

Perception of Voice and Tone Onset Time Continua in Children with Dyslexia with and without Attention Deficit/Hyperactivity Disorder

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Tasks assessing perception of a phonemic contrast based on voice onset time (VOT) and a nonspeech analog of a VOT contrast using tone onset time (TOT) were administered to children (ages 7.5 to 15.9 years) identified as having reading disability (RD; $n = 21$), attention deficit/hyperactivity disorder (ADHD; $n = 22$), comorbid RD and ADHD ($n = 26$), or no impairment (NI; $n = 26$). Children with RD, whether they had been identified

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as having ADHD or not, exhibited reduced perceptual skills on both tasks as indicated by shallower slopes on category labeling functions and reduced accuracy even at the end-points of the series where cues are most salient. Correlations between performance on the VOT task and measures of single word decoding and phonemic awareness were significant only in the groups without ADHD. These findings suggest that (a) children with RD have difficulty in processing speech and nonspeech stimuli containing similar auditory temporal cues, (b) phoneme perception is related to phonemic awareness and decoding skills, and (c) the potential presence of ADHD needs to be taken into account in studies of perception in children with RD. © 2001 Academic Press

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Dyslexia, or specific reading disability (RD), is a developmental disorder that is characterized by difficulties in single word decoding that are unexpected in relation to chronological age and other academic abilities and are not the result of general developmental disability or sensory impairment (Shaywitz, Fletcher, & Shaywitz, 1995). While it is well established that phonemic awareness, as measured by the ability to segment and blend the basic phonological elements of spoken language, is a salient deficit in RD (Blachman, 2000; Fletcher et al., 1994; Shankweiler & Crain, 1986; Stanovich, 1988), the etiology of this deficit and its relationship to other linguistic and perceptual skills remain a matter for continued study. One hypothesis, the auditory temporal deficit hypothesis, suggests that at least a subgroup of children with RD have a deficit in low level auditory temporal processing that affects the perception of short transitional acoustic elements that provide important acoustic cues for phonemic contrasts (Tallal, Miller, & Fitch, 1993). Deficits in phoneme perception, in turn, may account for poor development of phonological processing skills, including phonemic awareness, phonological memory, rapid naming, phonological decoding, and spelling, which are generally found to be deficient in children with RD (Manis et al., 1997; McBride-Chang, 1995, 1996; Reed, 1989; Tallal et al., 1993).

Initial studies regarding the relationship of auditory temporal processing, phoneme perception, and reading disability involved children with specific language impairment (SLI) who have more general receptive and expressive language deficits than children with RD, but otherwise are not mentally deficient. Children with SLI have difficulty on tasks that require identification and/or discrimination of stop consonants in the context of phonemic contrasts such as place (e.g., /ba/ and /da/) (Sussman, 1993; Tallal & Piercy, 1974) or voice onset time (VOT; e.g., /ga/ and /ka/) (Elliott, Hammer, & Scholl, 1989) as well as confusable vowels (Post, Swank, Hiscock, & Fowler, 1999; Stark & Heinz, 1996). They also have difficulty in temporal order judgment of complex nonspeech tones when brief interstimulus intervals are involved (Tallal & Piercy, 1973), exhibit reduced ability to localize dynamic binaural stimuli (Visto, Cranford, & Scudder, 1996), and are more sensitive to auditory backward masking (Wright et al., 1997), suggesting the possibility of an auditory temporal processing deficit. Children (Adlard & Hazan, 1998; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Manis et al., 1997; Post et al., 1999; Reed, 1989) and adults (Cornelissen, Hansen, Bradley,

& Stein, 1996; Steffens, Eilers, Gross-Glenn, & Jallad, 1992; Watson & Miller, 1993) with RD also exhibit deficits in tasks that require identification and/or discrimination of stop consonants (Manis et al., 1997; McBride-Chang, 1995), as well as reduced sensitivity on tasks assessing auditory temporal acuity such as sensitivity to amplitude (Menell, McAnally, & Stein, 1999) and frequency (Witton et al., 1998) modulation, binaural fusion (Hari & Kiesila, 1996), and auditory stream segregation (Helenius, Uutela, & Hari, 1999). In addition, phoneme perception correlates with measures of reading skill (Post et al., 1999) and phonemic awareness (Manis et al., 1997; Watson & Miller, 1993) as well as phonological memory (Elliott et al., 1989) and rapid automated naming (McBride-Chang, 1996), all of which are deficient in children with RD.

Given the possibility that deficits in low level acoustic processing may act through a negative impact on speech perception to produce poor phonological processing skills, determining the level and nature of an auditory processing deficit in children with RD is potentially important to the search for an etiology and effective intervention. However, there continues to be controversy regarding whether deficits in perception in children with RD are specific to speech stimuli or extend to nonspeech stimuli as well and whether they are limited to auditory temporal cues. The speech specific hypothesis, an alternative to the auditory temporal deficit hypothesis, suggests that phonological processing deficits are due to an impairment in the representation of phonological information at higher levels in the neuraxis specialized for the processing of linguistic stimuli (Brady, Shankweiler, & Mann, 1983; Liberman & Mattingly, 1989; Liberman, Meskill, Chatillon, & Schupack, 1985; Mody, Studdert-Kennedy, & Brady, 1997). According to this view, low level deficits in auditory temporal processing are not necessary to explain impairment in phoneme perception or phonological processing (Bishop, Carlyon, Deeks, & Bishop, 1999; Mody et al., 1997). Rather, deficits in phoneme perception in children with RD may be due to a failure to distinguish between phonologically contrastive, but phonetically similar, speech sounds (Mody et al., 1997) and are therefore limited to linguistic stimuli and consistent with the speech specific hypothesis. This view is supported by some studies that fail to find evidence for a general auditory temporal processing deficit in children with RD (Bishop et al., 1999; Helzer, Champlin, & Gillam, 1996; Mody et al., 1997; Schulte-Korne, Deimel, Bartling, & Remschmidt, 1998), as well as those that find a deficit specific to speech, but not nonspeech sounds (Adlard & Hazan, 1998; Brady et al., 1983; Mody et al., 1997).

In order to compare these two competing hypotheses, it is not enough to demonstrate deficits in low level auditory processing and speech perception in the same participants. It is important that salient cues in nonspeech stimuli are clearly analogous to those used for discrimination of speech stimuli during a specific experiment (Nittrouer, 1996). In the current study we evaluate perception of both speech and nonspeech stimuli in children with RD when performance in each case depends on detecting delays (over a 0 to 60-ms range) in the onset of lower frequency energy relative to the onset of higher frequency energy within the same

stimulus. While a number of studies find evidence for a deficit in phoneme perception (Brady et al., 1983; Godfrey et al., 1981; Lieberman et al., 1985; Manis et al., 1997; Mody et al., 1997; Reed, 1989; Tallal, Stark, Kallman, & Mellits, 1980) and others find deficits in perception of temporal cues in nonspeech stimuli (Farmer & Klein, 1995; McAnally & Stein, 1996; Menell et al., 1999; Wright et al., 1997) in children with RD, few have evaluated perception of both speech and nonspeech stimuli in matching experimental paradigms where performance is dependent on perception of analogous acoustic cues. If children with RD have reduced sensitivity to phonemic stimuli due to a general reduction in auditory temporal processing, a deficit should be apparent in their perception of nonspeech analogs where sensitivity to similar temporal information is tested without a linguistic referent. Conversely, if deficits in phoneme perception are specific to impaired linguistic processing, a dissociation in performance with speech and nonspeech stimuli might be expected.

For the current study we chose a category labeling paradigm for a VOT contrast (/ga/-/ka/) to characterize phoneme perception. Category labeling places relatively modest demands on short-term memory (Manis et al., 1997; McBride-Chang, 1996) and none on speech output mechanisms. A series of stimuli are said to be perceived categorically when: (a) phoneme labeling performance yields relatively sharp category boundaries along the dimension of stimulus variation, and (b) the ability to discriminate between adjacent stimuli along the dimension of variation is at or near chance within a phoneme category and at or near 100% accuracy when a stimulus pair straddles the boundary between two phoneme categories. Normal listeners exhibit a strong tendency toward *categorical perception* of speech stimuli varying along certain phonetic dimensions, such as place of articulation (e.g., /ba/ vs. /da/ or /da/ vs. /ga/) or voicing status (e.g., /ba/ vs. /pa/ or /ga/ vs. /ka/) (Harnad, 1987). Identification of utterance-initial stop consonants as voiced or voiceless is largely dependent on VOT, acoustically defined as the interval between the release burst and the onset of waveform periodicity associated with vocal-fold vibration, or voicing. In American English, consonant-vowel syllables with VOT values of less than 20 or 25-ms tend to be identified as voiced, whereas syllables with VOT values of greater than 35 or 40-ms tend to be perceived as voiceless. Identification and discrimination of syllables varying in VOT have been shown to be categorical for normal listeners (Abramson & Lisker, 1970; Lisker & Abramson, 1970). Children as well as adults with RD exhibit deficits in category labeling tasks involving contrasts based on VOT (Godfrey et al., 1981; Manis et al., 1997) as well as place of articulation (Brandt & Rosen, 1980; de Gelder & Vroomen, 1998; Reed, 1989).

One method of studying, in isolation, an acoustic cue that may signal a phonemic contrast is to create a nonspeech contrast where discrimination is dependent only on that cue (Parker, 1988; Pisoni, 1977; Pisoni & Lazarus, 1974). For the present study we use a tone onset time (TOT) series, a well-established nonspeech analog of a VOT series (Pisoni, 1977). TOT stimuli consist of two tones that are either presented simultaneously or apart at various onset asynchronies

that mimic the VOT onset times. Participants are asked to place the stimuli into one of two categories, either "together" or "apart." Studies in adults without RD using similar stimuli have shown evidence for a category boundary (Pisoni, 1977), although this boundary is not always as sharp as in VOT labeling experiments (Parker, 1988). Use of the TOT series allowed us to compare performance on speech and nonspeech stimuli when similar cues are used in both tasks, in the same participants, using the same experimental paradigm.

As part of our experimental design we included children with and without attention deficit/hyperactivity disorder (ADHD) as well as RD. ADHD is a common behavioral disorder that exhibits substantial comorbidity with RD, affecting 30–70% of the RD population depending on the sample and how the disorder is defined (Shaywitz & Shaywitz, 1994); however, most studies of perception in children with RD 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 a variety of tasks, including those involving phoneme perception. Norrelgen, Lacerda, and Forssberg (1999) found deficits in children with comorbid motor deficiencies and ADHD on tasks involving immediate memory for strings of phonemes of increasing length, but no deficit in discriminating between pairs of phonemes. However, the Norrelgen et al. (1999) study did not include children with RD and comorbid RD and ADHD, therefore not allowing for analysis of possible additive or synergistic effects of the two disorders. We therefore addressed the issue of the possible effects of comorbidity of RD and ADHD through the use of a 2 (RD, no-RD) by 2 (ADHD, no-ADHD) design. Green's (1995) model of the effects of attention on psychoacoustic tasks predicts shallower psychometric functions for inattentive observers. Therefore, we expected that the presence of ADHD would affect both children with and children without RD, reducing between-group differences, and hypothesized that controlling for ADHD in examining the effects of RD on category labeling would enhance the differences between RD and no-RD groups. We also examined the effect of ADHD on the relationship between phoneme perception and measures of reading, spelling, and phonological processing, including phonemic awareness, single word and pseudoword decoding, rapid automated naming, spelling, reading fluency, and phonological memory. RD is usually associated with deficits in all of these abilities (McBride-Chang, 1996; Watson & Miller, 1993); however, the effect of the presence of ADHD on the relationship between phoneme perception and these linguistic skills has never been characterized.

METHODS

Participants

Ninety-five children served as participants in the VOT study. A subset of 74 subjects participated in the TOT study, which was initiated after the VOT study

was already in progress. Children ranged in age from 7.5 to 15.9 years. 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 good temporal stability (Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). The Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999) was administered to estimate Full Scale IQ. In order to eliminate children with below average intelligence, a standard score above 80 was required for participation in the study. In addition, as IQ scores of children with RD tend to be somewhat lower than those obtained by children without RD, children with IQ scores above 129 were excluded from the study to avoid creating groups with large IQ discrepancies. The Hollingshead two-factor index of social position (Hollingshead, 1957) was used to assess socioeconomic status (SES). All children had normal hearing by bilateral, pure-tone threshold audiometric screening at 250, 500, 1000, 2000, 5000, and 8000 Hz at 25 dB HL (Institute, 1969), normal middle ear function by tympanogram, English as the primary language, and no history of neurological disorder. The protocol used in this study received full approval from the Institutional Review Board of the University of Texas Medical School at Houston. Parents who might be interested in having their children participate in the study were identified through contacts maintained by the authors with parents and professionals who work with the local school districts. 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 specific RD based on several achievement measures, including: (1) 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; (2) the Spelling subtest of the Wechsler Individual Achievement Test (Wechsler, 1992); and, (3) 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 2 of the 3 tests being at or below this cutoff. We used this approach 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 et al., 1999).

Children were also identified as specifically language impaired (SLI) 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 of 7 or below on all three tests were identified as SLI (Joanisse, Manis, Keating, & Seidenberg, 2000). Only one child, from the ADHD/RD group, met these criteria. Removing this child's results from the data set had no effect on the results, so the child was retained in the study.

In addition to the above tests, all children were administered subtests from the Comprehensive Test of Phonological Processing (CTOPP) (Wagner, Torgesen, & Rashott, 1999) to assess phonemic awareness and rapid naming as follows:

(1) *Phoneme elision*. Children are asked to say a word presented by the examiner, and then say what the word would be if a specified speech sound in the word were omitted. The omitted speech sound is either a word (e.g., say the word "cowboy"—now say it without the "boy") or phoneme (e.g., say the word "smack"—now say it without the sound "/m/"). The task moves from deletion of words or phonemes from a whole word to form another whole word. Three practice items are followed by up to 25 test items consisting of three- to five-phoneme, one- and two-syllable words.

(2) *Segmenting words into phonemes*. Children listen to words presented by the examiner and are first asked to repeat the entire word. They are then asked to say the word one sound at a time, in the order that they hear the sounds in the word. Two practice items are followed by up to 26 test items consisting of two- to five-phoneme, one-, two-, or three-syllable words

(3) *Segmenting nonwords into phonemes*. Identical to (1) except stimuli are nonwords.

(4) *Rapid letter naming*. Four rows of nine single letters per row are arrayed on a card and children are instructed to name the letters as fast as they can from left to right beginning at the top. There are two trials using two cards with different arrangements of letters.

The diagnosis of ADHD was made by licensed clinical neuropsychologists (authors JIB and JMF) through: (a) semistructured clinical interview of the caretaker during the evaluation, (b) caretaker and teacher responses on the SNAP-IV (Swanson, 1992); and (c) clinical observation. Twenty-six children who had been previously diagnosed with ADHD had this diagnosis confirmed, 23 were newly diagnosed. All inclusion and exclusion criteria specified by DSM-IV (American Psychological Association, 1994) were followed, and children with ADHD were placed into ADHD/predominantly inattentive and ADHD/combined groups based on these criteria. In particular, children were required to show impairment in more than one setting with age of onset before 7 years. Children who exhibited evidence of psychiatric disorders, other than oppositional defiant and adjustment disorder, such as anxiety disorders, conduct disorder, obsessive-compulsive disorder, depression, and Tourette's syndrome, were excluded from the study. Children with both ADHD/predominantly inattentive and ADHD/combined type were included in the study as both potentially affect behavioral tests (Barkley, 1997b). In order to assess the effects of ADHD on phoneme perception independent of the effects of medication on performance, children with ADHD who were medicated with stimulants ($n = 20$) discontinued their medication 24 h prior to testing (Purvis & Tannock, 2000). These procedures resulted in the formation of 4 groups: (1) specific reading disability without ADHD (RD; $n = 21$); (2) ADHD without RD (ADHD; $n = 23$); (3) RD with ADHD (RD/ADHD; $n = 26$); and, (4) not impaired (NI; $n = 26$).

Demographic and diagnostic test data for each group are presented in Table 1. Group differences for continuous variables were analyzed using a general linear model approach to analysis of variance with group (NI, RD, ADHD, RD/ADHD) as the between subjects variable. Fisher's exact test was used for categorical variables. Follow-up analyses to examine significant group effects used a Bonferroni correction to analyze pairwise comparisons. Scores that are significantly different are marked with different numbers of asterisks (*) in Table 1. As expected, there were significant differences between RD and no-RD groups on Full Scale IQ, Verbal IQ, and the reading composite test scores. However, there were no significant group differences on Performance IQ score or age. The percentage of males was significantly higher in the RD as compared to the no-RD groups (Fisher's exact test, $p > .006$), while the proportion of children with the predominantly

TABLE 1
Demographic and Diagnostic Test Data

Measure	Ni (<i>n</i> = 26)	ADHD (<i>n</i> = 22)	RD (<i>n</i> = 21)	ADHD/RD (<i>n</i> = 26)
WASI Full Scale IQ (Standard Score)				
Mean	112.4	106.1	99.7*	101.5*
SD	9.9	11.3	11.7	11.9
WASI Verbal IQ (Standard Score)				
Mean	112.5	109.5	98.5*	102.2*
SD	10.5	12.2	7.5	12.2
WASI Performance IQ (Standard Score)				
Mean	109.8	100.6	101.0	100.7
SD	13.1	15.6	16.4	13.4
Age (Years)				
Mean	10.8	10.3	10.5	10.4
SD	1.7	2.1	1.6	1.9
Composite (Standard Score)				
Mean	102.0	96.4	77.2*	81.1*
SD	8.8	5.9	8.8	6.6
ADHD/combined type	N/A	14	N/A	17
ADHD/predominantly inattentive type	N/A	8	N/A	9
SES (Hollingshead Social Class)				
I	2	4	0	3
II	8	6	5	4
III	14	9	12	15
IV	2	3	4	4
Race				
White	21	21	21	22
Black	3	0	0	4
Hispanic	1	1	0	0
Asian	1	0	0	0
Gender				
Male	11	14	17	20
Female	15	8	4	6

inattentive as compared to combined types of ADHD within the RD and no-RD groups was not significantly different ($p > .6$). The associations between SES and RD (Fisher's exact test, $p > .4$) and ADHD (Fisher's exact test, $p > .36$) group membership were not significant, nor were the associations between ethnicity and RD (Fisher's exact test, $p > .5$) and ADHD (Fisher's exact test, $p > .9$) group membership.

Stimuli and Procedures

The VOT series consisted of seven consonant-vowel (CV) stimuli with VOT values ranging from 0 to 60 ms in 10-ms steps. These stimuli ranged perceptually from /ga/ to /ka/. Syllables were prepared using the cascade branch of the Klatt88 software synthesizer. Variation of VOT was achieved by (1) broadening the bandwidth of the first formant (F1) and thus severely attenuating its energy level relative to the higher formants and (2) exciting the second and third formants (F2 and F3) with a noise source during the period between stimulus onset and voicing source onset. This effectively delayed the onset of F1 relative to the onsets of F2 and F3 by an amount equal to the VOT interval. The fundamental frequency (F0) was constant at 120 Hz for all syllables. The nominal frequencies of F1, F2, and F3 at stimulus onset were 300, 1840, and 1960 Hz and changed linearly across a 55-ms transition period to 768, 1333, and 2522 Hz. The transitions were followed by a 200-ms steady-state segment resulting in a total stimulus length of 255-ms. In addition, the relative balance of the low-frequency energy in the voicing source was enhanced by setting the spectral tilt parameter of the Klatt synthesizer to 10 along the entire length of the syllable. The voiced portions of the stimuli were low pass filtered at 3200 Hz. Stimuli were presented binaurally at 80 dB SPL over phase-matched TDH-49 stereo headphones.

The TOT series consisted of 7 two-tone tokens created using parameters described by Pisoni (1977). The tones were 500 and 1500 Hz. The 500-Hz tone was always 12 dB louder in amplitude than the 1500-Hz tone, which mimics the amplitude relationship between the first two formants in neutral vowels. The tones were presented at an overall level of 80 dB SPL. The onset of the 500-Hz tone lagged that of the 1500 Hz tone by delays ranging from 0 to 60-ms in 10-ms steps. Both tones concluded at the same time with a total stimulus length of 255-ms. Stimuli were again presented binaurally. All stimuli were calibrated with a Bruel and Kjaer 4152 artificial ear, Bruel and Kjaer 2235 sound level meter, and Hewlett-Packard P 3561A dynamic signal analyzer.

Children were tested in a sound attenuated chamber at the Otolaryngology laboratory at the University of Texas Medical School at Houston, Texas with a single tester present. For the VOT series, children were first trained to associate the endpoints (/ga/, /ka/) with a colored key on the computer (red, green) for 12 trials. They were then introduced to the task in a practice session during which they were required to correctly identify 9 of a consecutive run of 12 randomly presented endpoint stimuli ($p < .05$). The practice session lasted for a maximum of 50 trials. All children were able to reach criteria within the required number of

trials. During experimental blocks each of the 7 stimuli were presented 12 times in random order and children were told to press the key that indicated which CV they had heard. There was no feedback during practice or experimental sessions. An identical procedure was used for the TOT series, except the endpoints (0, 60-ms) were labeled during practice as “together” or “apart” and different keys, colored blue and yellow, were used on the computer for response. In addition, during practice children were required to identify 12 of a consecutive run of 16 randomly presented endpoint stimuli to provide more practice with these unfamiliar stimuli. All children met criterion within the required number of trials before proceeding to the test. Again, during the test, 12 tokens were presented in random order and children were told to press the appropriate key to indicate which sound (together, apart) they heard. The order of presentation of VOT and TOT series was randomized across participants.

RESULTS

Group Effects on Category Labeling of VOT Stimuli

Averaged category labeling functions for the VOT series (percentage identified as /ka/ plotted as a function of VOT) are presented for each group in Fig. 1. As can be seen, individuals with RD tended to perform less consistently at either end

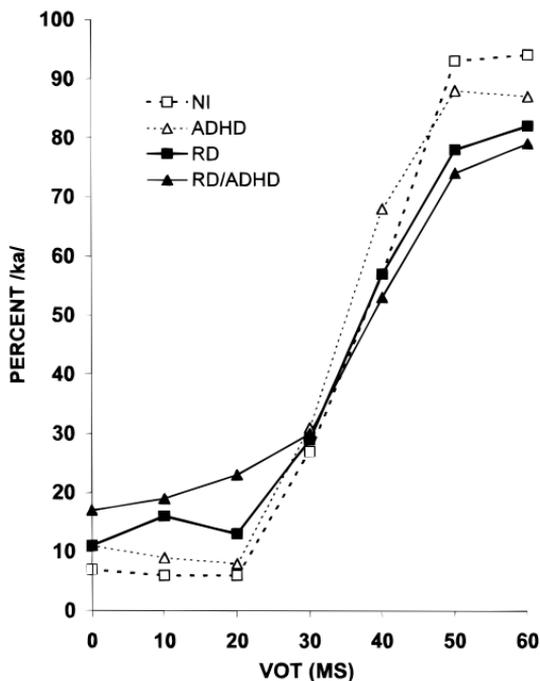


FIG. 1. Percentage stimuli identified as /ka/ plotted as a function of VOT for the NI (open squares), ADHD (open triangles), RD (filled squares), and RD/ADHD (filled triangles) groups.

of the series, with shallower slopes, regardless of the presence of ADHD. These trends were evaluated statistically by first fitting each child's data using logistic regression analysis (McBride-Chang, 1996) and extracting the slope parameter, the two intercept parameters (representing percent /ka/ at 0-ms VOT, or the consistency of detection of the voiced feature, and percent /ka/ at 60-ms VOT, or the consistency of detection of the voiceless feature, respectively), and the mean parameter or category boundary (VOT at 50% correct or the maximum confusion point) of the individual curves. The effects of group membership on the slope, intercept, and mean parameters were examined in separate analyses using a general linear model approach to analysis of variance with RD group (RD, no-RD) and ADHD group (ADHD, no-ADHD) as the between subjects variables. Age was used as a covariate.

For the slope parameter the main effect of RD group was significant, $F(1, 90) = 13.93, p < .0003$. Neither the main effect of ADHD group, $F(1, 90) = 2.42, p > .12$, nor the RD group by ADHD group interaction, $F(1, 90) = .58, p > .44$, was significant. For the 0-ms intercept parameter the main effect of RD group was significant, $F(1, 90) = 10.82, p < .001$. Neither the main effect of ADHD, $F(1, 90) = 2.43, p > .12$, nor the RD group by ADHD group interaction, $F(1, 90) = .49, p > .48$, was significant. For the 60-ms intercept parameter the main effect of RD group was significant, $F(1, 90) = 15.78, p < .0001$. Neither the main effect of ADHD group, $F(1, 90) = 1.41, p > .24$, nor the RD group by ADHD group interaction, $F(1, 90) = .83, p > .37$, was significant. For the mean parameter none of the effects, including RD group, $F(1, 90) = 3.48, p < .065$, ADHD group, $F(1, 90) = 1.67, p > .19$, and the RD group by ADHD group interaction, $F(1, 90) = 1.42, p > .23$, were significant. Results of all analyses remained unchanged when Performance IQ was used as a covariate.

These results indicate that the category boundary between the /ga/ and /ka/ percepts is less sharp, or well defined, for children with RD and that performance is less consistent for this group at both extremes of the category series where stimuli are most salient. However, the location of the boundary is essentially the same for RD and no-RD groups. Group means for the parameters of the category labeling functions estimated using logistic regression are presented in Fig. 2, including: (a) the slope, (b) the boundary, (c) the 0-ms intercept where a smaller number (fewer stimuli identified as /ka/) indicates more accurate performance, and (d) the 60-ms intercept where a larger number (more stimuli identified as /ka/) indicates more accurate performance. Children with RD exhibited shallower labeling functions and less accurate performance at the VOT extremes as compared to children without RD, regardless of the presence of ADHD.

As both the ADHD/combined and ADHD/predominantly inattentive types were included in the ADHD group, the above analyses were repeated with the ADHD factor broken down into three levels (no-ADHD, ADHD/combined type, ADHD/predominantly inattentive type). The results were essentially the same as reported above. Means for RD groups with and without both types of ADHD are presented in Fig. 3. While there is an indication that children with the ADHD/combined type per-

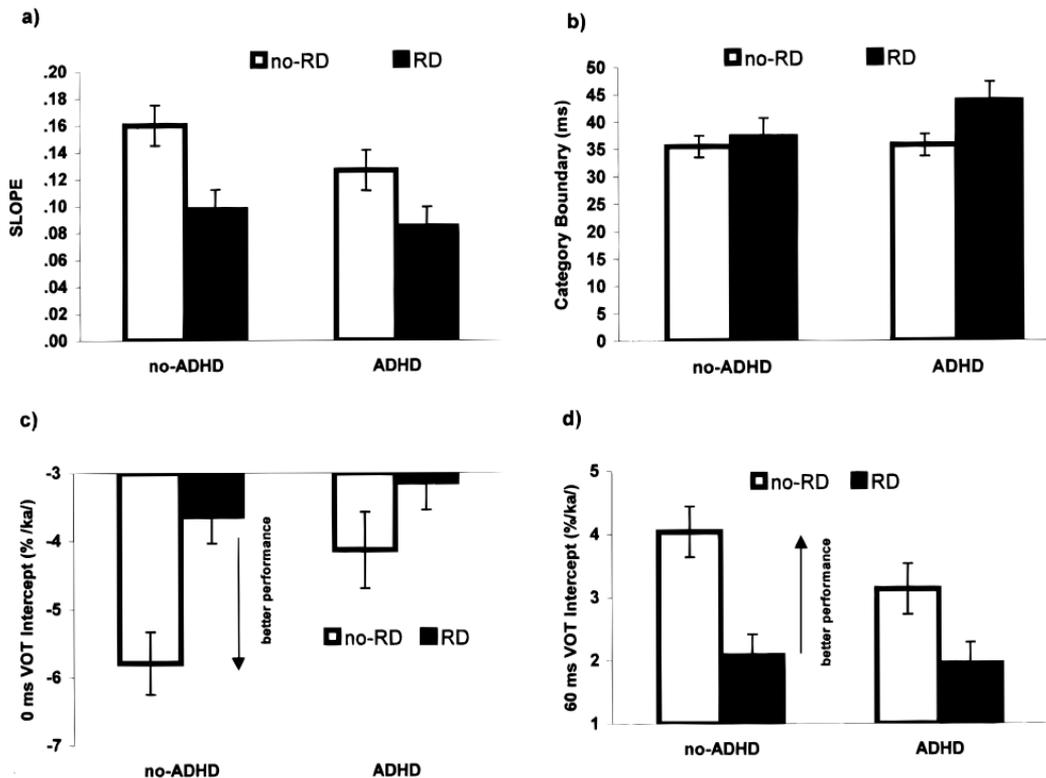


FIG. 2. Group means for parameters of the VOT category labeling functions estimated using logistic regression, including: (a) slope, (b) boundary, (c) 0-ms intercept—where a smaller number indicates greater consistency in labeling, and (d) 60-ms intercept—where a larger number indicates greater consistency in labeling. Note that children with RD have shallower slopes and that their 0 and 60-ms VOT intercepts suggest less consistent labeling regardless of the presence of ADHD. Error bars represent standard error of the mean.

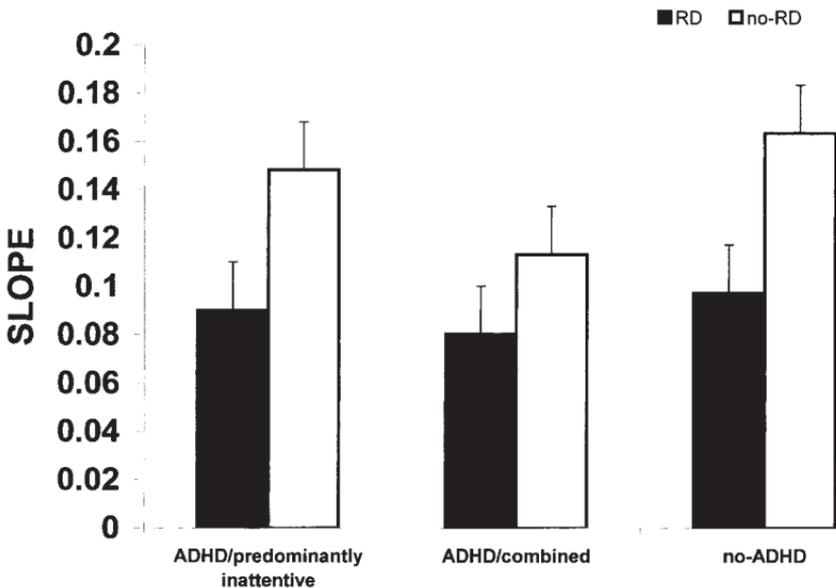


FIG. 3. Group means for slope of VOT category labeling functions for the three different ADHD groups (predominantly inattentive, combined, no-ADHD). Note that the presence of RD is associated with a reduction in performance regardless of the ADHD subgroup. Error bars represent standard error of the mean.

form somewhat below the other groups, the presence of RD reduces the slope of the VOT labeling function regardless of the ADHD group involved.

Group Effects on Category Labeling of TOT Stimuli

The TOT study was initiated after the VOT study was already in progress. For this reason a subset of 74 children participated in the TOT study: NI ($n = 17$), RD ($n = 17$); ADHD ($n = 20$), RD/ADHD ($n = 20$). There were no substantive differences in demographic variables between participants in the VOT and TOT studies. Averaged category labeling functions for the TOT series (percentage identified as “apart” plotted as a function of TOT) for the four groups are presented in Fig. 4. As in the VOT experiment, TOT labeling functions for children with RD had shallower slopes than functions for those without RD. As the TOT functions were clearly not ogival in shape, we used a multivariate approach to a within subjects design with performance at each TOT asynchrony (0, 10, 20, 30, 40, 50, 60-ms) as the within subjects variable and ADHD group (no-ADHD, ADHD) and RD group (RD, no-RD) as between subjects variables. Age was a covariate. There was a significant asynchrony by RD group interaction, $F(6, 64) = 3.33, p < .006$, indicating a different profile of performance across the seven tokens for the different RD groups. Neither the asynchrony by ADHD, $F(6, 64) = .59, p > .7$, nor the asynchrony by RD by ADHD interaction, $F(6, 64) = .48, p > .8$, terms were significant. A polynomial transformation, used to evaluate the source of between group

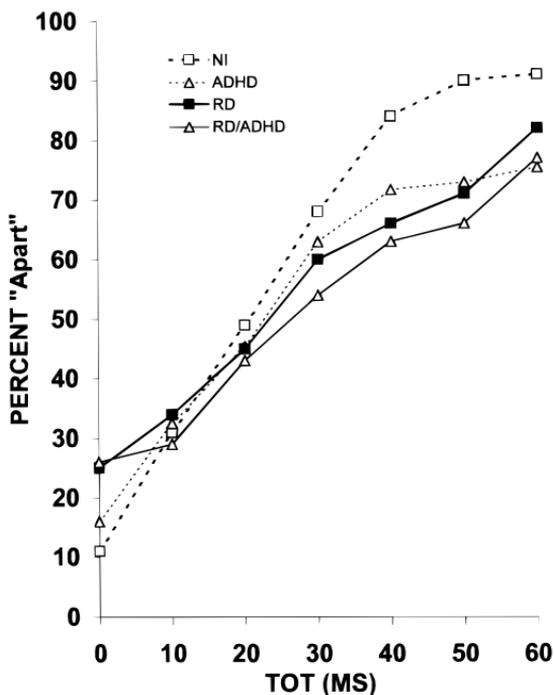


FIG. 4. Average percent identified as “apart” plotted as a function of TOT for the NI (open squares), ADHD (open triangles), RD (filled squares), and RD/ADHD (filled triangles) groups.

differences, indicated significant linear, $F(1, 69) = 5.73, p < .02$, and quadratic, $F(1, 69) = 9.69, p < .003$, effects for RD. There were no significant effects of ADHD or ADHD interaction terms for any of these analyses.

Each child’s data were fitted with a 2nd degree polynomial and the coefficients of the linear and quadratic trends, as well as the two intercepts (representing percentage “apart” at 0-ms TOT and percentage “apart” at 60-ms TOT, respectively), were extracted. As indicated above, the effect of RD group was significant for both the linear and the quadratic trends. Separate analyses using a general linear model approach to analysis of variance with RD group and ADHD group as between subjects variables and age as a covariate indicated a significant effect of RD group for the 0-ms intercept, $F(1, 69) = 6.48, p < .01$, but not for the 60-ms TOT intercept, $F(1, 69) = 1.63, p > .20$. There was, however, a significant effect of ADHD group for the 60-ms intercept, $F(1, 69) = 5.05, p < .02$. Group means for the parameters of the TOT labeling functions estimated using linear regression are presented in Fig. 5, including: (a) the coefficient of the linear trend (where a larger number indicates a steeper slope, or better performance), (b) the coefficient of the quadratic trend (where a more negative number indicates a sharper change at the boundary, or better performance), (c) the 0-ms TOT intercept (where a smaller number indicates more consistent performance), and (d) the 60-ms TOT intercept (where a larger number indicates more consistent performance). Again,

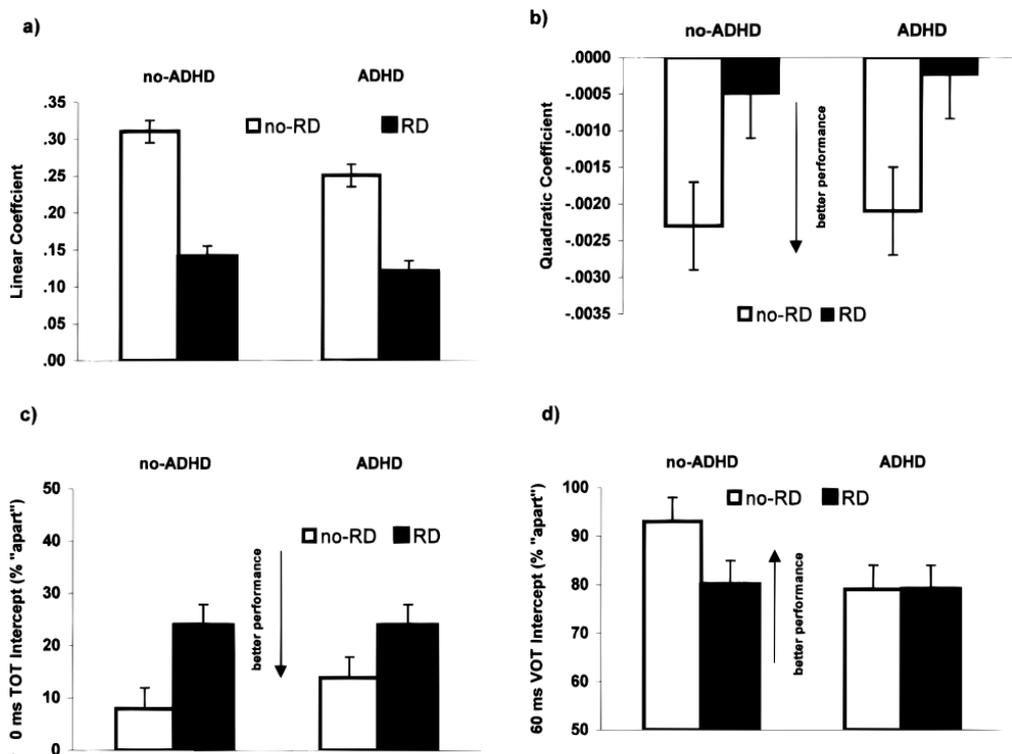


FIG. 5. Group means for parameters of the TOT category labeling functions estimated using linear regression, including: (a) coefficient of the linear trend—where a larger number indicates better performance, (b) coefficient of the quadratic trend where a more negative number indicates better performance, (c) 0-ms intercept—where a smaller number indicates greater consistency in labeling, and (d) 60-ms intercept—where a larger number indicates greater consistency in labeling. Note that children with RD exhibit shallower slopes and less consistent labeling at the 0-ms TOT regardless of the presence of ADHD. Error bars represent standard error of the mean.

as with the VOT series, children with RD exhibited shallower labeling functions and less consistent performance at the 0 TOT value as compared to children without RD. Also evident is a reduction in accuracy in children with ADHD at the 60-ms TOT that is independent of the presence of RD. Again, results of all analyses remained unchanged when Performance IQ was used as a covariate.

The Relationship between Reading, Spelling, and Phonological Processing Skills and Perceptual Abilities

Group means on measures of reading, spelling, and phonological processing, including single word decoding accuracy (WRMT-R: Word Identification), single word decoding speed (Test of Word Reading Efficiency), phonological decoding (WRMT-R: Word Attack), spelling (WIAT), phonemic awareness (mean of segmenting word and nonword and phoneme elision tests from the CTOPP), rapid automatized naming (CTOPP), and phonological memory (recalling sentences from the CELF) are presented in Table 2. Group differences on each of the measures were analyzed using a 1-way ANOVA with the measure as the dependent variable and group (NI, RD, ADHD, RD/ADHD) as the independent variable. Follow-up comparisons used a Bonferroni correction to maintain experimentwise alpha at $p < .05$. Scores that are significantly different are marked with an asterisk (*). As expected, all measures distinguished the no-RD and RD groups.

TABLE 2
Group Means on Measures of Reading, Spelling, and Phonological Processing Skills

Measure	NI	ADHD	RD	ADHD/RD
Word Decoding Accuracy (SS)				
Mean	103.0	99.5	83.7*	87.1*
SD	8.7	4.8	8.5	6.4
Word Decoding Speed (SS)				
Mean	95.2	90.7	66.1*	72.2*
SD	6.0	7.0	14.5	12.2
Phonological Decoding (SS)				
Mean	104.7	101.0	88.1*	91.3*
SD	8.4	7.8	8.2	5.4
Spelling (SS)				
Mean	106.9	98.4*	80.8**	83.3**
SD	13.6	9.2	7.6	7.5
Phonemic Awareness (SS)				
Mean	98.7	95.8	85.9*	90.8*
SD	8.0	9.6	12.8	11.2
Rapid Naming (SS)				
Mean	99.0	98.6	80.1*	79.4*
SD	10.5	12.6	25.1	27.6
Phonological Memory (SS)				
Mean	105.2	104.3	94.5*	94.6*
SD	10.3	10.5	15.5	13.5

Note. SS, standard score.

We were interested in determining if there was a significant relationship between measures of language function and measures of speech and nonspeech perception and whether this relationship was independent of RD and/or ADHD group effects. As there were a number of language variables, as well as a number of parameters of performance on speech and nonspeech perception tasks, we used multivariate analysis of variance (MANOVA) for initial analyses to control Type I error (Cohen, 1988; Tabachnick & Fidell, 2000). In this approach, language measures formed a single multivariate dependent variable and the specific parameter of performance on the VOT or TOT task served as the independent, or predictor, variable. RD group and ADHD group were included as independent variables in a factorial design. Age and Performance IQ were included as covariates. We were particularly interested in main effects and interactions involving the parameter of performance on the perceptual task, including the 0-ms VOT intercept, 60-ms VOT intercept, VOT slope, and the coefficients for the linear and quadratic terms and intercept parameters for the TOT labeling function. The presence of a significant ADHD and/or RD by parameter interaction would suggest that RD and/or ADHD affect the relationship between perception and language performance. The absence of such interactions suggests that the relationship between perception and language measures, if significant, is independent of RD and/or ADHD group membership. Significant parameter by ADHD or RD group interactions were followed up within the appropriate group using Bonferroni correction to maintain familywise Type I alpha at .05. In the presence of a significant relationship between a specific measure of perception and the multivariate language measure, follow-up analyses were conducted within each of the language measures separately, again using Bonferroni correction, to determine which language measures contributed the most to the relationship.

For the 0-ms VOT intercept parameter significant effects included the ADHD group by intercept interaction, $F(7, 79) = 2.57, p < .02$, as well as the main effects of intercept, $F(7, 79) = 3.28, p < .004$, RD group, $F(7, 79) = 7.98, p < .0001$, and ADHD group, $F(7, 79) = 2.28, p < .04$. The 2-way RD group by intercept, $F(7, 79) = 1.51, p > .17$, and 3-way RD group by ADHD group by intercept, $F(7, 79) = 1.27, p > .27$, interactions were not significant. For the VOT slope parameter significant effects included the ADHD group by slope interaction, $F(7, 79) = 2.59, p < .02$, as well as the main effects of slope, $F(7, 79) = 2.78, p < .01$, RD group, $F(7, 79) = 7.70, p < .0001$, and ADHD group, $F(7, 79) = 2.24, p < .04$. The 2-way RD group by intercept, $F(7, 79) = 1.17, p > .33$, and 3-way RD group by ADHD group by intercept, $F(7, 79) = 1.08, p > .38$, interactions were not significant. There were no significant effects for the VOT 60-ms intercept parameter or any of the TOT parameters except for the expected effects of RD group.

As these results indicate that the relationships between linguistic and specific perceptual measures are different for children with and without ADHD, follow-up analyses were performed within the ADHD and no-ADHD groups separately for the 0-ms VOT intercept and VOT slope parameters. The same MANOVA

design was used, with the ADHD group removed as a factor. A critical value of $p < .025$ ($.05/2$) was used to evaluate effects in order to maintain familywise alpha at $p < .05$. Within the ADHD group there were no significant effects for any of the measures of performance on perceptual tasks. Within the no-ADHD group there were significant effects for both the intercept, $F(7, 35) = 3.55$, $p < .006$, and slope, $F(7, 35) = 3.31$, $p < .008$, parameters. The effects of RD group were also significant for both the intercept, $F(7, 35) = 6.58$, $p < .0001$, and slope, $F(7, 35) = 5.56$, $p < .0002$, analyses. No other effects were significant. These results indicate a significant relationship between the perceptual and linguistic measures for children with ADHD that is independent of RD group membership.

As there was no relationship in multivariate analyses between language and perceptual measures in the ADHD groups with and without RD, the relationship between specific linguistic measures and measures of phoneme perception were examined in follow-up analyses within the no-ADHD group only. A general linear model approach to analysis of variance was used to determine which measures contributed most to the multivariate relationship, with age and RD group as covariates. A critical value of $p < .007$ ($.05/7$) was chosen for each analysis. A significant relationship was found between the 0-ms VOT intercept and the phonemic awareness, $F(1, 42) = 12.61$, $p < .001$, phonological decoding, $F(1, 42) = 9.48$, $p < .004$, and single word decoding, $F(1, 42) = 10.36$, $p < .003$, measures. For the VOT slope parameter there was a significant relationship with the phonemic awareness, $F(1, 42) = 7.93$, $p < .007$, and single word decoding, $F(1, 42) = 9.28$, $p < .004$, measures.

The relationships between the composite measure of phonemic awareness and the 0-ms VOT intercept parameter and single word decoding and the VOT slope parameter for children without ADHD are presented in Figs. 6a and 6b, respectively. As can be seen, phonemic awareness improves with performance on the 0-ms intercept (better performance is indicated by a lower value for the intercept), which is a measure of the consistency of identification of the VOT stimulus as being voiced (/ga/), as well as with increased precision of the boundary between the voiced (/ga/) and voiceless (/ka/) percepts (better performance is indicated by a higher value for the slope).

In sum, these data indicate significant relationships between phoneme perception and phonemic awareness, as well as single word and phonological decoding abilities that are independent of RD group effects. The data also indicate that these relationships are not independent of the presence of ADHD and are significantly reduced in ADHD groups.

DISCUSSION

This study indicates that children with RD have a deficit in phoneme perception that is evident in inconsistent labeling of tokens in a VOT (/ga/-/ka/) series. Children with RD were also less consistent in their labeling of TOT tokens, supporting the hypothesis that deficits in speech perception in this group extend to nonspeech as well as speech stimuli containing similar acoustic cues. The study

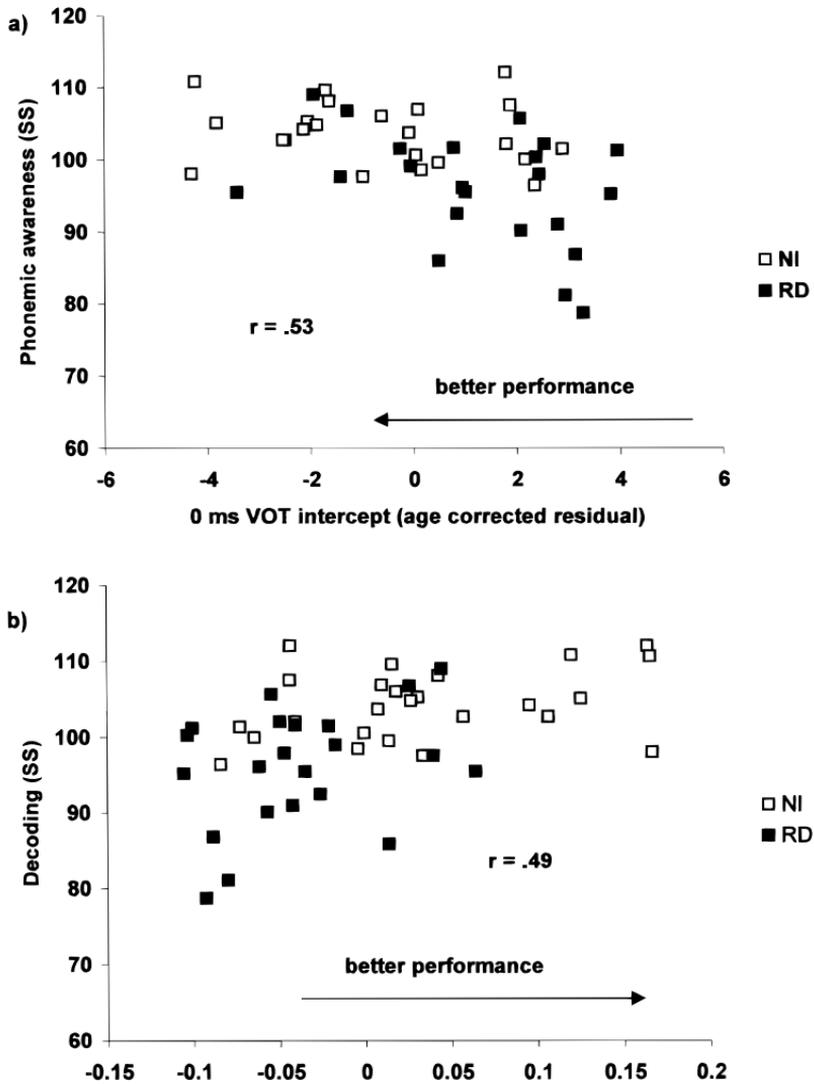


FIG. 6. Plots of (a) phonemic awareness as a function of the age corrected 0-ms VOT intercept, and (b) single word decoding as a function of the age corrected VOT category labeling slope. Data points are from the no-ADHD group only. Note that less consistency and precision on the VOT labeling task is associated with poorer performance on phonemic awareness and decoding measures.

also confirms that these deficits are independent of the presence of ADHD, a behavioral disorder that represents a potential confound in studies of perception (Green, 1995) and exhibits substantial comorbidity with RD. In addition, deficits in phoneme perception were associated with reduction in performance on tasks assessing phonemic awareness and decoding skills when the presence of ADHD was taken into account.

The difference in performance on the VOT task between the RD and the no-RD groups was evident in both the slope and intercept parameters of the VOT category labeling functions, indicating that children with RD are inconsistent in their identification of tokens across the entire range of VOTs, even when cue values are at their minimum or maximum and tokens should be the most easily identifiable. The current findings are consistent with previous studies that indicate a deficit in phoneme perception in both children (Brandt & Rosen, 1980; Godfrey et al., 1981; Manis et al., 1997; Reed, 1989; Tallal, 1980; Werker & Tees, 1987) and adults (Lieberman et al., 1985; Steffens et al., 1992; Watson & Miller, 1993) with RD and extend previous results by demonstrating that this deficit is not an artifact of the association of RD and ADHD and is not limited to children with SLI. Children with RD exhibited consistently lower performance on the VOT task when compared to children without RD, both within and across ADHD subtypes. As this study was designed to evaluate the effects of attention on differences between RD and no-RD groups, this consistency allowed us to collapse the two ADHD groups to achieve greater power.

Children with RD also exhibited deficits in the ability to consistently label TOT stimuli, which consist of two tones presented with the same onset asynchronies between the low and high frequency regions as in the VOT series, thus serving as a nonspeech analog to the VOT series (Pisoni, 1977). Again, labeling functions for children with RD were neither as sharp across the range of stimuli, nor as consistent at the point where the cue value was at its minimum (0-ms asynchrony). The presence of a deficit in perception of onset asynchrony in speech and nonspeech stimuli containing analogous acoustic cues is consistent with the hypothesis that a low level deficit in the auditory system is present in children with RD and that this deficit could account for observed difficulty in perception of speech stimuli (Tallal et al., 1993, 1998; Wright et al., 1997). While the cue for discriminating between tokens in the VOT and TOT tasks is temporal in nature, the current study did not address the issue of the specificity of the deficit to temporal cues because no nontemporal control stimuli were included. Whether the deficit generalizes to other temporal cues, and whether auditory function is affected in nontemporal domains, is a matter for further research.

In contrast to the robust effects of RD on the sharpness of the VOT category labeling functions, the effect of RD on the mean of the function, or category boundary, was marginal and did not reach statistical significance. Three of the four groups exhibited essentially the same category boundary at a VOT of approximately 35-ms. This boundary location is consistent with that found using similar stimuli in various other studies (Rosner, 1984; Simos et al., 1998). The RD/ADHD group did exhibit a tendency toward a higher boundary at about 45-ms, suggesting that these children required a greater VOT onset asynchrony to identify the /ka/ percept. These results are generally consistent with other studies that do not find differences in category labeling boundaries in children with RD (relative to controls) despite evidence for less consistent labeling of tokens (Godfrey et al., 1981; Manis et al., 1997). In the absence of ADHD, children with

and without RD appear to have similar category labeling boundaries; however, children with RD do not perform as consistently across these boundaries, and their category labeling functions do not appear to be as "sharp."

In addition to deficits in single word and phonological decoding, children with RD often exhibit deficits in phonemic awareness (Morris et al., 1998; Shaywitz et al., 1999), rapid automated naming of letters, digits, and objects (Cornwall, 1992), and immediate phonological memory (Baddeley & Wilson, 1993). We found evidence for significant relationships between measures of phoneme perception and phonemic awareness and decoding skills. This finding was independent of the effects of RD group membership. However, it was not independent of ADHD group membership and analyses did not indicate significant relationships between measures of language and perception within ADHD groups. Manis et al. (1997) also found that slopes of category labeling functions correlated with phonemic awareness as well as single real word decoding across their study sample, which included NI controls and potentially children with ADHD. While causal relations cannot be directly addressed in the current study, these results do support the possibility of an underlying deficit in phoneme perception in at least a subgroup of children with RD who exhibit poorly developed phonemic awareness and decoding deficiencies.

Interestingly, while children with RD exhibited some difficulty on the TOT labeling experiment, analyses did not indicate significant relationships between performance on this nonspeech analog and linguistic measures that were independent of RD group membership. One possibility is that deficits in general auditory temporal processing and phonological processing and decoding are concomitant, but not causally related in children with RD. Another possibility is that the effects of low level auditory temporal processing deficits on phonological processing and decoding skills are mediated through speech perception. The current data do not allow us to distinguish between these two hypotheses.

Both real and pseudoword decoding measures are typically used to identify children with RD. In addition to these measures, we included single word reading fluency and spelling measures in order to avoid placing children with a history of reading disability into either of the no-RD groups. All of the children in this study had been previously identified as having RD and had received some form of intervention. Although intervention may result in improved phonological decoding, residual deficits in word reading fluency and spelling are often evident (Torgesen et al., 1999). This pattern of relatively better phonological decoding as compared to real word reading, spelling, and reading fluency was evident in our RD sample. It is virtually impossible to do a study of this kind with large samples without including children who have received some form of remediation, and the presence of children in the RD study sample who have become accurate (but not fluent) word decoders likely explains some of the variance in the data. However, despite this variance, findings remained robust.

Recent theory and research suggest that difficulty with response inhibition is the core deficit in ADHD (Barkley, 1997a, 1997b; Barkley & Biederman, 1997;

Pennington & Ozonoff, 1996; Rubia, Oosterlaan, Sergeant, Brandeis, & v. Leeuwen, 1998; Schachar, Tannock, Marriott, & Logan, 1995) while RD is characterized by deficits in single word decoding and poor phonological processing skills (Blachman, 2000; Fletcher et al., 1994; Shankweiler & Crain, 1986; Shaywitz et al., 1995; Stanovich, 1988). Studies regarding the effects of comorbidity of the two disorders on reading and associated linguistic abilities generally suggest that children with RD and ADHD exhibit deficits associated with both disorders, but that these deficits do not necessarily interact in a synergistic manner (Fletcher, Shaywitz, & Shaywitz, 1999; Purvis & Tannock, 1997, 2000; Shaywitz et al., 1995). However, little is known regarding the effects of comorbid ADHD on performance on perceptual tasks in children with RD. Green's (1995) model of the effects of attention on psychoacoustic tasks predicts shallower psychometric functions for inattentive observers, and we therefore expected children with ADHD to exhibit shallower slopes on the category labeling functions for both speech and nonspeech stimuli. However, while children with ADHD did exhibit a trend in this direction on both the VOT and TOT tasks, these trends did not reach significance, and the effects of RD were generally independent of the presence of ADHD. In addition, although the ADHD group did exhibit less accurate performance at the 60-ms TOT, there was little evidence for a significant perceptual deficit in the ADHD group, a finding consistent with that of Norrelgen et al. (1999). In contrast, a significant effect of ADHD was evident in correlation analyses relating phoneme perception to measures of reading and phonological processing. Relationships between phoneme perception and phonemic awareness, as well as single word and phonological decoding skills that were robust in children without ADHD were significantly reduced in groups of children with ADHD. The reduction in these relationships is potentially due to behavioral deficits associated with ADHD acting in a nonsystematic fashion across tasks, a hypothesis that would suggest that ADHD is a nonspecific factor that may need to be accounted for in studies of perception in children with RD, particularly when relationships among tasks are being evaluated.

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