution (Moore, 1995).

Absolute Threshold. Threshold for detection of both short (32 ms) and long (512 ms) tones in quiet was determined because stimuli for the temporal tasks spanned a wide range of duration.

Results

Raw Data

Mean performance on each of the psychoacoustic tasks for each group is presented in Table 3. For comparison purposes, performance by normal adults for the same tasks using similar parameters has been added to the table. Data for NI children were generally within the adult range.

The Effects of Group Membership on Profile of Performance on Psychoacoustic Tasks

The effects of group membership on performance on psychoacoustic tasks were examined using a multivariate approach to a Statistical Profile Analysis (Bernstein, Garbin, & Teng, 1988; Fletcher et al., 1994; Harris, 1975). Profile analysis examines three hypotheses: (a) flatness, or whether performance, collapsed across between-subjects groupings, differs across measures; (b) shape, or the effect of group membership on the pattern of performance among within-subjects measures; and (c) elevation, or the effect of between-group membership on an average, or composite, of the within-subjects variables. These effects are independent of the ordering of within-subjects measures.

Within-subjects variables were performance on the six psychoacoustic tests (gap detection threshold, threshold for detection of a 32 ms tone in quiet, threshold for detection of a 512 ms tone in quiet, TOT thresholds, homophasic and antiphasic conditions of the BMLD). Between-subjects variables were RD group membership (RD, no-RD) and ADHD group membership (ADHD, no-ADHD). Age was used as a covariate in all analyses. The auditory temporal deficit hypothesis predicts an effect of shape or, in terms of multivariate analysis, an RD group by psychoacoustic task interaction, with a deficit for only those tasks assessing temporal function. An RD group by ADHD group interaction might suggest a synergistic interaction of the two disorders.

As profile analysis requires comparability of scaling for dependent variables, performance on each of the six psychoacoustic tasks was standardized within the study sample. Group means are plotted as a function of

Table 3. Mean performance on each of the psychoacoustic tests for each of the child groups and typical adults.

	NI	ADHD/ no-RD	RD/ no-ADHD	RD/ ADHD	Adults
Threshold for detection of a 32-ms tone in silence					
dB	20.9	23.8	18.6	27.6	17.6
SD	7.9	10.5	11.9	17.1	(Watson & Gengel, 1969)
Threshold for detection of a 512-ms tone in silence					
dB	8.1	10.6	10.5	16.1	11.5
SD	7.0	13.0	11.8	19.6	(ANSI, 1969)
Homophasic condition of BMLD					
dB	63.1	63.6	63.8	65.4	62.0
SD	3.8	6.9	4.3	5.3	(van de Par & Kohlrausch, 1999)
Antiphasic condition of BMLD					
dB	53.3	55.4	53.5	54.5	52.0
SD	8.0	10.2	7.4	9.2	(Grantham, 1995)
Gap detection threshold					
ms	2.7	2.5	2.5	3.1	2–3
SD	1.6	1.3	1.9	2.2	(Fitzgibbons & Wightman, 1982)
Threshold for detection of a tone onset time asynchrony					
ms	15.4	21.0	25.9	27.7	15–20
SD	10.8	16.7	17.5	19.6	(Summerfield, 1982)

Note. NI = no impairment; ADHD = attention deficit/hyperactivity disorder; RD = reading disability; BMLD = binaural masking level differences.

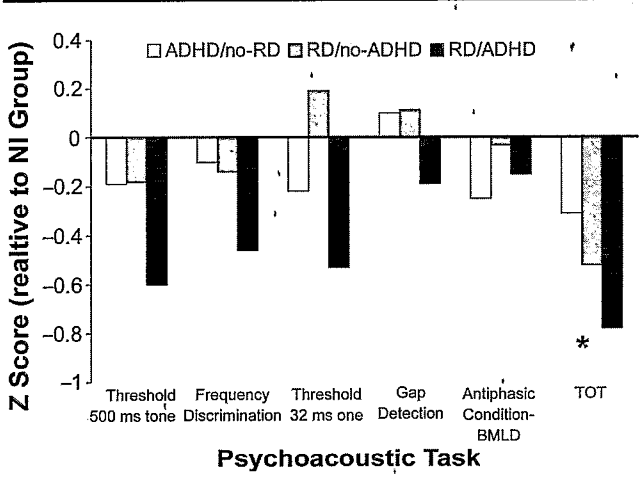
task in Figure 1. For purposes of comparison, performance by the NI group has been subtracted from each of the other groups so that each data point represents performance for that group relative to the NI group for that task.

Omnibus analyses indicated a significant RD group by psychoacoustic task interaction, $F(5, 141) = 2.49, p < .033, \eta^2 = .08$, indicating a difference in the effects of RD group membership for different psychoacoustic tasks. Omnibus analyses also indicated a significant overall effect of ADHD across psychoacoustic tasks, $F(1, 145) = 5.06, p < .026, \eta^2 = .03$, indicating a general effect of the presence of ADHD across tasks independent of the presence of RD. There was also a significant overall effect of age, $F(1, 145) = 21.01, p < .0001, \eta^2 = .13$.

Follow-up univariate analyses evaluated the effect of RD group within task using a critical value of $p < .0083$ (.05/6). The only significant effect of RD group membership was for TOT threshold, $F(1, 145) = 15.39, p < .0001, \eta^2 = .10$.

These data suggest that children with RD may have difficulty detecting a tone onset time asynchrony, which is one measure of auditory temporal acuity. There were no effects of RD group membership on other tasks assessing perception of either temporal or nontemporal cues, however. In particular, gap detection thresholds, which are also a measure of auditory temporal acuity, were not significantly different between children with and without RD. Data also suggest that the presence of ADHD is associated with a general reduction in performance across tasks and groups. Although the group with comorbid RD and ADHD tended to perform below the

Figure 1. Performance on psychoacoustic tasks for the ADHD/no-RD (attention deficit hyperactivity disorder/no reading disability; open bars), RD/no-ADHD (light gray bars), and RD/ADHD (dark gray bars) groups relative to controls. There was a significant effect of shape for the RD group, with threshold for detection of a tone onset time asynchrony (TOT) being the only significant deficit (*). The presence of ADHD was associated with a significant effect of elevation, or a reduction in performance across tasks.



other groups, the RD by ADHD interaction was not significant. Repetition of analyses with the inclusion of Performance IQ as a covariate did not alter the pattern of results.

The Relationship Between Reading Disability as a Continuous Variable and Performance on Perceptual Tasks

Although the analyses presented above treat reading ability as a categorical variable, reading ability is a continuous variable that is normally distributed (Rodgers, 1983; S. E. Shaywitz et al., 1992), and cutpoints are arbitrary. Therefore, the generalizability of results across RD definitions was assessed by examining the relationship between psychoacoustic tasks and reading ability operationalized as a continuous variable using a composite reading score formed as the average of performance on the Woodcock Reading Mastery Tests–Revised (Woodcock, 1998) Basic Reading Cluster and Word Reading Efficiency tests. The relationship between the reading composite and performance on psychoacoustic tasks was analyzed using a multivariate approach to a repeated measures design similar to that described above. The psychoacoustic tasks served as the dependent variables. The reading composite and ADHD group membership (ADHD, no-ADHD) served as the independent variables, with age as a covariate. The auditory temporal deficit hypothesis predicts a significant relationship between the reading composite and dependent variables that is independent of ADHD, with significant relationships only with tasks measuring temporal function.

Omnibus analyses indicated a significant reading composite by ADHD interaction, $F(1, 145) = 9.98$, $p < .002$, $\eta^2 = .06$, suggesting that the relationships between psychoacoustic tasks and reading ability were different for groups with and without ADHD. Follow-up analyses repeated the multivariate analyses within the ADHD and no-ADHD groups using a critical value of $p < .025$ (.05/2). Within the no-ADHD group there was a significant reading composite by psychoacoustic task interaction, $F(5, 74) = 2.82$, $p < .022$, $\eta^2 = .16$, indicating a difference in the strength of relationship between different tasks and the reading composite. Follow-up univariate analyses using a critical value of $p < .004$ (.025/6) indicated a significant relationship between the reading composite and TOT threshold within only this group, $F(1, 80) = 10.16$, $p < .002$, $\eta^2 = .11$. Repetition of analyses using a more liberal value for alpha ($p < .05$) did not change results.

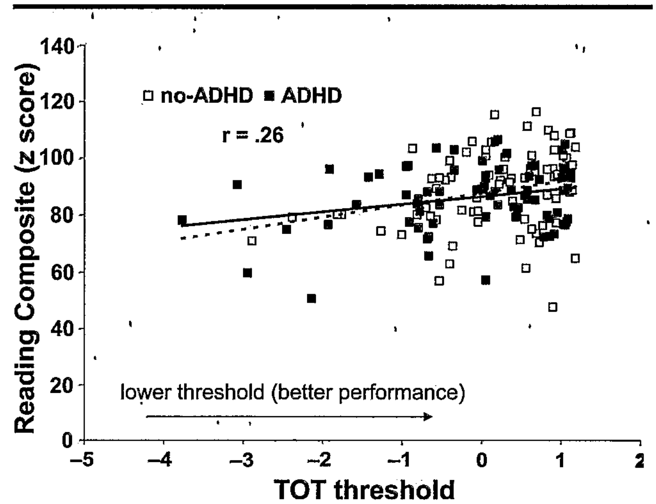
Within the ADHD group, only the overall relationship between the reading composite and performance on psychoacoustic tasks reached significance, $F(1, 66) = 15.3$, $p < .0008$, $\eta^2 = .19$.

Again, these data suggest that the presence of ADHD is a significant factor in the relationship between reading ability and performance on psychoacoustic tests. Consistent with the group analyses presented above, TOT threshold was the only task to exhibit a significant relationship to the reading composite within the no-ADHD group, although within the ADHD group there was evidence for a relationship with reading ability across psychoacoustic tasks. A plot of the reading composite as a function of TOT threshold for children without ADHD (open squares) and with ADHD (closed squares) is presented in Figure 2. There is a significant relationship between reading ability and TOT thresholds for both groups ($r = .26$), with reading ability scores improving with lower TOT thresholds (higher z scores). Again, repetition of analyses with the inclusion of Performance IQ as a covariate did not alter the pattern of results.

Discussion

Using a range of psychoacoustic tasks assessing various aspects of auditory function, we found that the presence of RD was associated with a specific deficit in the detection of a tone onset time asynchrony. There were no effects of RD for the other tasks, regardless of whether cues were temporal or nontemporal in nature. In contrast, the presence of ADHD was associated with a general reduction of performance across psychoacoustic tasks, with no significant differences in the degree

Figure 2. Plot of the reading composite (see text), a measure of reading ability, as a function of threshold for detection of a tone onset time asynchrony (TOT). A higher number in both cases indicates better performance. Note that the relationship was significant within both the ADHD (black squares, dotted line; $r = .26$, $p < .028$) and no-ADHD (white squares, solid line; $r = .26$, $p < .018$) groups.



of deficit between tasks assessing auditory temporal and nontemporal function. Results were essentially identical when analyses were repeated with reading ability treated as a continuous variable.

The auditory temporal deficit hypothesis predicts that children with RD will exhibit deficits in performance when perception of the temporal properties of a stimulus is required. Although there was no evidence for a pervasive auditory temporal processing deficit, children with RD did exhibit difficulty in detection of a tone onset time asynchrony, a measure of auditory temporal acuity. Similar to previous studies (Helzer et al., 1996; Schulte-Korne et al., 1998), a deficit for a second measure of temporal acuity, gap detection, was not evident. One explanation for these results would be a relative sensitivity to backward masking, which has been previously reported in children with SLI (Wright et al., 1997). As detection of a tone onset asynchrony is dependent on detection of the presence of two successive signals, excessive backward masking of the first tone by the second would result in higher thresholds. In contrast, gap detection is dependent on detection of a silent gap between two signals, and would not be affected by backward masking.

Previous studies examining perception of nonspeech stimuli in children with ADHD generally have reported intact functioning, including normal simple detection thresholds, binaural masking level differences (Pillsbury, Grose, Coleman, Conners, & Hall, 1995), and gap detection thresholds (Ludlow, Culdahy, Bassich, & Brown, 1983). In the current study the presence of ADHD was associated with a decrement in performance across tasks regardless of the presence of RD. Although it is possible that the relative reduction in performance in children with ADHD represents an auditory processing disorder, all children in this study had auditory hearing sensitivities of 20 dB or better by audiometric screening. One of the core deficits in children with ADHD/combined type is an inability to inhibit maladaptive responses, which manifests itself as impulsive behavior (Barkley, 1997a, 1997b). Such behavior might result in increased variability in performance and a greater number of trials to complete accurate (asymptotic) threshold estimation. We used a single adaptive run to estimate psychophysical thresholds in order to allow, without fatigue, the evaluation of performance on a wide variety of psychophysical tasks in relatively large numbers of young children who had received adequate training on each task. Performance by the NI group was at adult levels, suggesting that the methodology was successful in estimating thresholds in the nonclinical population of children. Helzer et al. (1996) found, however, that children with SLI required a greater number of trials to reach the same thresholds as age-matched controls, which they interpreted as being related to attentional factors. It is possible, therefore, that children with ADHD would have improved to normal levels given a greater number of trials. In any case, the nature and source of deficits in performance on psychoacoustic tasks by children with ADHD remains a matter for further research.

As reviewed above, findings regarding the performance of children with RD on psychoacoustic tests in previous studies are mixed. It is, however, difficult to compare and contrast findings across studies in order to determine the source of discrepancies for a number of reasons. Criteria for group membership vary widely across studies, important variables such as socioeconomic status and ethnicity are not always reported, the presence of children with SLI is not always controlled for, most studies do not consider treating reading ability as a continuous variable allowing comparisons across RD definitions, and many studies do not control for the potential comorbidity of RD and ADHD. The current study was designed to address these issues and provide an opportunity to compare performance on a wide variety of psychoacoustic tests within the same participants in relatively large groups of children with RD and ADHD that had been defined using criteria validated in previous studies. Although results did not indicate a pervasive deficit in auditory temporal function, they did suggest the possibility of a specific sensitivity to backward masking. Results also suggested that ADHD is potentially a significant factor in performance on psychoacoustic tasks by children with RD.

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