SCIENTIFIC STUDIES OF READING, *11*(3), 259–286

Auditory Processing of Amplitude Envelope Rise Time in Adults Diagnosed With Developmental Dyslexia

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Studies of basic (nonspeech) auditory processing in adults thought to have developmental dyslexia have yielded a variety of data. Yet there has been little consensus regarding the explanatory value of auditory processing in accounting for reading difficulties. Recently, however, a number of studies of basic auditory processing in children with developmental dyslexia have suggested that a reduced ability to discriminate the rate of change in amplitude envelope onsets (rise time) may be linked to phonological processing difficulties and thereby to reading difficulties. Here, we select a range of different rise-time tasks used with children, and give them to adults with developmental dyslexia, along with 2 other auditory tasks (intensity discrimination and temporal order judgment). Deficits in both rise-time perception and temporal order judgment were found to predict literacy attainment in adults with developmental dyslexia, but the data were suggestive of different causal pathways.

Developmental dyslexia is characterized by difficulties with fluent word recognition and spelling, and it is typically accompanied by a cognitive deficit in the accurate representation of phonology (e.g., Lyon, Shaywitz, & Shaywitz, 2003; Snowling, 2000). Children and adults with developmental dyslexia have problems with reading and spelling that cannot be accounted for by hearing or visual impairments, low intelligence, neurological damage, or poor educational opportunities. Studies seeking a potential sensory cause for the core phonological deficit have investigated a variety of hypotheses. Some researchers have suggested

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that magnocellular impairment in both the visual and auditory systems causes impaired phonological representation (e.g., Stein & Talcott, 1999). Others have proposed a general sensory processing deficit (Ramus, 2003), a deficit in the cerebellum (Nicolson, Fawcett, & Dean, 1995), or a deficit in discriminating signals from noise (Sperling, Lu, Manis, & Seidenberg, 2005). The hypothesis we focus on here is that the phonological impairments observed in individuals with developmental dyslexia result from lower level auditory processing deficits. Auditory processing deficit accounts of developmental dyslexia are theoretically attractive, as the primary source of language input is usually auditory.

The auditory deficit hypothesis tested in this study is derived from recent studies of basic auditory processing in children with developmental dyslexia. Studies suggested that dyslexic children are relatively insensitive to auditory cues important for processing the prosodic patterns in speech, in particular cues to speech rhythm and stress. Prosodic cues found to be impaired in children with dyslexia include the rate of change of the amplitude envelope at onset (rise time), amplitude modulation (AM) depth, duration, and pitch contour (Foxton, Talcott, & Witton, 2003; Goswami et al., 2002; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Richardson, Thomson, Scott, & Goswami, 2004; Rocheron, Lorenzi, Fullgrabe, & Dumont, 2002). Individual differences in sensitivity to these cues are reliably associated with reading and phonology, even when IQ is controlled for. For example, individual differences in rise-time measures predicted 25% of unique variance in reading and spelling after controlling for age and IQ in the developmental cohort studied by Goswami et al. (2002), whereas individual differences in sensitivity to duration predicted 12% of unique variance in nonword reading in the cohort studied by Richardson et al. (2004). Sensitivity to rise time is also impaired in children with dyslexia across languages. Children with dyslexia learning both stress-timed (English: Richardson et al., 2004) and syllable-timed (French: Muneaux et al., 2004; Hungarian: Csépe et al., 2006) languages have difficulties in auditory tasks based on rise time. These difficulties typically characterize the majority of a particular sample (e.g., 63% of children with dyslexia studied by Richardson et al., 2004) and have diagnostic value (e.g., 81% of Hungarian children with dyslexia were identified on the basis of a high threshold in a rise-time task, Csépe et al., 2006).

It is currently unclear whether the auditory processing deficits that characterize children with developmental dyslexia persist into adulthood, whether different auditory processing deficits characterize adult dyslexics, or whether auditory processing improves as a result of maturation or remediation. For example, a recent review of studies of both children and adults (Ramus, 2003, pp. 212–213) suggested that auditory processing deficits are characteristic of, at best, a "fraction" of individuals diagnosed with dyslexia, suggested to be around 39%. Ramus claimed that "[auditory] disorders … have little influence on the development of phonology and reading" (p. 213). However, as many of the studies in his review were of adults with developmental dyslexia, conclusions regarding the influence of auditory processing deficits on the development of phonology and reading are difficult to draw. In contrast, it has been argued that auditory disorders may have a profound early effect on the development of phonology, and therefore of language and reading, with recent studies demonstrating subtle auditory processing disorders in infants at genetic risk of dyslexia (see Goswami, 2003). The role of auditory maturation also deserves study. For example, some researchers have noted that although both auditory and phonological deficits may characterize children with developmental dyslexia, auditory processing may improve with age, leading to adult developmental dyslexics who show phonological but not auditory deficits (Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006). These alternative theoretical possibilities make it timely to study sensitivity to the auditory cues that are prominent in the auditory difficulties exhibited by young children in adults with developmental dyslexia.

One of these auditory cues is the rate of change of the amplitude envelope at onset (rise time; see Goswami et al., 2002; Richardson et al., 2004). Only two prior studies of auditory processing in adults with developmental dyslexia have explored rise-time sensitivity. Hämäläinen, Leppänen, Torppa, Müller, and Lyytinen (2005) used a same–different judgment task based on two tones with either identical rise times (both 10 ms) or different rise times (10 ms vs. 30 ms, and 10 ms vs. 80 ms). None of the adult participants could detect the difference between 10-ms and 30-ms rise times (even the normal readers), but a group difference was found in detecting 10-ms versus 80-ms rise times, with significantly poorer performance by the adults with dyslexia. Hämäläinen et al. reported a significant relation between rise-time sensitivity and phonological and reading abilities in their sample, even after controlling for IQ and short-term memory (digit span). In Hämäläinen et al.'s study, rise time contributed 35% of unique variance to phonological skills (rhyme recognition), and contributed 18% of unique variance to a lexical decision task. A second study explored sensitivity to rise time, intensity, and duration cues, but not temporal order judgment (TOJ), in English adults with developmental dyslexia (Thomson, Fryer, Maltby, & Goswami, 2006). The adults with dyslexia were significantly poorer than IQ-matched controls in all the auditory tasks, and sensitivity to rise time and duration (but not intensity) was related to reading and spelling after controlling for both verbal and nonverbal IQ. The adults with developmental dyslexia were also poorer at generating an internal rhythm when asked to continue tapping to a beat determined by a metronome. This rhythm generation task was strongly correlated with performance in the auditory rise-time task only. Thomson et al. suggested that as those adults who found it most difficult to generate an internally consistent rhythm were also those who found it most difficult to detect the primary cue for rhythmic timing in speech (rise time), a supra-modal explanation might lie in P-center detection. The concept of a P-center was introduced by Morton, Marcus, and Frankish (1976) to refer to that moment in an extended auditory event (e.g., a syllable, a musical note) that is the perceptual moment of occurrence.

When speech is rhythmic or periodically produced, or when any sequence of events is spoken or heard as rhythmically regular, then the P-centers (by definition) occur at regular intervals. In speech, P-centers depend primarily on the rise time associated with the vowel in a syllable. Long onsets before the vowel (e.g., "skate") move the P-center temporally to the left, whereas long codas (e.g., "banks") can move it to the right (see Port, 2003). The concept of P-centers was also extended to motor timing by Morton et al., who noted its importance in coordinating auditory and motor rhythms (e.g., in dance). A rise-time perception difficulty may thus contribute to the problems with motor and musical timing noted in some studies of dyslexic individuals (e.g., Wolff, 2002).

Most studies of auditory processing in adults with developmental dyslexia have used other auditory tasks. These include gap detection (Ahissar, Protopapas, Reid, & Merzenich, 2000; McAnally & Stein, 1996), frequency discrimination (Amitay, Ahissar, & Nelken, 2002; Hill, Bailey, Griffiths, & Snowling, 1999), backwards masking (France et al., 2002; Griffiths, Hill, Bailey, & Snowling, 2003), TOJ (Kinsbourne, Rufo, & Gamzu, 1991; Laasonen, Service, & Virsu, 2001), stream segregation (Helenius, Uutela, & Hari, 1999), and tone detection (McAnally & Stein, 1996). However, methodological weaknesses in design complicate interpretation of the group differences that have been reported in many of these auditory processing studies. Some of the studies failed to match IQ between participating dyslexics and controls (e.g., Ahissar et al., 2000; Helenius et al., 1999), and very few studies controlled for individual variation in IQ in the analyses exploring possible relations between the auditory tasks used and reading (of the studies noted previously, only Griffiths et al., 2003, and Kinsbourne et al., 1991, controlled for IQ in such analyses). Yet IQ is a critical variable in studies of auditory processing. For example, Banai and Ahissar (2004) showed that poor auditory performance (frequency discrimination) is related to low nonverbal IQ for both good and poor readers. Clearly, group matching does not preclude individual variation within groups playing a significant role in any relations between auditory processing and literacy–phonology that may be found.

When studies failing to control for IQ are excluded from consideration, then rather few auditory variables aside from rise time are associated with developmental dyslexia in adults. The most consistent findings concern TOJ, AM, and frequency modulation (FM) at lower rates. TOJ tasks requiring participants to judge the order of sounds that follow each other closely in time are thought to be one of the best measures of the ability to process rapidly presented acoustic information (Tallal & Piercy, 1973), and TOJ has been linked to reading difficulties in a study of children (Tallal, 1980). This has led to a number of investigations of potential relations between TOJ and reading in adults. Kinsbourne et al. (1991) asked adults to judge the order of two sounds delivered to the left versus right ear (one click to each ear). They found that a group of 23 adults with dyslexia performed significantly more poorly than 21 controls matched for both verbal and nonverbal IQ.

Kinsbourne et al. also found significant relations between TOJ and reading and spelling after verbal IQ was controlled for in their sample. Ramus et al. (2003) tested 16 adults, who had formal childhood diagnoses of dyslexia, using a TOJ task based on two sounds easily identifiable as the beeping of a car horn and the barking of a dog. Participants had to judge which sound came first. Significant group differences in TOJ threshold compared to IQ-matched controls were found; however, no relation was found between TOJ and phonology or reading once the data were corrected for multiple comparisons. Laasonen et al. (2001) gave 16 dyslexic participants and 16 controls, matched for full-scale IQ, TOJ tasks in three modalities: auditory, visual, and tactile. Participants were asked to decide on the order of two tones, two flashes of light, or two pressure pulses to the left index and middle fingers. A significant group difference was found in the auditory and tactile TOJ tasks. Auditory TOJ was also significantly linked to nonverbal IQ. Once IQ was controlled for, TOJ did not correlate with phonological processing. Therefore, although all of these studies found a group difference in TOJ, only Kinsbourne et al. (1991) found a relation between TOJ and literacy.

However, Griffiths et al. (2003) failed to find group differences in temporal order detection in an extensive study of adults with dyslexia and IQ-matched controls. Their TOJ task consisted of four pairs of tones, the second or third of which reversed the standard high–low order. Participants were asked to identify the low–high tone pair. The dyslexic group did not differ significantly from the control group in either 20-ms inter–stimulus interval (ISI) or 200-ms ISI conditions, although both groups found the 20-ms condition (rapid presentation) more difficult. Partial correlations controlling for vocabulary showed a significant relation between a composite phonology variable and the 20-ms measure for both groups, but no relation with literacy. In fact, the question of whether rapid auditory processing plays any role at all in literacy development remains a highly contentious issue (see Marshall, Snowling, & Bailey, 2001; McArthur & Bishop, 2001; Rosen, 2003; Studdert-Kennedy & Mody, 1995). For example, more recent studies with children have shown difficulties in judging temporal order whether stimulus presentation is rapid or slow (e.g., Heath, Hogben, & Clark, 1999; Marshall et al., 2001; Nittrouer, 1999). Whether TOJ has a role to play in literacy development and whether the rapidity of presentation is important are both open questions.

Modulation tasks are theoretically interesting because of their possible connection with rise-time processing. For example, when frequency is modulated at slower rates, rise time becomes salient, and in AM tasks rise time will covary with modulation depth. FM detection in adult dyslexics has been explored by Stein and McAnally (1995); Witton et al. (1998); Witton, Stein, Stoodley, Rosner, & Talcott (2002); Ramus et al. (2003); and Hill et al. (1999). All studies matched dyslexic and control groups for IQ, and all studies found that detection of FM at slower rates was impaired in the group with dyslexia. Witton et al. (2002) also controlled for IQ in fixed-order hierarchical regressions exploring relations with reading. They found that 9.4% of additional variation in nonword reading was explained by FM detection at 2 Hz (analogous to a slow syllable rate). AM detection was measured in IQ-matched groups by Menell, McAnally, and Stein (1999); Witton et al. (2002); and Amitay et al. (2002). Menell et al. determined adaptively the modulation depth required to discriminate one of two noise bursts containing AM for six different modulation frequencies: 10, 20, 40, 80, 160, and 320 Hz. AM detection thresholds were found to be significantly higher for the dyslexic participants compared to controls. This difference in AM detection ability was consistent across modulation frequency. Witton et al. (2002) used a similar AM detection task at 2 Hz and 20 Hz only. They found significant group differences for the 20-Hz task but not for the 2-Hz task. When they carried out fixed-order hierarchical regressions controlling for IQ to explore relations with nonword reading, AM detection in the 20-Hz condition was found to predict 14.5% of unique variance. Amitay et al. (2002) studied AM detection at four modulation frequencies: 4, 10, 100, and 500 Hz. No overall group deficit was found. However, this sample of poor readers was not diagnosed dyslexics.

The consistent finding that adults with dyslexia have difficulties in FM tasks, specific to slower modulations, is consistent with the rise-time detection difficulties in children with developmental dyslexia discussed earlier (Csépe et al., 2006; Goswami et al., 2002; Muneaux et al., 2004; Richardson et al., 2004). Children with developmental dyslexia are accurate in detecting fast rise times, but have difficulties as rise times become extended (in Richardson et al., 2004, they had difficulties once rise times were longer than 60 ms). Slower modulations have more extended rise times. The findings with AM tasks suggest that adults with dyslexia appear to need deeper modulations for detection. As rise time covaries with modulation depth, this is consistent with the demonstration that children diagnosed with developmental dyslexia need sharper rise times to perceive “beats” in AM signals (Goswami et al., 2002). Hence, findings from studies of rise time, FM, and AM converge in suggesting that rise-time perception may be impaired in adults with developmental dyslexia.

The findings for TOJ lack such convergence and clearly require further investigation. Theoretically, accounts of why TOJ should matter for phonology and literacy development are quite distinct from the theoretical accounts based on rise time, as the latter rely on speech rhythm, stress, and prosody (see Corriveau, Pasquini, & Goswami, in press). According to rapid auditory processing theory (RAP), TOJ is related to literacy via phoneme awareness (see Tallal, 1980, 2004). The theory is that brief, rapidly successive acoustic cues are critical for the identification of phonemes in the speech signal. These local and transient cues to phonetic identity are thought to be critical to recovering linguistic structure. For example, the brief formant transitions (40 ms) preceding the vowel are said to be the sole differentiating feature between syllables such as “ba” and “da” (Tallal, 2004). In contrast, rise time and AM–FM measures of auditory processing are thought to be linked to literacy because of a more global relation between prosodic perception and language acquisition (Corriveau et al., in press). Developmentally, children seem to build a phonological system by first attending to rhythm and prosody (infant-directed speech, or "Motherese," is characterized by the use of a small set of highly distinctive melodic contours; e.g., Fernald, Taeschner, Dunn, & Papoušek, 1989). Speech rhythm provides a cue to potential word boundaries (e.g., Cutler & Mehler, 1993), and rhythmic stress is actively used by infants for segmenting words from the speech stream (e.g., Jusczyk, Houston, & Newsome, 1999). Recently, Curtin, Mintz, and Christiansen (2005) showed that stress combines additively with transitional probabilities for phonemes in word segmentation by infants. They showed that the early phonological representations of infants aged 7 months encoded lexical stress as well as segmental information.

Nittrouer (2006) emphasized the complementary developmental roles of global and local signal structure in language acquisition. Pointing out that listeners can recover linguistic structure when all of the traditional cues to phonemic identity are eliminated from the signal (Remez, Rubin, Pisoni, & Carrell, 1981), she argued that amplitude envelopes have a clear role to play in understanding speech. Cochlear implant users, for example, have access to very few channels of information, and receive primarily amplitude envelope information, and yet they learn to recognize speech relatively well. Nittrouer argued that although adults are sensitive to both global spectral structure and local acoustic detail, younger children attend primarily to the global level of information, attending mainly to the acoustic changes that arise from the slow modulations of the vocal tract. These are also the modulations that they learn to produce first in development (de Boysson–Bardies, Sagart, Halle, & Durand, 1986). With increasing experience of their native language, infants learn the phonetic significance of local details (e.g., the articulatory features captured by RAP theory), although of course they can perceive these details from birth (Kuhl, 2004). Developmentally, therefore, insensitivity to global cues to speech rhythm and stress might be expected to affect the initial setup of phonological representations. Insensitivity to rapid auditory cues to phonetic detail may not have such strong effects in early development, as there are many complementary cues to phoneme identity in natural speech. The origins of the phonological deficit in dyslexia may, hence, lie in the auditory processing of temporal cues to rhythm and stress—cues such as rise time and duration. Impairment in the auditory processing of rapid cues to phonetic features may become more important in later childhood and adulthood, when relations with literacy may become stronger.In this study, we therefore focus on auditory measures of rise time and RAP in adults with developmental dyslexia. The rise-time measures chosen are those that had been used in our prior studies with children at the time that this study was conducted (Goswami et al., 2002; Richardson et al., 2004). The RAP measure chosen was the dog–car TOJ used in our prior studies (Goswami et al., 2002; Richardson et al., 2004). This is the same RAP measure used by Ramus et al. (2003). In our studies with children, the rise-time measures used here have been more important for reading and phonology than the RAP measure used here (Goswami et al., 2002; Richardson et al., 2004). However, both children (Goswami et al., 2002) and adults (Ramus et al., 2003) with dyslexia show a group deficit compared to IQ-matched controls in this RAP measure. Given inconsistencies in the prior literature, we did not have any strong expectations regarding significant relations between TOJ, phonology, and literacy in adults. We did, however, expect significant relations between rise-time processing, phonology, and literacy.

METHOD

Participants

Twenty-nine university students with dyslexia from the two universities in Cambridge, England were recruited for the study. Participants were recruited via the learning disabilities centers at the two universities. All dyslexic participants spoke British English as their first language and had been diagnosed with developmental dyslexia by a registered educational psychologist. Prior to testing, volunteers completed a questionnaire about their medical history. Current dyslexic status was then assessed by the experimenters using standardized tests (see next). Volunteers indicating a hearing impairment or another co-morbid disorder (e.g., dyspraxia, attention deficit disorder, epilepsy) were excluded from the study (N = 9). Of the remaining 20 participants, 2 did not meet the inclusion criteria of full-scale IQ of more than 100 and a mean discrepancy between verbal IQ and standardized reading and spelling of at least 10 standardized points as measured by the Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999) and the Wide Range Achievement Test (Wilkinson, 1993). The mean discrepancy for the dyslexic group was 26.85 standardized points, as compared to 3.95 points in the control group. The final group of 18 participants ranged in age from 19 to 27 years; 17 were from the University of Cambridge. Eight of the final 18 participants had had a diagnosis of dyslexia since childhood, and the others had received a diagnosis on entering the university.

Twenty control participants between the ages of 19 and 28 years were recruited from the University of Cambridge and the surrounding area. A questionnaire was used to confirm the absence of impaired hearing, learning disability, and other neurological or psychiatric conditions. Of the 20 volunteers, 2 did not meet the inclusion criteria of full-scale IQ of more than 100, and no individual standardized reading or spelling score was less than 90. The resulting 18 control participants were between 19 and 28 years of age.

Participant characteristics for both groups are shown in Table 1. Prior to participation in the study, all participants were informed about the nature of the tasks and

TABLE 1
Mean Participant Characteristics (Standard Deviations)

	Dyslexic[a]		*Control*[a]		
Group	*M*	*SD*	*M*	*SD*	*F(1, 34)*
Age	21.63	2.33	21.96	2.39	0.17
Verbal IQ[b]	121.16	9.47	117.28	7.61	1.84
Nonverbal IQ	115.15	6.54	117.22	6.95	0.85
WRAT math	99.89	14.14	103.67	15.08	0.60

Note. WRAT = Wide Range Achievement Test.
[a]$N = 18$. [b]Verbal IQ, Nonverbal IQ, and WRAT math represent standard scores ($M = 100$, $SD = 15$).

gave written consent to participate. All participants were paid £5.00 per hour for their participation. One-way analyses of variance (ANOVAs) with group (dyslexic, control) confirm that the groups did not differ significantly on age, verbal IQ, performance IQ, full scale IQ, or mathematical ability.

Tasks

Participants received a battery of psychometric, phonological, and psychoacoustic tests lasting about 2 hr with a break after the first 1 hr. The auditory tasks were chosen to include all the rise-time tasks used previously with children (Goswami et al., 2002; Richardson et al., 2004), the dog–car TOJ task from Goswami et al. (which has good ecological validity and showed a group difference for adult developmental dyslexics in Ramus et al., 2003), and an auditory control task to check for attention difficulties in the psychoacoustic paradigm. The control task chosen was an intensity discrimination task, as intensity has not been a difficult auditory discrimination for dyslexic children in previous studies (e.g., Richardson et al., 2004). Phonological tasks were chosen to represent the three related areas of phonological processing identified in the literature: phonological awareness (spoonerisms, phoneme deletion), rapid automatized naming (object), and phonological memory (digit span). Testing was administered one on one, in quiet rooms at the Faculty of Education, University of Cambridge, by the first two authors (Elisabeth S. Pasquini and Kathleen H. Corriveau).

Standardized Psychometric Tests

All four subtests of the Wechsler (1999) Abbreviated Scale of Intelligence were used to assess verbal and nonverbal intelligence. Untimed single-word reading and spelling were measured using the Wide Range Achievement Test (Wilkinson, 1993). As a control measure, the Wide Range Achievement Test in Mathematics was also administered to ensure that basic auditory processing did not predict educational outcomes in general. Timed single-word and pseudoword reading were assessed using the Test of Word Reading Efficiency (Torgesen et al., 1999)

Experimental Phonological Processing Tasks

Spoonerisms. This task was drawn from the Phonological Assessment Battery (Fredrickson, 1996). Participants heard three sets of 10 items presented orally by the experimenter. Participants were asked to replace or "swap" the initial phoneme or phonemes in the test items. The three sets of items were presented in order of increasing difficulty. In the first set of items, the participant replaced the onset phonemes of a word with a given target phoneme (e.g., "cot" "g"; the participant responded "got"). In the second set of items, the participant heard two words and was asked to replace the onset of the first word with the onset of the second word (i.e., for "die pack" the correct response was "pie"). In the last set of items, the participant swapped the onset phonemes of a pair of words (e.g., for "sad cat"; the participant responded "cad sat"). Scores on this measure were out of a possible 30 points (internal consistency reliability for this task in our sample was $a = .65$).

Phoneme deletion. In this task, the experimenter orally presented 18 pseudowords (including 3 practice words), followed by a target phoneme contained in the pseudoword. Participants were asked to produce the pseudoword, omitting the target phoneme (e.g., Say "bice" without the "b"; Say "splow" without the "p"). Phonemes were deleted from a variety of positions within the pseudoword (initial, medial, and final). This is an abbreviated version of a similar deletion task designed by McDougall, Hulme, Ellis, and Monk (1994). Scores on this task were out of 15 (internal consistency reliability for this task in our sample was a = .70).

Rapid automatized naming. The rapid automatized naming measure was drawn from the Phonological Assessment Battery (Fredrickson, 1996). Participants were presented with an array of 50 pictures of five common objects (door, chair, hat, ball, and table) and were asked to name the objects from left to right as quickly as possible. This was followed by a second trial in which participants named a different 50-item array of the same five pictures. The final score on this measure was the mean of the two trial times (in seconds), disregarding accuracy. The test–retest correlation for this task in our sample was $r = .87$, $p < .001$.

Digit span. The Wechsler (1998) Adult Intelligence Scale digit span task was used to assess auditory short-term memory. Raw scores on this measure were the mean of the number of correct answers, out of a possible 14. Standard scores are normalized to have a mean of 10 and a standard deviation of 3.

Psychoacoustic Tasks

With the exception of the audiometer screening (see next), all psychoacoustic tasks were presented on a laptop with AKG model K141 and JVC model HA–D570D headphones. Earphone sensitivity was calculated using a Zwislocki coupler in one ear of a KEMAR manikin (Burkhard & Sachs, 1975) such that the loudness of the stimuli was kept constant at 73 dB, and the standard stimulus for the intensity discrimination task was at 73 dB. Three of the tasks were presented using the dinosaur threshold estimation program created by Dorothy Bishop at Oxford University. Here the computer presented pairs of sounds in an adaptive two-interval forced choice format, with a 500-ms interstimulus interval. Each sound was associated with one of two dinosaurs depicted on the screen, and the participant was asked to choose one of the two dinosaurs based on task-specific instructions. The participant's response was entered by the experimenter, and online feedback was provided. A maximum of 40 trials was presented. The point at which the participant gave correct responses 75% of the time was adaptively determined by the more virulent form of parameter settings by sequential estimation (Findlay, 1978). Scores on these measures represent the 75% correct threshold over the last four reversals.

Two of the tasks were presented adaptively using Speech Pattern Audiometer II, a C++ based program developed by Stuart Rosen, University College London. These tasks were adaptive and each subsequent stimulus was determined using a modification of Levitt's (1971) adaptive procedure, also created by Stuart Rosen. Probit analysis was used to estimate the slope, category boundary, and 75% correct threshold of the categorization function (Finney, 1971). This program and procedure are described in detail by Goswami et al. (2002).

Audiometer screening. To confirm that participants' hearing was unimpaired, all participants were required to pass an audiometer hearing test given at the 25-dB level. Tones were presented by the audiometer in both the right and left ear at six frequencies (0.25, 0.50, 1, 2, 4, and 8 kHz).

Intensity discrimination. In the intensity discrimination task, the dinosaur program presented pairs of 50 ms, 1-kHz pure tones. Each pair of tones comprised a 73-dB standard tone and a second tone that was drawn adaptively from a stimulus set of 31 pure tones that ranged in loudness from 73 dB to 81.1 dB, with 0.27 dB between each step. Participants were asked to identify which of the dinosaurs made a louder sound. This measure is based on the loudness perception task as described in Ivry and Keele (1989). This measure was intended as a control task for the attentional demands of the psychoacoustic procedure, in that participants with dyslexia were not expected to have an auditory difficulty with this task.[1]

[1]Note that chronologically this study was carried out before that reported by Thomson, Fryer, Maltby, and Goswami (2006).

Rise time of a single amplitude envelope (one-ramp task). In this task, participants heard pairs of modulated 500-Hz pure tones. One of the tones in each pair was always the standard tone, which had a 300-ms linear rise-time envelope. The linear rise-time envelope of the second tone varied logarithmically from 15 ms to 300 ms. The shortest rise time was set at 15 ms to avoid spectral splatter. The overall duration of the stimuli remained constant at 800 ms, and the duration of the linear fall time was fixed at 50 ms. Children were asked to choose the dinosaur that made the sound that was sharpest at the beginning. Figure 1 shows schematic examples of the stimuli for this task and the other rise-time tasks.

Rise time from a pedestal (two-ramp task). In this task, 40 stimuli were created from 500-Hz sinusoidal carriers, which were amplitude modulated at 0.7 Hz and had a depth of 50%. Each stimulus was 2.5 cycles long (3,570 ms). The AM envelope was a modified square wave, with a fixed 350-ms fall time and a rise time that varied logarithmically from 15 ms to 300 ms. The 300-ms, rise-time tone was the standard sound and was included in every pair of stimuli. Participants were instructed to identify the dinosaur that made the sound with a sharper beat. This task is depicted in Richardson et al. (2004).

Beat-perception task (five-ramp rise time). This task was delivered using the Speech Pattern Audiometer II. The task used a continuum of 40 stimuli identical to those used in the two-ramp, rise-time task, except that they comprised five ramps. Thus, the stimuli were of longer duration (7,857 ms). The 15-ms, rise-time stimulus is subjectively perceived as having a strong rhythmic beat, and it was described as the timing of the motion of a double swing for the toys Tigger and Eeyore, who were depicted on the screen of the computer. As one animal swung forward, the beat would sound. The 300-ms stimulus is subjectively perceived as a single sound waxing and waning in intensity. It was described as the sound of the Winnie-the-Pooh toy going down a helter-skelter slide, getting alternately nearer to and further away from the participant. Stimuli were presented individually, and participants were asked to categorize each stimulus as sounding more like Winnie-the-Pooh or Tigger and Eeyore, although some participants chose to categorize them as sharp (Tigger) and smooth (Winnie-the-Pooh). The experimenter entered the participant's response on the laptop keyboard.

Prior to the first trial, all participants completed a practice session, requiring that they correctly label six practice stimuli ranging from very "smooth" Winnie-the-Pooh rise times (300 ms) to very "sharp" Tigger and Eeyore rise times (15 ms). Examples of stimuli for the experimental task are depicted in Goswami et al. (2002).

TOJ. For this task, stimuli were presented using the same Speech Pattern Audiometer II program that was used for the beat perception (five-ramp, rise-time

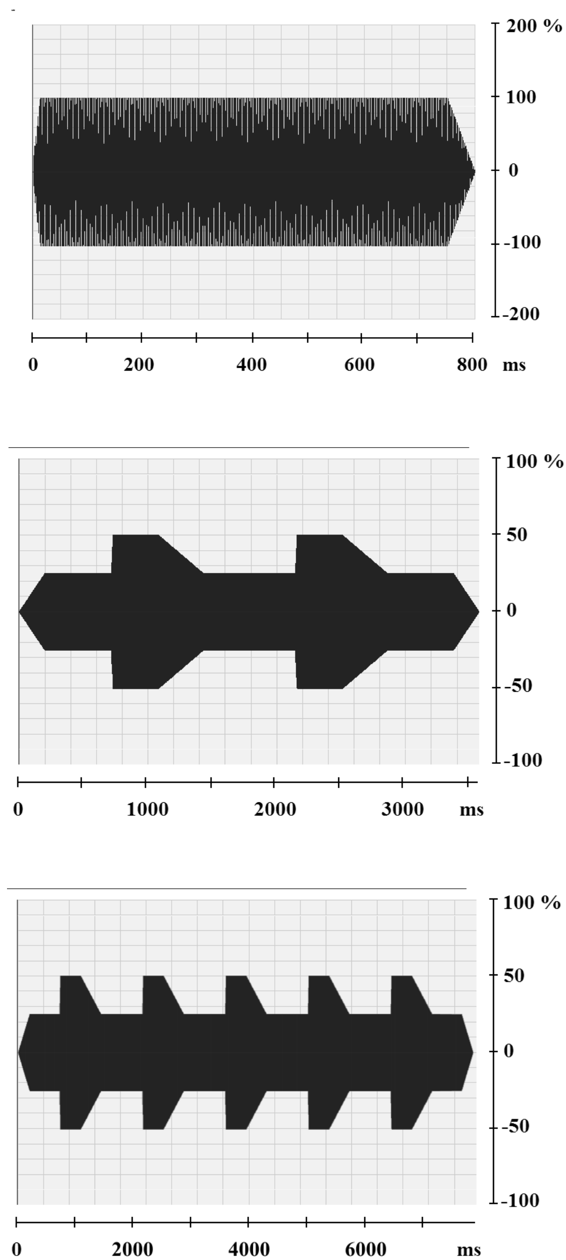

FIGURE 1 Schematic depiction of the rise-time stimuli with 15-ms onsets used in the (a) one-ramp, rise-time task; (b) two-ramp, rise-time task; and (c) five-ramp, rise-time task.

task). Participants' ability to judge the temporal sequence of two rapidly presented auditory stimuli was measured. A continuum of 40 stimuli was used in this task, each of which included two sounds with a fundamental frequency of 400 Hz, easily identifiable as the sound of a dog barking and the sound of a car horn honking. The task was identical to that used by Richardson et al. (2004) and similar to that used by Ramus et al. (2003). Both sounds were 115 ms in length and were presented with variable stimulus onset asynchrony (SOA), ranging from –405 ms (i.e., car first, with an inter-stimulus interval of 290 ms) to 405 ms (i.e., dog first, with an inter-stimulus interval of 290 ms), with a step size of about 20 ms. Participants were asked to judge which of the two sounds came first, and their responses were entered by the experimenter. A maximum of 40 trials were presented. Prior to the first trial, all participants completed a practice session, requiring that they correctly label six practice stimuli, ranging from easy SOAs of ±405 ms to difficult SOAs of ±74 ms. This task was included as a measure of rapid auditory processing.

RESULTS

The mean scores for the dyslexic and control groups on the phonological awareness, literacy, and memory tasks are displayed in Table 2, along with effect sizes (Cohen's *d*). Before group means on these variables were compared, the distribution of each variable was inspected for normality. All variables were found to have normal distributions, with the exception of the phonemic decoding and sight word subtests of the Test of Word Reading Efficiency. These two tasks had irregular distributions as a result of ceiling effects in the control group. The Test of Word Reading Efficiency scores for sight word and phonemic decoding are based on the number of words (or nonwords) read in 45 sec. Ceiling effects arose because 15 participants completed at least one of the two word lists in less than the allotted time. To capture this variance in reading rates for participants who finished the list, new variables were constructed for both the phonemic decoding and sight word subtests. These phonemic decoding and sight word scores were calculated by dividing the total number of words read correctly by the total time in which these words were read. Means and standard deviations for these two variables are displayed in Table 2.

One-way, between-participants ANOVAs with group (dyslexic, control) were conducted, taking each of the phonological processing, literacy, and memory tasks as dependent variables. A significant main effect of group was found for all measures. The dyslexic group was always impaired relative to the control group.

Mean dyslexic and control performance in the psychoacoustic tasks is displayed in Table 3. In the tasks using the dinosaur paradigm (intensity, one-ramp rise time, two-ramp rise time), performance is measured in terms of the 75% threshold: the point at which participants choose the appropriate stimulus with

TABLE 2
Scores and One-Way Analysis of Variance F-Values for the Phonological Awareness, Reading, and Memory Measures

Group	*Dyslexic* *M*	*Dyslexic* *SD*	*Control* *M*	*Control* *SD*	*F(1, 34)*	*Cohen's d*
PhAB RAN (sec)	35.33	6.23	30.58	3.77	7.657*	0.92
PhAB spoonerisms (maximum = 40)	33.3	3.48	36.89	2.35	12.904**	1.19
Phoneme deletion (maximum = 15)	10.94	2.24	13.50	1.54	14.976**	1.29
TOWRE sight word efficiency[a]	90.56	14.30	110.83	5.29	31.846**	1.88
TOWRE sight word rate (words/ pers sec)	1.92	.389	2.45	.251	23.446***	1.62
TOWRE phonemic decoding efficiency	85.28	8.80	110.78	8.08	81.926**	3.02
TOWRE phonemic decoding rate (words/per sec)	.389	.939	1.47	.198	53.983***	2.45
WRAT reading	101.83	7.45	114.67	5.28	35.528**	1.99
WRAT spelling	99.56	9.55	117.06	5.36	45.951**	2.26
Digit span[b]	9.33	1.91	12.56	3.36	12.486*	1.18

Note. PhAB = Phonological Assessment Battery; TOWRE = Test of Word Reading Efficiency; WRAT = Wide Range Achievement Test; RAN = Rapid Automatised Naming.

[a]TOWRE sight word efficiency, TOWRE phonemic decoding efficiency, WRAT reading, and WRAT spelling represent standard scores ($M = 100$, $SD = 15$).

[b]Digit span scores are standard scores ($M = 10$, $SD = 3$).

$^{**}p < .01$. $^{***}p < .001$.

75% accuracy. Thus, a participant with an intensity threshold of 2 dB reliably identified the louder of two tones with 75% accuracy when the tones differed by 2 dB. On the one- and two-ramp, rise-time tasks, threshold scores are reported out of 40. These tasks included a total of 40 stimulus levels, with stimulus rise time increasing logarithmically with increasing level. Participants with lower numerical thresholds were sensitive to smaller differences between the target and standard stimuli than participants with higher numerical threshold scores.

In the tasks using the SPA program (five-ramp rise time, TOJ), performance is measured in terms of the categorization slope, representing the extent to which participants reliably categorized the stimuli. Participants with more negative slopes categorized stimuli more reliably than participants with less negative slopes. Although this slope measure captures the extent to which participants were reliable in categorizing stimuli, it does not describe the extent to which participants were accurate in discerning category boundaries. Category boundary is not relevant in the five-ramp, rise-time task, as the stimuli in this task represent a continuum without a discernable boundary. However, in the TOJ task, there is a true boundary point at which the temporal order of the two sounds is indistinguishable.

TABLE 3
Scores and Number of Outliers Removed for the Psychoacoustic Measures. (Means for Thresholds Represent Jnds in Each Case)

		Dyslexic		*Control*			
Measure	*N removed*	*M*	*SD*	*M*	*SD*	*F(max df = 1, 35)*	*Cohen's d*
Intensity threshold (dB)	0	2.31	1.09	1.89	.85	1.697	.43
Two-ramp threshold (level)	2	7.892	5.168	7.481	3.918	.068	.09
Two-ramp threshold (ms)		104.61	51.46	82.82	29.49		
One-ramp threshold (level)	3	5.592	3.408	4.217	1.809	2.065	.50
One-ramp threshold (ms)		136.31	66.67	131.00	50.54		
Five-ramp slope	2	–.124	.077	–.318	.282	7.11**	.92
TOJ slope	2	–.196	.141	–.280	.138	3.127	.61
TOJ boundary (ms)	1	51.20	40.00	25.00	15.80	6.37**	.85
TOJ threshold (ms)	1	94.4	51.8	53.2	27.0	8.55***	.99

Note. TOJ = temporal order judgment; JND = just noticeable difference.
$^*p < .10$. $^{**}p < .05$. $^{***}p < .01$.

Thus, a boundary measure was calculated for the TOJ task. Scores on this measure represent the difference between the true category boundary (SOA = 0) and the point at which participants judged the category boundary to occur. In contrast to the category judgments required in the five-ramp, rise-time task, judgments on the TOJ task were verifiably correct or incorrect. Thus, a 75% threshold measure was calculated for the TOJ task. Threshold scores indicate the SOA at which participants categorized the order of stimuli with 75% accuracy. Recall that dog–car stimuli were 115 ms in length. Therefore, a participant with a threshold score of 150 would require a silent interval of 35 ms between the dog and car stimuli to judge their temporal order with 75% accuracy.

Inspection of the data reveals at least one extreme outlier on each of the psychoacoustic tasks with the exception of the intensity task. Thus, prior to all data analysis, points falling more than 1.5 inter-quartile ranges away from the 1st and 3rd quartile boundaries were omitted. Table 3 notes the number of outliers removed for each measure. A series of one-way, between-participants ANOVAs by group (dyslexic, controls) reveals a significant main effect of group only for the five-ramp, rise-time measure and the TOJ boundary and threshold measures. Recall that the TOJ boundary measure is an estimate of the SOA of subjective equality for a given participant, and that the TOJ threshold measure is an estimate of the

SOA at which a participant can perform at 75% accuracy. Because TOJ threshold is a more direct measure of accurate performance, only this measure was selected for subsequent analyses exploring relations with phonology and literacy.

To examine potential relations between the phonological processing, reading, math, and memory tasks and the psychoacoustic measures, a series of simple correlations was conducted. These correlations are displayed in Table 4. An examination of Table 4 reveals that nonverbal IQ was not related to the auditory variables of interest, with the exception of the two-ramp, rise-time task. The one-ramp and five-ramp measures and the TOJ task correlated with a number of the literacy and phonological processing variables, but not with performance in mathematics or with each other. Performance on the five- and two-ramp measures was, however, significantly correlated. The significant correlations found between auditory processing abilities and literacy and phonological skills did not seem to be a result of the attentional demands of the psychoacoustic (dinosaur) paradigm. A different auditory task using the same paradigm (intensity discrimination) was not significantly correlated with literacy or phonology.

To further explore the relations between the phonological processing, reading, math, and memory tasks and the psychoacoustic measures, a series of fixed-order multiple regressions was conducted with the following steps: Step 1 is age, Step 2 is full-scale IQ (verbal and nonverbal), and Step 3 is a psychoacoustic measure (intensity, one-ramp rise time, two-ramp rise time, five-ramp rise time, and TOJ threshold). For these analyses, raw scores were used in lieu of standardized scores, as all the regression models controlled for age. Outliers in the auditory tasks entered at Step 3 were removed for each regression, resulting in some variation between models in the variance accounted for in Steps 1 and 2. For each of these regression models, the change in R^2 was calculated to estimate the unique variation accounted for by the psychoacoustic measure. The change in R^2 values for each of these models is displayed in Table 5.

An examination of Table 5 reveals that two of the amplitude envelope onset tasks (one-ramp rise time and five-ramp rise time) and the TOJ threshold measure accounted for unique variation in the phonological and reading tasks. The rise-time measures explain up to 22% of additional variation in outcome measures, and TOJ threshold accounts for up to 26% of additional variation. The TOJ threshold predicted unique variance in spoonerisms (19%), phoneme deletion (12%), nonword reading rate (17%), and spelling (26%). The one-ramp, rise-time task predicted unique variance in phoneme deletion (22%), nonword reading rate (15%), and spelling (20%). The five-ramp, rise-time task only predicted unique variance in untimed reading (13%). The two-ramp, rise-time task was not a significant predictor of any of the outcome measures. As expected, no psychoacoustic variables account for significant unique variance in mathematics. Performance on the intensity task did not account for significant unique variance in any of the outcome measures, confirming that attentional difficulties with the psychoacoustic dinosaur

TABLE 4
Simple Correlations Between Experimental Measures

Measure	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*
1. Age	—	–.157	–.077	–.260	–.066	–.088	–.134	–.125	–.140	.189	–.035	–.295*	.090	.008	–.122	.151	.176
2. Verbal IQ		—	.106	–.125	.233	.104	–.004	–.332**	–.285*	–.073	–.018	–.031	–.147	–.168	–.074	–.077	–.101
3. Nonverbal IQ			—	.388**	.034	.392**	.264	.051	.169	.185	.171	.258	–.154	–.372**	–.133	–.009	–.202
4. WRAT math				—	.015	.065	.241	.162	.242	.065	.143	.272	.005	.033	–.135	.108	–.170
5. PhAB RAN					—	–.174	–.204	–.444***	–.347**	–.267	–.176	.371**	.030	–.110	–.239	.196	.411**
6. PhAB spoonerisms						—	.256	.262	.461***	.360**	.585****	.369**	–.110	–.280	–.106	–.171	–.454***
7. Phoneme deletion							—	.489***	.682****	.667****	.538***	.593****	–.044	–.103	–.431**	–.347**	–.414**
8. TOWRE sight word rate								—	.776****	.480***	.537***	.469***	.031	–.129	–.098	–.176	–.207
9. TOWRE phonemic decoding rate									—	.707****	.803****	.543***	–.091	.000	–.325*	–.327*	–.376**
10. WRAT reading										—	.685****	.462***	–.211	.007	–.347**	–.337*	–.141
11. WRAT spelling											—	.384**	–.229	–.036	–.431**	–.292	–.422**
12. Digit span												—	–.155	–.169	–.123	–.453***	–.448***
13. Intensity threshold													—	.363**	.271	.232	.195
14. Two– ramp threshold														—	.174	.357**	.188
15. One– ranp threshold															—	.252	.221
16. Five–ramp slope																—	.313*
17. TOJ threshold																	—

Note. WRAT = Wide Range Achievement Test; PhAB = Phonological Assessment Battery; TOWRE = Test of Word Reading Efficiency; TOJ = temporal order judgment; RAN = Rapid Automatised Naming.

*$p < .10$. *$p < .05$. **$p < .01$. ***$p < .001$.

TABLE 5
Change in R^2 Values for Stepwise Regressions Controlling for Age and IQ

	Phonological Awareness			*Reading and Spelling*				*Working Memory*	*Math*
Step (No. of Observations Excluded)	*PhAB RAN*	*Spoonerisms*	*Phoneme Deletion*	*Sight Word Rate*	*Phonemic Decoding Rate*	*Untimed Reading*	*Spelling*	*Digit Span*	*WRAT Math*
Step 1: Age	.006	.023	.079	.051	.052	.008	.025	.108	.115
Step 2: FSIQ	.040	.066	.004	.017	.012	.005	.005	.001	.002
Step 3: Intensity (0)	.007	.002	.000	.000	.013	.046	.045	.016	.002
Step 3: 2-Ramp (2)	.001	.045	.006	.002	.003	.002	.000	.025	.002
Step 3: 1-Ramp (3)	.047	.006	.216**	.024	.146*	.110	.202**	.030	.030
Step 3: 5-Ramp (2)	.048	.024	.107	.025	.096	.134*	.088	.172*	.022
Step 3: TOJ threshold (1)	.108	.194**	.122*	.086	.172*	.067	.256**	.174*	.026

Note. PhAB = Phonological Assessment Battery; WRAT = Wide Range Achievement Test; TOJ = temporal order judgment; RAN = Rapid Automatised Naming.

$^*p < .05$. $^{**}p < .01$.

paradigm cannot account for the significant auditory processing findings. However, the two psychoacoustic tasks that did not use the dinosaur paradigm, TOJ, and five-ramp rise time both show strong associations with short-term memory (digit span).

To explore whether the TOJ and rise-time measures made distinct or overlapping contributions to phonological processing and literacy, and to control for the potential influence of working memory, a second series of fixed-order multiple regressions was conducted. This time it was conducted with four steps: Step 1 is age, Step 2 is digit span, Step 3 is TOJ, and Step 4 is one-ramp rise time. A parallel set of equations reversed the order of the final two steps. The results are displayed in Table 6. As can be seen, the TOJ measure seems to share overlapping variance with the one-ramp, rise-time measure, whereas the reverse does not seem to be true. The TOJ measure at Step 4 does not account for any significant, unique variation in the phonological and literacy measures. The rise-time measure at Step 4 accounts for unique variance in rapid naming (11%), phoneme deletion (13%), untimed reading (10%), and spelling (16%).

To explore whether the TOJ and one-ramp, rise-time measures would contribute any unique variance to literacy once phonology was controlled for, a third series of fixed-order multiple regressions was conducted. This time it was conducted with four steps: Step 1 is age, Step 2 is full-scale IQ, Step 3 is phoneme deletion, and Step 4 is one-ramp rise time or TOJ. The results are displayed in Table 7. As can be seen, the relation between individual differences in sensitivity to rise time and individual differences in manipulating phonology appear to explain the relations with reading and spelling shown in Table 5 for rise time, but this is not the case for TOJ. TOJ threshold still predicts unique variance in spoonerisms (15%) and spelling (11%), although not in nonword reading rate (3%). This suggests that TOJ is not related to literacy via phonological awareness. The one-ramp, rise-time task no longer predicts unique variance in nonword reading rate (0%) or in spelling (5%), suggesting that the relations with literacy documented in Tables 5 and 6 arise via phonological awareness.

DISCUSSION

In this study, we compared high-functioning adults with developmental dyslexia on a range of auditory processing measures comprising three measures of rise time, a RAP measure (dog–car TOJ), and a measure of intensity discrimination. Prior studies reported difficulties in processing rise time for both children and adults with developmental dyslexia, and individual differences in rise-time sensitivity were predictive of literacy and phonology when IQ was controlled for (Goswami et al., 2002; Muneaux et al., 2004; Richardson et al., 2004; Thomson et al., 2006). Some prior studies of TOJ in adults with developmental dyslexia also

TABLE 6
Change in R^2 Values for Fixed-Order Hierarchical Regressions Using Two Auditory Measures

	Phonological Processing			*Reading and Spelling*				*Math*
Step (No. of Observations Excluded)	*PhAB RAN*	*Spoonerisms*	*Phoneme deletion*	*Sight Word Rate*	*Phonemic Decoding Rate*	*Untimed reading*	*Spelling*	*WRAT Math*
Step 1: Age	.007	.022	.081	.052	.052	.009	.025	.116
Step 2: Digit span	.178*	.135*	.294**	.300**	.276**	.316**	.150*	.023
Step 3: One-ramp	.097	.004	.137**	.006	.086	.099*	.186**	.037
Step 4: TOJ	.056	.101	.000	.003	.019	.002	.082	.001
Step 3: TOJ	.033	.104	.004	.004	.028	.000	.109*	.002
Step 4: One-ramp	.110*	.001	.134*	.005	.077	.100*	.159*	.035

Note. PhAB = Phonological Assessment Battery; WRAT = Wide Range Achievement Test; TOJ = temporal order judgment; RAN = Rapid Automatised Naming.

*$p < .05$. **$p < .01$.

TABLE 7
Change in R^2 Values for Stepwise Regressions When Phonology Is Controlled at Step 3

	Phonological Awareness		*Reading and Spelling*				*Working Memory*	*Maths*
Step (No. of Observations Excluded)	*PhAB RAN*	*Spoonerisms*	*Sight Word Rate*	*Phonemic Decoding Rate*	*Untimed Reading*	*Spelling*	*Digit Span*	*WRAT Math*
Step 1: Age	.006	.023	.051	.052	.008	.025	.108	.115
Step 2: Full scale IQ	.040	.066	.017	.012	.005	.005	.001	.002
Step 3: Phoneme deletion	.059	.046	.240**	.477**	.480**	.282**	.314**	.042
Step 4: One-ramp (3)	.146*	.001	.016	.004	.000	.053	.010	.018
Step 4: TOJ threshold (1)	.065	.151*	.013	.032	.000	.112*	.054	.000

Note. PhAB = Phonological Assessment Battery; WRAT = Wide Range Achievement Test; TOJ = temporal order judgment; RAN = Rapid Automatised Naming.

*$p < .05$. **$p < .001$.

found deficits at the group level in RAP (Kinsbourne et al., 1991; Laasonen et al., 2001; Ramus et al., 2003), but only Kinsbourne et al. found that individual differences in TOJ performance were related to literacy. In this study, deficits at the group level were found for the adults with dyslexia in the TOJ task and the five-ramp, rise-time tasks, but not in the other rise-time tasks or in the intensity measure. These problems were severe. Investigation of the number of adults falling below the 5th percentile based on control scores show that one half of the dyslexic participants fell below the 5th percentile of control performance in the TOJ task. Furthermore, no dyslexic participant performed above the 50th percentile of control performance in the five-ramp, rise-time task. In addition, 47% of the dyslexic adults performed below the 5th percentile of control performance in another measure of rise-time sensitivity—the one-ramp, rise-time task—even though group differences were not significant. However, only 4 adult participants with dyslexia showed severe deficits in both the one-ramp rise time and TOJ tasks, suggesting that in general these were distinct auditory deficits. The severity of these deficits is particularly striking when it is recalled that our dyslexic group is a literate population of adults who are functioning successfully in a top university.

Exploration of concurrent predictive relations with phonology and literacy also reveal distinctive patterns. Taking rise time first, when multiple regression equations were computed controlling for full-scale IQ, the one-ramp, rise-time measure explained significant unique variance in both phonological measures (phoneme deletion, 22%) and also literacy measures (nonword reading rate, 15%; spelling, 20%). When memory and TOJ were controlled for in further multiple regression equations, the one-ramp, rise-time measure still accounted for a significant 13% of unique variance in phoneme deletion and 16% unique variance in spelling, as well as 11% of unique variance in rapid automatized naming (another phonological measure) and 10% of unique variance in untimed reading. In contrast, when multiple regression equations were computed controlling for phonological skills (phoneme deletion) before exploring the unique contribution of rise-time processing to the outcome measures, no significant relations were found, except for that between one-ramp rise time and rapid automatized naming (assessed by the Phonological Assessment Battery). These analyses suggest that rise time is important for most literacy tasks because of its importance for phonological development. It appears to tap different auditory processing mechanisms to those tapped by the TOJ measure. This would be expected theoretically, as rise time should be important for syllabic representation, whereas TOJ should be important for phonemic representation (see Nittrouer, 2006).

When comparable multiple regression equations controlling for full-scale IQ were constructed for TOJ, then significant unique variance was explained in phoneme deletion (12%), nonword reading rate (17%), spelling (20%), and spoonerisms (19%). However, once memory and rise time were controlled for in further equations, no significant relations were found. This suggests that the relations found between TOJ and literacy–phonology depend on shared variance between TOJ and rise time and that TOJ does not, in itself, affect the development of phonological representations. In fact, when phonology (phoneme deletion) was controlled for in a further set of multiple regression equations, then TOJ continued to explain a significant 11% of unique variance in spelling and 15% of unique variance in spoonerisms. One possibility, therefore, is that these relations depend on shared variance with short-term memory or attention.

One notable effect in this study is the lack of uniformity between findings for the different rise-time tasks. Despite strong data with all of these tasks from young children with developmental dyslexia, in this study with adults only one-ramp, rise-time sensitivity was a consistent contributor to individual differences in literacy and phonology. Since running this study, we have also run further studies with young children in which we have compared directly the utility of the one- and two-ramp, rise-time measures used here in explaining individual differences in literacy and phonological development. These more recent studies showed that the one-ramp, rise-time measure is the consistently stronger measure of individual differences in amplitude envelope processing by young children. In particular, in a study of children with specific language impairment, the one-ramp, rise-time measure was the most sensitive in multiple regression equations predicting phonology and literacy, despite significant group differences for both the one- and the two-ramp, rise-time tasks used here (Corriveau et al., in press). Similarly, in their study of adults with developmental dyslexia, Thomson et al. (2006) reported that the one-ramp measure was the most sensitive in multiple regression equations predicting phonology and literacy. This is despite significant group differences again occurring for both the one- and two-ramp measures.[1] Clearly, the different rise-time measures are not equal measures of individual differences in sensitivity to amplitude envelope onsets. It is not obvious that psychometric factors explain these differential patterns, as the two-ramp, rise-time measure was a very significant predictor of individual differences in phonology in the study of children with developmental dyslexia reported by Richardson et al. (2004). In that study, the one-ramp, rise-time measure used here was not used. Only longitudinal studies using the same tasks with the same children as they mature are likely to be able to explain these intriguing patterns.

A second notable effect in this study is that although there is considerable overlap in the variance in phonology and literacy tasks shared by TOJ and rise time when rise time was entered first, the reverse was not the case when TOJ was entered first. In the latter case, rise time retained significant unique relations with phonology and literacy. Similar patterns have been found with children. Goswami et al. (2002) compared the relative contributions of a rise-time measure (the

[1]Note that chronologically the current study was carried out before that reported by Thomson, Fryer, Maltby, and Goswami (2006).

five-ramp, rise-time measure) and a TOJ measure (a rapid frequency detection measure modeled closely on Tallal, 1980) by entering each variable at Step 5 in regression equations predicting reading development (the prior four steps were age, IQ, and vocabulary as Steps 1, 2, and 3 respectively, with one of the auditory measures at Step 4 [rise time or TOJ]). In this study with 9- to 11-year-old dyslexic participants, the rise-time measure contributed 19% of unique variance to reading ($p < .001$) once TOJ was controlled for, whereas the TOJ measure contributed only 4% of unique variance to reading when rise time was controlled for ($p < .05$). This is interpreted as showing that a large proportion of the variance in reading predicted by the TOJ task was shared with rise-time sensitivity, but not vice versa. Why should the two auditory measures be related in this way? One possibility is that this overlap reflects the fact that judgments about temporal order require the accurate detection of P-centers, which require rise-time sensitivity (see Hirsh, 1959). However, the accurate detection of rates of change of amplitude envelope onsets does not require TOJs. Certainly the relation between the two tasks deserves further investigation.Overall, the results of this study indicate that auditory processing of amplitude envelope onsets is related to literacy outcomes even after impressive literacy skills have been acquired, via phonological awareness. This does not support the theoretical viewpoint advanced by Ramus (2003) that auditory processing difficulties have little connection with phonology and reading. In the study presented here, auditory processing difficulties are linked with phonology, reading, and spelling, but not with mathematics. This rules out potential causal explanations based on general attentional deficits. In summary, our results indicate that impairments in the auditory processing of amplitude envelope onsets and in making accurate TOJs characterize high-functioning dyslexic adults even when IQ is controlled for and current dyslexic status is ascertained. The presence of these auditory deficits in adults with developmental dyslexia means that it is unlikely that the auditory impairments observed in children with developmental dyslexia ameliorate with maturation, at least as far as rise time is concerned (see also Hämäläinen et al., 2005; Thomson et al., 2006). Future research should determine the relation between TOJ tasks and rise-time tasks, as theoretically these tasks measure different aspects of basic auditory processing (local vs. global). It should also explore the extent to which the results from this study can be extended to the adults with developmental dyslexia in other languages.

REFERENCES

Ahissar, M., Protopapas, A., Reid, M., & Merzenich, M. M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Sciences of the United States of America, 97*(12), 6832–6837.

Amitay, S., Ahissar, M., & Nelken, I. (2002). Auditory processing deficits in reading disabled adults. *Journal of the Association for Research in Otolaryngology, 3,* 302–320.

Amitay, S., Ben-Yehudah, G., Banai, K., & Ahissar, M. (2002). Disabled readers suffer from visual and auditory impairments but not from a specific magnocellular deficit. *Brain*, *125*(10), 2272–2284.

Banai, K., & Ahissar, M. (2004). Poor frequency discrimination probes dyslexics with particularly impaired working memory. *Audiology and Neuro-Otology, 9*(6), 328–340.

Ben-Yehudah, G., Banai, K., & Ahissar, M. (2003). Patterns of deficit in auditory temporal processing among dyslexic adults. *Neuroreport, 15*(4), 627–631.

Burkhard, M. D., & Sachs, R. M. (1975). Anthropometric manikin for acoustic research. *Journal of the Acoustical Society of America, 58*(1), 214–222.

Corriveau, K. H., Pasquini, E., & Goswami, U. (2007). Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech, Hearing & Language Research, 50,* 1–20.

Curtin, S., Mintz, T. H., & Christiansen, M. H. (2005). Stress changes the representational landscape: Evidence from word segmentation. *Cognition, 96,* 233–262.Cutler, A., & Mehler, J. (1993). The periodicity bias. *Journal of Phonetics, 21*(1–2), 103–108.

de Boysson–Bardies, B., Sagart, L., Halle, P., & Durand, C. (1986). Acoustic investigations of cross-linguistic variability in babbling. In B. Lindblom & R. Zetterstrom (Eds.), *Precursors of early speech* (pp. 113–126). New York: Stockton Press.

Findlay, J. M. (1978). Estimates on probability functions: A more virulent PEST. *Perception and Psychophysics, 23,* 181–185.

Finney, D. J. (1971). *Probit analysis* (3rd ed.). Cambridge, England: Cambridge University Press.

Fernald, A., Taeschner, T., Dunn, J., & Papoušek, M. (1989). A cross-language study of prosodic modifications in mothers' and fathers' speech to preverbal infants. *Journal of Child Language, 16*(3), 477–501.

Foxton, J. M., Talcott, J. B., & Witton, J. B. (2003). Reading skills are related to global, but not local, acoustic pattern perception. *Nature Neuroscience, 6*(4), 343–344.

France, S. J., Rosner, B. S., Hansen, P. C., Calvin, C., Talcott, J. B., Richardson, A. J., et al. (2002). Auditory frequency discrimination in adult developmental dyslexics. *Perception & Psychophysics, 64,* 169–179.

Fredrickson, N. (Ed.). (1996). *Phonological assessment battery: Research edition.* London: National Foundation for Educational Research (NFER-Nelson).

Galaburda, A. M., LoTurco, J., Ramus, F., Fitch, H. R., & Rosen, G. D. (2006). From genes to behaviour in developmental dyslexia. *Nature Neuroscience, 9,* 1213–1217.

Goswami, U. (2003). Why theories about developmental dyslexia require developmental designs. *Trends in Cognitive Sciences, 7*(12), 534–540.

Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., et al. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences of the United States of America, 99*(16), 10911–10916.

Griffiths, Y. M., Hill, N. I., Bailey, P. J., & Snowling, M. J. (2003). Auditory temporal order discrimination and backward recognition masking in adults with dyslexia. *Journal of Speech, Language, & Hearing Research, 46*(6), 1352–1366.

Hämäläinen, J., Leppänen, P. H. T., Torppa, M., Müller, K., & Lyytinen, H. (2005). Detection of sound rise time by adults with dyslexia. *Brain and Language, 94,* 32–42.

Helenius, P., Uutela, K., & Hari, R. (1999). Auditory stream segregation in dyslexic adults. *Brain, 122*(5), 907–913.

Hill, N. I., Bailey, P. J., Griffiths, M., & Snowling, M. J. (1999). Frequency acuity and binaural masking release in dyslexic listeners. *Journal of the Acoustical Society of America, 107*(4), 2291–2294.

Hirsh, I. J. (1959). Auditory perception of temporal order. *Journal of the Acoustical Society of America, 31,* 759–776.

Ivry, R. B., & Keele, S. W. (1989). Timing functions and the cerebellum. *Journal of Cognitive Neuroscience*, *1*(2), 136–152.

Jusczyk, P. W., Houston, D. M., & Newsome, M. (1999). The beginnings of word segmentation in English–learning infants. *Cognitive Psychology, 39,* 159–207.

Kinsbourne, M., Rufo, D. T., & Gamzu, E. (1991). Neuropsychological deficits in adults with dyslexia. *Developmental Medicine & Child Neurology, 33*(9), 763–775.

Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews Neuroscience, 5,* 831–843.

Laasonen, M., Service, E., & Virsu, V. (2001). Temporal order and processing acuity of visual, auditory and tactile perception in developmentally dyslexic young adults. *Cognitive, Affective & Behavioral Neuroscience, 1*(4), 394–410.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49,* 467–477.

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of Dyslexia, 53,* 1–14.

Marshall, C. M., Snowling, M. J., & Bailey, P. J. (2001). Rapid auditory processing and phonological ability in normal readers and readers with dyslexia. *Journal of Speech, Language, & Hearing Research, 44*(4), 925–940.

McAnally, K. I., & Stein, J. F. (1996). Auditory temporal coding in dyslexia. *Proceedings of the Royal Society of London, Series B: Biological Sciences, 263,* 961–965.

McArthur, G. M., & Bishop, D. V. M. (2001). Auditory perceptual processing in people with reading and oral language impairments: Current issues and recommendations. *Dyslexia, 7,* 150–170.

McDougall, S., Hulme, C., Ellis, A., & Monk, A. (1994). Learning to read: The role of short-term memory and phonological skill. *Journal of Experimental Child Psychology, 58,* 112–133.

Menell, P., McAnally, K. I., & Stein, J. F. (1999). Psychophysical sensitivity and physiological response to amplitude modulation in adult dyslexic listeners. *Journal of Speech Language and Hearing Research, 42*(4), 797–803.

Morton, J., Marcus, S. M., & Frankish, C. (1976). P-centres. *Psychological Review, 83,* 405–408.

Muneaux, M., Ziegler, J. C., Truc, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: Evidence from French. *Neuroreport, 15*(7), 1–5.

Nicolson, R. I., Fawcett, A. J., & Dean, P. (1995). Time estimation deficits in developmental dyslexia: Evidence of cerebellar involvement. *Proceedings of the Royal Society of London, Series B: Biological Sciences*, *259*(1354), 43–47.

Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems? *Journal of Speech Language and Hearing Research, 42,* pp. 925–942.

Nittrouer, S. (2006). Children hear the forest. *Journal of the Acoustical Society of America, 120*(4), 1799–1802.

Port, R. F. (2003). Meter and speech. *Journal of Phonetics, 31,* 599–611.

Ramus, F. (2003). Developmental dyslexia: Specific phonological deficit or general sensorimotor dysfunction? *Current Opinion in Neurobiology, 13,* 212–218.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., et al. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain, 126,* 841–865.

Remez, R. E., Rubin, P. E., Pisoni, D. B., & Carrell, T. B. (1981). Speech perception without traditional speech cues. *Science, 212,* 947–949.

Richardson, U., Thomson, J., Scott, S. K., & Goswami, U. (2004). Auditory processing skills and phonological representation in dyslexic children. *Dyslexia: An International Journal of Research & Practice, 10*(3), 215–233.

Rocheron, I., Lorenzi, C., Fullgrabe, C. & Dumont, A. (2002). Temporal envelope perception in dyslexic children. *Neuroreport, 13*(3), 1683–1687.

Rosen, S. (2003). Auditory processing in dyslexia and specific language impairment: Is there a deficit? What is its nature? Does it explain anything? *Journal of Phonetics, 31*(3–4), 509–527.

Sperling, A. J., Lu, Z. L., Manis, F. R., & Seidenberg, M. S. (2005). Deficits in perceptual noise exclusion in developmental dyslexia. *Nature Neuroscience, 8,* 862–863.

Snowling, M. J. (2000). *Dyslexia.* Oxford, England: Blackwell.

Stein, J. F., & McAnally, K. (1995). Auditory temporal processing in developmental dyslexics. *Irish Journal of Psychology, 16*(3), 220–228.

Stein, J., & Talcott, J. (1999). Impaired neuronal timing in developmental dyslexia: The magnocellular hypothesis. *Dyslexia: An International Journal of Research & Practice, 5*(2), 59–77.

Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading impaired: A critical review of the evidence. *Psychonomic Bulletin & Review, 2*(4), 508–514.

Surányi, S., Csépe, V., Richardson, U., Thomson, M. J., Honbolygó, F., & Goswami, U. (2006). *Sensitivity to rhythmic parameters in dyslexic children: A comparison of Hungarian and English*. Paper submitted for publication.

Tallal, P. (1980). Auditory temporal perception, phonics and reading disabilities in children. *Brain and Language, 9,* 182–198.

Tallal, P. (2004). Opinion: Improving language and literacy is a matter of time. *Nature Reviews Neurosciences, 5*(9), 721–728.Thomson, J. M., Fryer, B., Maltby, J., & Goswami, U. (2006). Auditory and motor rhythm awareness in adults with dyslexia. *Journal of Research in Reading, 29,* 334–348.

Tallal, P. & Piercy, M. (1973). Defects of non–verbal auditory perception in children with developmental aphasia. *Nature, 241,* 468–469.

Torgesen, J., Wagner, R. K., & Rashotte, C. (1999). *Test of word reading efficiency (TOWRE).* Austin, TX: Pro-Ed.

Wechsler, D. (1998). *The Wechsler Adult Intelligence Scale* (3rd ed.). London: The Psychological Corporation.

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence.* San Antonio, TX: The Psychological Corporation.

Wilkinson, G. S. (1993). *Wide Range Achievement Test 3.* Wilmington, DE: Wide Range.

Witton, C., Stein, J. F., Stoodley, C. J., Rosner, B. S., & Talcott, J. B. (2002). Separate influences of acoustic AM and FM sensitivity on the phonological decoding skill of impaired and normal readers. *Journal of Cognitive Neuroscience, 14,* 866–874.

Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., et al. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology, 8*(14), 791–797.

Wolff, P. (2002). Timing precision and rhythm in developmental dyslexia. *Reading & Writing, 15,* 179–206.