Journal of Learning Disabilities

http://ldx.sagepub.com/

Auditory Processing and Early Literacy Skills in a Preschool and Kindergarten Population

Kathleen H. Corriveau, Usha Goswami and Jennifer M. Thomson

J Learn Disabil 2010 43: 369 originally published online 10 May 2010
DOI: 10.1177/0022219410369071

Hammill Institute on Disabilities

Journal of Learning Disabilities
43(4) 369–382
© Hammill Institute on Disabilities 2010
Reprints and permission:
sagepub.com/journalsPermissions.nav
DOI: 10.1177/0022219410369071
http://journaloflearningdisabilities
.sagepub.com
SAGE

Auditory Processing and Early Literacy Skills in a Preschool and Kindergarten Population

Kathleen H. Corriveau[1], Usha Goswami[2], and Jennifer M. Thomson[1]

Abstract

Although the relationship between auditory processing and reading-related skills has been investigated in school-age populations and in prospective studies of infants, understanding of the relationship between these variables in the period immediately preceding formal reading instruction is sparse. In this cross-sectional study, auditory processing, phonological awareness, early literacy skills, and general ability were assessed in a mixed sample of 88 three- to six-year-old children both cross-sectionally and longitudinally. Results from both cross-sectional and longitudinal analyses suggest the importance of early auditory rise time sensitivity in developing phonological awareness skills, especially in the development of rhyme awareness.

Keywords

auditory processing, phonological awareness, preschool, kindergarten, rise time

Children who struggle to learn to read in the primary grades will likely manifest continued reading difficulties as they progress through their school careers (Astrom, Wadsworth, & DeFries, 2007; Francis, Shaywitz, Stuebing, Shaywitz, & Fletcher, 1996; Konold, Juel, & McKinnon, 2003). Many of these children are at a disadvantage because of the prereading skills with which they enter the classroom. Therefore, it is essential to identify areas of difficulty even before kindergarten, so that the disadvantages faced by children at risk for reading failure can be minimized before reading instruction begins. In this study our aim was to better understand the development of prereading skills, with a view to improving our ability to detect and intervene effectively with preschoolers at risk for reading failure.

One of the most powerful findings of the last decades is the relationship between one specific prereading skill, phonological awareness, and early reading ability. Phonological awareness is a unified skill that manifests as an ability to recognize, discriminate, and manipulate the sounds in one's language. The grain size of children's phonological sensitivity changes with development, with awareness of the grain sizes of syllable and rhyme emerging as part of natural language acquisition processes (Ziegler & Goswami, 2005, 2006). Early phonological sensitivity at these larger grain sizes in turn predicts how rapidly children will acquire letter-size sound units, or phonemic awareness, as letters are taught (Anthony & Francis, 2005). Once it can be measured, phonemic awareness, alongside letter knowledge, has consistently been found to account for 40% to 60% of the variance in a kindergartner's subsequent reading achievement (Scanlon & Vellutino, 1996; Share, Jorm, Maclean, & Matthews, 1984; Wagner, Torgesen, & Rashotte, 1994). Bryant and colleagues showed that for younger children (e.g., 3-year-olds), awareness of larger phonological units, assessed via rhyming ability, correlated strongly ($r = .59$) with subsequent reading ability (at 6 years of age; (Maclean, Bryant, & Bradley, 1987). Similar findings have been reported in other languages (e.g., Chinese; see Ho & Bryant, 1997).

Although these findings are powerful, there are several limitations. First, the predictive relations found for phonemic awareness and letter knowledge are arguably byproducts of the reading acquisition process itself. It is therefore unclear whether they are measuring weak precursor skills per se or just alphabetic exposure, dependent upon varied home and preschool environments. There is no evidence to suggest that children who are not exposed to early literacy materials before school will be unable to acquire these skills upon school entry (Wood, 2004) (although early

---

[1]Harvard Graduate School of Education, Cambridge, MA, USA
[2]Centre for Neuroscience in Education, University of Cambridge, Cambridge, UK

Corresponding Author:
Jennifer M. Thomson, Harvard Graduate School of Education,
14 Appian Way, Cambridge, MA 02138, USA
Email: thomsoje@gse.harvard.edu.

exposure may confer certain advantages, and individual differences in acquiring phonemic awareness and letter-sound knowledge following school entry would still be expected to show a relationship to large grain size phonological sensitivity). Second, as Scarborough noted (1998), phonemic awareness is consistently stronger at predicting reading ability, as opposed to reading disability, which creates a significant problem if phonemic awareness is used in isolation as a diagnostic tool.

Phonological awareness prior to literacy acquisition is likely to depend upon the integrity of lower level auditory processing. Logically, if an individual's auditory processing is compromised, accurate reflection upon the sounds in words will not be possible, resulting in impaired phonological processing. Auditory processing integrity thus may be a valuable measure in predicting variation in phonological awareness and subsequent reading progress that is not itself a product of reading instruction. Speech is a complex acoustic signal, and models of the auditory processing of speech have changed in recent years. Clearly, acoustic information is primarily temporal, changing moment by moment, and this was recognized in early attempts to link auditory processing to phonological information (Tallal, 1980). Classical models assumed that rapid changes in frequency and intensity (formants) were the acoustic correlates of phonemes (Blumstein & Stevens, 1981). Accordingly, most research exploring links between auditory processing and prereading ability focused on rapidly varying temporal cues (Tallal, 1980; Tallal & Piercy, 1973, 1974). Tallal and her colleagues devised the Auditory Repetition Test (ART) to measure rapid auditory processing abilities in children. This test requires same/different and temporal order judgments of two 75-msec nonverbal complex tones differing only in fundamental frequency. Assessing a group of twenty 8- to 12-year-old reading-disabled children alongside age-matched controls, Tallal (1980) found that 45% of the reading-disabled children performed more poorly than the lowest performing controls, but only in the short (≤305 ms) ISI conditions. She concluded that the children with specific reading disability evinced an auditory deficit specific to the perception of rapidly changing or brief sounds. Given that discrimination of many phonemic contrasts without context depends upon the ability to process frequency formant transitions and voice onset times occurring within very brief temporal windows, the accompanying assumption was that difficulties in rapid temporal processing might lead to degraded phonological encoding.

Tallal's findings with school-age children with reading disabilities, as well as those with specific language impairment (Tallal & Piercy, 1973, 1974), generated intense interest in the relationship between auditory processing and reading ability and led to much use of the ART, with varying success at replication (De Martino, Espesser, Rey, & Habib, 2001; Heiervang, Stevenson, & Hugdahl, 2002; Marshall, Snowling, & Bailey, 2001; Nittrouer, 1999; Reed, 1989; Rey, De Martino, Espesser, & Habib, 2002; Waber et al., 2001). Among the handful of studies that examined the relationship between auditory processing and prereading and/or emergent literacy skills in children before first grade, Tallal's ART has predominated as the index of auditory processing used (Heath & Hogben, 2004; Hood & Conlon, 2004; Share, Jorm, Maclean, & Matthews, 2002; but note Boets, Wouters, van Wieringen, De Smedt, & Ghesquire, 2008). Share et al. (2002), for example, administered a battery of phonological and language measures, alongside the ART, to a group of 500 unselected kindergartners (mean age at beginning of study: 5 years, 4 months), who were followed through to third grade (mean age 8 years, 10 months). Although the results using the ART confirmed the presence of auditory processing deficits in children later classified as reading disabled, certain findings were anomalous with Tallal's rapid temporal processing hypothesis: Children classified as reading disabled demonstrated difficulties at school entry with the long interstimulus intervals (ISIs) rather than the short ISIs. Furthermore, early deficits on the ART did not predict later phonological impairment, pseudoword processing difficulties, or specific reading disability.

In a study by Heath and Hogben (2004), 108 kindergartners selected as having either good or poor phonological awareness (mean age at beginning of study across groups was approximately 5 years, 6 months) were assessed on a similar range of phonological, language, and literacy tests and followed until second grade. In a discriminant analysis to identify poor readers at second grade from the original poor phonological awareness group, the repetition test did not improve the classification accuracy offered by phonological and oral language measures.

Interpretation of these results with kindergartners is tempered by the context of increasing criticisms of both the ART and the accompanying rapid temporal processing hypothesis. Empirically, the ability to measure auditory processing thresholds using a nonadaptive measure reliably has been questioned and may be a factor contributing to the failures to replicate Tallal's original findings. The ART also imposes significant nonperceptual attentional demands on top of the frequency discrimination/identification component, including the ability to categorize sounds as well as associate a sound with a contingent response. Conceptually, the theoretical link between rapid auditory processing deficits and impaired perception of rapidly changing phonetic information has been weakened by much evidence of difficulties for individuals with dyslexia on nonrapid tasks, for example, detection of frequency modulation (FM) at 2 Hz (Witton et al., 1998) and amplitude modulation discrimination (Goswami et al., 2002), as well as nonimpaired performance on other rapid auditory processing tasks, for example, perceiving a short tone following a masker (forward masking; Rosen & Manganari, 2001). Studdert-Kennedy and Mody (1995) also argued that rapid and brief presentation of invariant tone stimuli does not necessarily equate with temporal processing, of which the defining feature is stimulus change over time. In summary, although there is some evidence that preschool auditory processing as measured by the ART does relate to early reading skills, this evidence is clouded by reliance on a measure that is theoretically very difficult to interpret and empirically inconsistent.

A complementary approach is to explore the potential importance of slower temporal information in speech for phonological development (Nittrouer, 2006). Slower amplitude and frequency modulations are direct measures of stimulus change over time and relate to an alternative way of modeling the acoustic information in speech. This alternative model factors the speech signal mathematically into the product of a slowly varying envelope (also called amplitude modulation) and a rapidly varying fine time structure (Smith, Delgutte, & Oxenham, 2002). Experiments with adults suggest that the slowly varying envelope cues are the most critical for speech intelligibility (e.g., Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). Envelope cues are suprasegmental, primarily facilitating syllabic segmentation of the acoustic signal and the perception of prosodic-level features such as speech rhythm and stress. If preliterate phonological awareness is at the coarser grain sizes of syllables and rimes, then assessing the integrity of auditory processing that supports this level of perception makes intuitive sense. Accurate perception of speech envelope cues for phonological development has been explored previously in the studies of Goswami and colleagues (e.g., Corriveau, Pasquini, & Goswami, 2007; Goswami et al., 2002; Richardson, Thomson, Scott, & Goswami, 2004; Thomson & Goswami, 2008).

Theoretically, the slowly varying fluctuations in fundamental frequency, amplitude, and duration in the speech envelope can be measured independently (see Richardson et al., 2004). However, prior investigations suggest that an important integrative cue is rise time, which is the rate of change in the amplitude envelope onsets that correspond to each syllable in the speech stream (the amplitude “beats”). In natural speech, rise time will incorporate changes in intensity, duration, and fundamental frequency. If a syllable onsets rapidly, for example, via a plosive (“ba”, “da”), rise time will be fast and the perceived change in intensity will be relatively sharp. If a syllable onsets more slowly, for example, via a sonorant (“la”, “wa”), rise time will be extended in duration and the perceived change in intensity will be more gentle. There is growing evidence that amplitude and duration changes play a greater role in prosodic prominence than previously recognized (Choi, Hasegawa-Johnson, & Cole, 2005; Greenberg, 1999; Kochanski, Grabe, Coleman, & Rosner, 2005). Goswami and colleagues’ prior studies suggest that individual differences in perceiving rise time or changes in amplitude modulation predict unique variance in phonological processing and literacy ability in school age children (Goswami et al., 2002; Richardson et al., 2004; Thomson & Goswami, 2008). Rise time is also important in predicting individual differences in phonology and literacy in adult populations (Pasquini, Corriveau, & Goswami, 2007; Thomson, Fryer, Maltby, & Goswami, 2006) and across a number of different languages (Hamalainen, Leppanen, Torppa, Muller, & Lyytinen, 2005; Muneaux, Ziegler, True, Thomson, & Goswami, 2004; Suranyi et al., in press). Amplitude onsets are a very important aspect of the temporal structure of the speech envelope, and so reduced sensitivity to onset differences will also result in reduced sensitivity to speech rhythm and syllabic segmentation of the speech stream. These results converge with studies that have found direct links between young children’s speech rhythm sensitivity and phonological awareness and reading skills (Holliman, Wood, & Sheehy, 2008; Whalley & Hansen, 2006).

The most recent longitudinal study to feature kindergartners (Boets et al., 2008) emphasizes the need to look beyond perception of rapid phonemic information to fully understand the relationship between auditory processing and prereading ability. Boets et al. tested 62 five-year-olds (mean age 5 years, 6 months) using a 2-Hz frequency modulation task similar to that of Witton et al. (1998) and followed up with literacy assessment at the end of the first grade (mean age 6 years, 9 months). A 2-Hz modulation is a slowly varying speech envelope cue that will yield prosodic-level phonological information. Using an adaptive paradigm, children were required to detect a 2-Hz sinusoidal frequency modulation within a 1-Hz carrier tone with varying modulation depth. Frequency modulation detection predicted both speech perception and phonological awareness at the end of first grade, the latter of which was a unique predictor of reading and spelling. The findings reported by Boets et al. (2008) suggest that investigation of the role of auditory processing at the level of speech envelope cues may be particularly promising in predicting later risk using preschool age groups.

Our goal in this study was to explore both concurrent and predictive relationships between preschoolers’ amplitude rise time sensitivity and their emerging phonological and literacy skills. In Goswami’s studies with older populations, a computer-based adaptive discrimination task has been used (Bishop, 2001). In this task, participants see two dinosaur characters on the computer screen, each of which makes a sound. The sounds used are sine wave tones that have a consistent rate of amplitude modulation. Because speech itself varies across so many parameters, sine

Table 1. Mean (Standard Deviation) Participant Characteristics by Age at First Time of Testing

	3-Year-Olds	4-Year-Olds	5-Year-Olds	6-Year-Olds	*F*(3, 84)
n	16	29	27	16	
Age	3;7 (0;4)	4;6 (0;4)	5;5 (0;4)	6;6 (0;4)	237.20***
Verbal IQ[a]	103.5 (12.9)	104.0 (13.63)	104.3 (10.3)	104.4 (8.2)	0.02
Nonverbal IQ[b]	102.1 (13.1)	106.9 (9.4)	100.6 (7.5)	101.3 (10.7)	2.24
Full-scale IQ[c]	103.5 (11.8)	106.6 (9.4)	103.0 (8.3)	103.4 (6.7)	0.90
Vocabulary[d]	99.8 (11.2)	98.9 (15.3)	100.1 (11.5)	106.8 (11.4)	2.32

[a] Kaufman Brief Intelligence Test-2 (KBIT) Verbal Standard score ($M = 100, SD = 15$).
[b] KBIT Nonverbal Standard score ($M = 100, SD = 15$).
[c] KBIT IQ Composite standard score ($M = 100, SD = 15$).
[d] Peabody Picture Vocabulary Test–III standard score ($M = 100, SD = 15$).
***$p < .001$.

waves are used to allow controlled variation of rise time of each amplitude modulation. If a rise time is fast, this results in the percept of a strong syllable beat, whereas if the rise time is slower, the percept of a distinct syllable beat is not present (Scott, 1998). A continuum of sine waves was created for the task, with varied rise times. Participants hear a pair of sine waves and have to decide which sound has the stronger beat. The task is adaptive (using a PEST algorithm, Findlay, 1978) so that assessment can focus most on trials at the participant's maximal level of competence. After 40 trial pairs, a threshold value is generated that represents the smallest difference between sounds that the participant can detect with 75% accuracy.

To adapt the task for younger children, two modifications were made for the present study. First, the rise time difference (in milliseconds) between the longest and shortest rise times on the continuum was expanded from 285 to 585 ms. This modification increased the perceptual difference between stimuli in the initial trials to optimize children's success and engagement on the task. The second modification was to add greater scaffolding to the practice trials (see Methods section). To maintain the reliability of the adaptive psychoacoustic procedure, the maximum trial number was kept at 40 trials. Using the same adaptive software, we also assessed children's sensitivity to intensity differences, that is, nonmodulating amplitude change. In previous studies with older populations, this parameter has not been strongly associated with phonological awareness or reading ability (Pasquini et al., 2007; Richardson et al., 2004) and so was included primarily to act as a control task for the demands of the psychoacoustic assessment procedure. We also wanted to compare the associations to phonological awareness and reading between amplitude rise time sensitivity, an envelope cue, with a measure of sensitivity to more transient and rapid cues. To this end a frequency sweep discrimination task was included in the task battery.

Method

Participants

Eighty-eight children aged between 3 and 6 years old participated in this study. Only children who had no diagnosed additional learning difficulties (e.g., dyspraxia, attention-deficit/hyperactivity disorder, autistic spectrum disorder, dyslexia), a nonverbal IQ above 80, and English as their first language spoken were included. Participant characteristics are shown in Table 1. Note that one-way analysis of variance (ANOVA) with age group indicated no significant differences across the age groups in verbal IQ, nonverbal IQ, full-scale IQ, or vocabulary ability. All children attended the same school, which serves students from Pre-K to grade 8. Formal reading instruction started in this school in grade 1, when the children were 6 years old. Because of the small number of children in this study who had received reading instruction, data on reading ability is reported only for 5- and 6-year-old children.

Of these 88 children, 25 were available for additional testing at two 6-month intervals, for a total of 3 time points. This allowed us to explore early reading development from both a cross-sectional and a longitudinal perspective.

Tasks

Psychometric Tasks. All children received psychometric tests of IQ, phonological awareness, letter-sound knowledge, and vocabulary. Intelligence was measured through the three subtests from the Kaufman Brief Intelligence Test-2 (KBIT; Kaufman & Kaufman, 1997). *Verbal knowledge* measured children's' ability to match a spoken word with one of four pictures. *Matrices* measured children's ability to match a picture/abstract design with one of four pictures. *Riddles* measured children's ability to choose a picture or a word when given a clue about the word.

Phonological awareness and letter-sound knowledge were measured through five subtests of the Pre-Reading

Inventory of Phonological Awareness (PIPA; Dodd, Crosbie, McIntosh, Teitzel & Ozanne, 2003):

1. Syllable Segmentation—the student's ability to segment words of 2 to 5 syllables. Students were given 12 words and were asked to clap the number of syllables while saying the word.
2. Rhyme Awareness—the student's ability to identify the nonrhyming word from a set of four words. The experimenter pointed to four pictures while saying the words. Students were asked to choose the word that did not sound the same as the other words.
3. Alliteration Awareness—the student's ability to identify the word that does not begin with the same sound from a set of four words. The experimenter pointed to four pictures while saying the words. Students were asked to choose the word that sounded different at the beginning.
4. Sound Isolation—the student's ability to identify the first sounds in a word. The experimenter pointed to a picture while saying the word. Students were asked to say the first sound in the word.
5. Letter-Sound Knowledge—the student's ability to say the sound that corresponds to a letter. The experimenter pointed to a letter or letter blend and asked the child what it sounded like.

Receptive vocabulary was measured through the Peabody Picture Vocabulary Test–III (PPVT; Dunn & Dunn, 1997). Students were asked to match a spoken word with one of four pictures.

Early reading ability was measured through two subtests of the Woodcock Word Reading Mastery Tests–Revised (Woodcock, 1987).

1. Letter-Word Identification—the student's ability to correctly name letters and words. The experimenter pointed to words on the page and asked the child to sound out the word.
2. Word Attack—the student's ability to correctly sound out nonwords. The experimenter pointed to the word and asked the child to sound it out just like they would a real word.

Psychoacoustic Tasks. All psychoacoustic stimuli were presented binaurally through headphones at 73 dB sound pressure level (SPL). Children's responses were recorded on the keyboard by the experimenter. All psychoacoustic measures used the "Dinosaur game" threshold estimation program created by Dorothy Bishop (Oxford University, 2001), which used a two-interval forced choice (2IFC) paradigm with a 500-ms ISI. In all tasks using the Dinosaur program, the child heard two cartoon characters make a sound and was asked to choose which character produced the target sound, according to the different instructions below. Feedback was given online throughout the course of the experiment. The Dinosaur program used the more virulent form of PEST (Parameter Settings by Sequential Estimation; Findlay, 1978) to staircase adaptively through the stimulus set based on the subject's previous answer. The number of trials completed by individual subjects therefore varied slightly (maximum number of trials = 40). The threshold score achieved was based on the 75% correct point for the last four reversals. For all tasks, children were first given training trials consisting of the standard tone and the tone that was most audibly different from the standard tone. Training trials were repeated until children were correct on four of five trials.

Amplitude rise time discrimination. For this task, a continuum of 40 stimuli was created from a 500-Hz sinusoid, amplitude-modulated at the rate of 0.7 Hz. The linear rise time of the amplitude modulations varied logarithmically from 15 to 602 ms. The overall duration of the stimuli remained constant at 3400 ms, and the duration of the linear fall time was fixed at 100 ms. If a rise time is short, this results in the percept of a strong syllable beat, whereas if the rise time is longer, the percept of a distinct syllable beat is not present (Scott, 1998). Pilot work determined that the concept of a beat could be conveyed to preschoolers by initially introducing a handbell and explaining that one dinosaur's sound would "have a bell in it." Children then heard two sounds from the computer, the standard stimulus, with the longest rise time (602 ms) alongside a sound with a shorter rise time (the order of sounds being randomized) and were asked to choose the dinosaur who made a sound that was like a bell (see Figure 1).

Intensity discrimination. This task was intended as a control task for the attentional demands of the psychoacoustic procedure. A continuum of forty 500-Hz stimuli was constructed by varying the intensity of the steady state logarithmically, values within a range of 30 dB. Each stimulus tone had linear onset and offset envelopes (50 ms) and fixed steady-state duration of 700 ms. The stimulus with 29.25-dB steady state was used as a standard. Children were presented with the standard stimulus alongside another stimulus from the continuum and ask to choose the stimulus that was quietest (see Figure 2).

Frequency sweep discrimination. A continuum of 40 stimuli was created. Each stimulus was 150 ms in duration with a 5-ms linear rise and fall time. The frequency of the stimuli started at 600 Hz and increased linearly within each stimulus. The final frequency of the stimuli varied logarithmically from

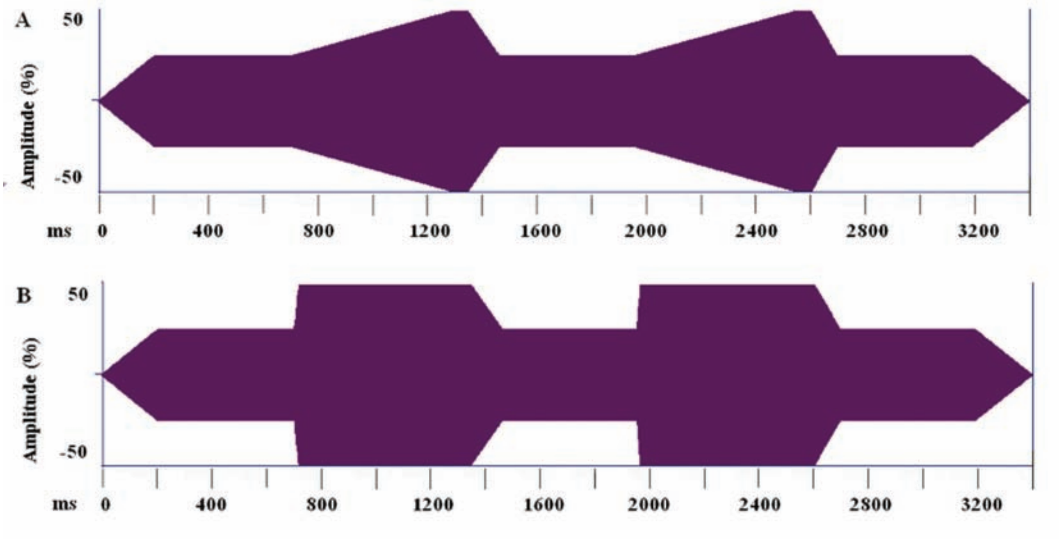

Figure 1. Schematic depiction of the wave form for the rise time task with (A) 602-ms rise time standard stimulus and (B) 15-ms rise time comparison stimulus.

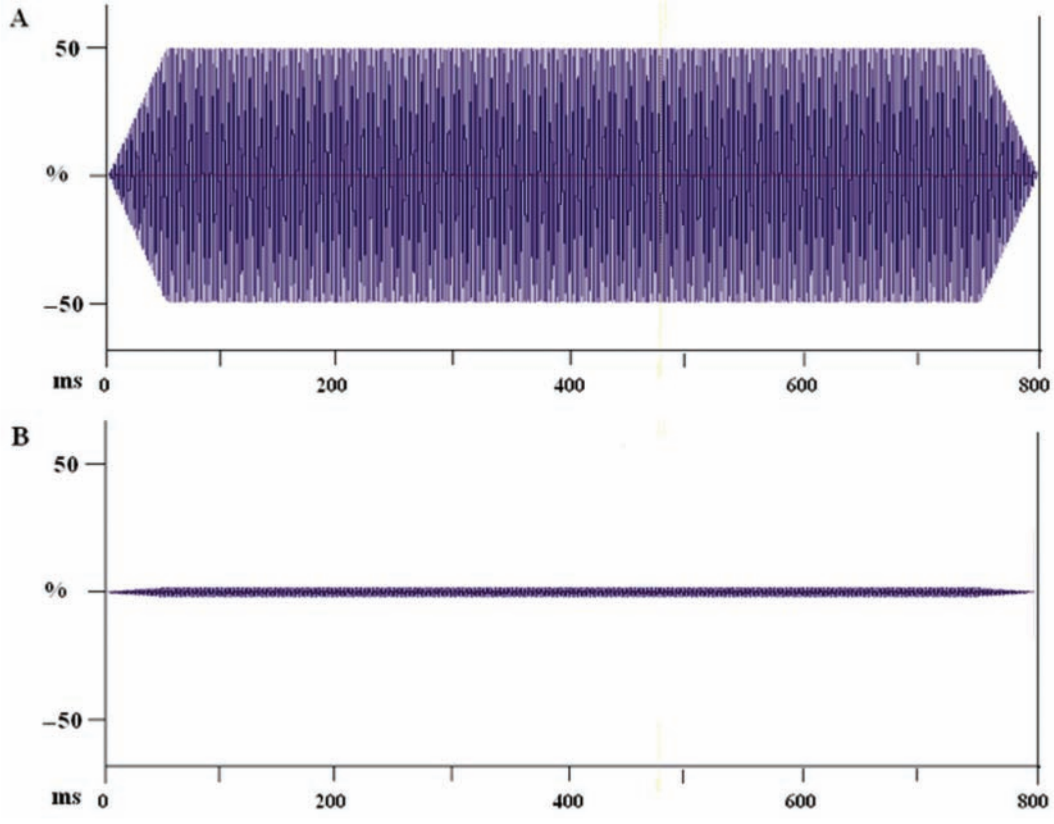

Figure 2. Schematic depiction of the wave form for the intensity task with (A) 29.25-dB standard stimulus and (B) 0-dB comparison stimulus.

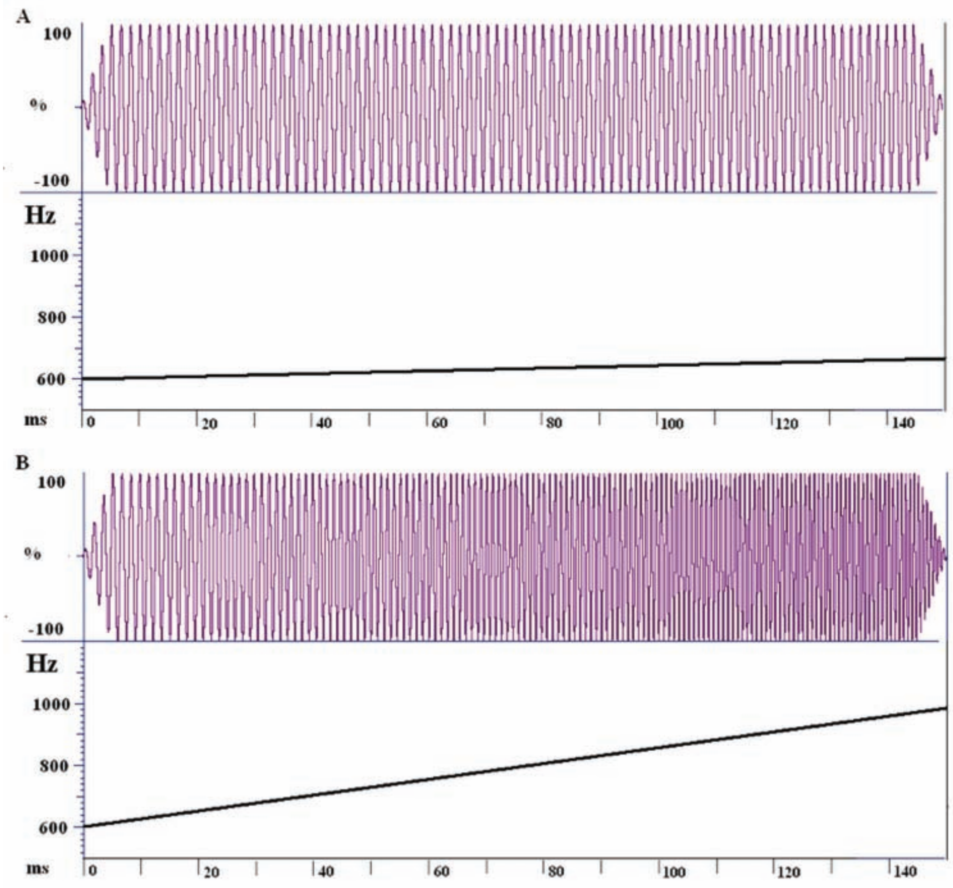

Figure 3. Schematic depiction of the wave form for the frequency task with (A) 25-Hz sweep standard stimulus and (B) 400-Hz sweep comparison stimulus.

625 to 1000 Hz. Children heard the stimulus with the shortest frequency sweep (from 600 to 625 Hz) as the standard sound and were asked to choose the sound that was highest.

Results

We first present results from the entire sample of 88 children at their first time of testing. We present mean scores for the phonological awareness, letter-sound knowledge, reading, and psychoacoustic measures and the relationship between these measures through correlation and regression. Next we present results from the longitudinal sample of 25 children. We present mean scores for the psychometric and psychoacoustic measures and the relationship between these measures over time through multilevel regression modeling. To anticipate, rise time discrimination ability was found to be a significant predictor of early reading skills in both the larger, cross-sectional sample and in the longitudinal subset.

Cross-Sectional Results

Children's mean performance in the phonological awareness, reading, and letter-sound knowledge tasks by age group is displayed in Table 2. With the exception of the reading tasks, one-way between-subjects ANOVAs by age group (3, 4, 5, 6 years old) were conducted for all of the tasks given. The ANOVAs revealed significant group differences for all measures, as shown in Table 3. Post hoc Bonferroni tests revealed that phonological awareness and letter-sound knowledge ability increased significantly across each age for every task. One-way between-subjects ANOVAs by age group (5, 6) were also conducted for the two reading measures. The results revealed that letter-word identification and word attack increased significantly between 5 and 6 years old.

Children's mean performance in the psychoacoustic measures is displayed in Table 3. For the intensity, frequency, and amplitude envelope rise time tasks, children's performance was measured in terms of the threshold at

Table 2. Mean (Standard Deviation) Participant Characteristics for the Standardized Phonological Awareness Tasks by Age at First Time of Testing

	3-Year-Olds	4-Year-Olds	5-Year-Olds	6-Year-Olds	*F*(3, 84)
Rhyme[a]	3.6 (2.0)	6.5 (2.6)	7.1 (2.8)	9.4 (2.3)	14.79***
Syllable[b]	4.3 (2.9)	5.7 (2.7)	6.6 (2.3)	8.6 (2.6)	7.64***
Alliteration[c]	4.0 (2.4)	5.2 (2.0)	6.4 (3.0)	10.1 (1.9)	17.54***
Isolation[d]	3.3 (4.0)	6.4 (4.1)	7.9 (3.2)	10.8 (1.2)	12.57***
Letter[e]	5.1 (6.2)	9.2 (6.7)	11.7 (6.4)	21.2 (6.2)	17.92***
Word ID[f]			5.7 (9.7)	26.8 (20.3)	13.32***
Word attack[g]			0.60 (1.4)	10.67 (10.7)	12.96***

[a] Pre-Reading Inventory of Phonological Awareness (PIPA) Rhyme Awareness subtest raw score (max = 12).
[b] PIPA Syllable Segmentation subtest raw score (max =12).
[c] PIPA Alliteration Awareness subtest raw score (max = 12).
[d] PIPA Sound Isolation subtest raw score (max = 12).
[e] PIPA Letter-Sound Knowledge raw score (max = 32).
[f] Woodcock-Johnson Letter-Word Identification raw score.
[g] Woodcock-Johnson Word Attack raw score.
***$p < .001$.

Table 3. Mean Performance (Standard Deviation) in the Experimental Psychoacoustic Measures by Age at First Time of Testing

	3-Year-Olds	4-Year-Olds	5-Year-Olds	6-Year-Olds	*F*(3, 84)	Standard Tone	Range of Tones
Rise[a]	22.38 (13.11)	22.16 (9.27)	37.45 (27.89)	44.13 (32.80)	5.27**	602 ms	15–602 ms
Intensity[a]	14.10 (7.50)	17.48 (6.00)	21.22 (4.70)	22.50 (1.95)	7.77***	29.25 dB	0–29.25 dB
Frequency[b]	884 (97)	857 (87)	783 (99.9)	765 (76)	3.25*	625 Hz	625–1000 Hz

[a] 3-year-olds = 4-year-olds < 5-year-olds = 6-year-olds.
[b] 3-year-olds < 6-year-olds.
*$p < .05$. **$p < .01$. ***$p < .001$.

which they were able to detect reliably the difference between the two sounds (75% of the time). For the intensity and rise time tasks, a lower threshold indicates poorer discrimination. For the frequency task, a higher threshold indicates poorer discrimination. For example, an intensity threshold of 26.25 dB would indicate that the subject could detect a difference between the standard stimulus (29.25 dB SPL) and a test stimulus with 75% accuracy as long as these two stimuli differ by 3dB. A rise time threshold of 190 ms would indicate that the subject can detect a difference between the standard stimulus (602 ms) and a test stimulus with 75% accuracy when the test stimulus has a rise time of 412 ms. A rise time threshold of 265 ms would indicate that the subject can detect a difference between the standard stimulus (602 ms) and a test stimulus with 75% accuracy when the test stimulus has a rise time of 337 ms. Finally, a frequency sweeps threshold of 885 would indicate that the subject can detect a difference between the standard stimulus (625 Hz) and a test stimulus with 75% accuracy as long as these two stimuli have a final frequency that differs by 260 Hz.

One-way between-subjects ANOVAs by age group (3, 4, 5, 6 years) were conducted for all experimental measures. Significant group differences were revealed on all tasks. Post hoc Bonferroni tests indicated that 3- and 4-year-olds were significantly less sensitive with respect to 5- and 6-year-olds (*p*s < .05) on the rise time and intensity tasks. In the frequency task, 3-year-olds were significantly less sensitive with respect to 6-year-olds ($p < .05$), but no other age differences were found.

Table 4 displays bivariate Pearson correlations and partial correlations controlling for age in months between the phonological awareness, letter-sound knowledge, and the psychoacoustic measures for all children. Inspection of Table 4 indicates significant relationships within the phonological awareness, letter-sound knowledge, and the psychoacoustic measures as well as between the measures, suggesting that these auditory measures may be related to early prereading abilities. After controlling for age, rhyme awareness was significantly related to alliteration awareness, sound isolation and the auditory measures, but was no longer associated with letter-sound knowledge and syllable segmentation. Thus, although rhyme awareness and letter-sound knowledge have both been found to be predictive of later literacy achievement, these two measures may be testing different aspects of prereading abilities. With the exception of rhyme awareness, intensity discrimination was not associated with any of the phonological or

Table 4. Bivariate Pearson Correlations (and Partial Correlations Controlling for Age in Months) Between the Phonological Awareness Measures and the Three Psychoacoustic Measures Across All Age Groups

	Rhyme	Syllable	Alliteration	Isolation	Letter	Rise Time	Frequency	Intensity
Rhyme	—	.39**	.61***	.61***	.41***	–.61***	–.47***	–.16
		_.13_	_.41***_	_.39***_	_.09_	_–.51***_	_–.26*_	_–.21*_
Syllable		—	.43***	.54***	.47***	–.31**	–.37***	–.35**
			.19~	.34***	.24*	_–.13_	_–.16**_	_–.12_
Alliteration			—	.63***	.69***	–.44***	–.59***	–.33**
				_.42***_	_.53***_	_–.27***_	_–.43***_	_–.02_
Isolation				—	.70***	–.41***	–.44**	–.29**
					_.54***_	_–.23*_	_–.22_	_.02_
Letter					—	–.21*	–.32**	–.25**
						_.05_	_–.04_	_.09_
Rise time						—	.48**	.24*
							_.27~_	_.03_
Frequency							—	.58**
								_.43***_
Intensity								—

~_p_ < .10. *_p_ < .05. **_p_ < .01. ***_p_ < .001.

psychoacoustic measures, suggesting that this may be used as an attentional control.

To explore the relationship between phonological awareness measures, we conducted bivariate Pearson correlations with psychoacoustic measures and early reading ability for 5- and 6-year-olds only ($n = 29$). The results indicated that letter-word identification was significantly associated with several phonological variables (rhyme: $r = .54$, $p < .01$; alliteration: $r = .64$, $p < .001$; isolation: $r = .38$, $p < .05$; letter-sound identification: $r = .45$, $p < .01$) as well as the rise-time discrimination variable ($r = –.38$, $p < .05$). Similarly, nonword abilities were significantly associated with several phonological variables (rhyme: $r = .51$, $p < .01$; syllable: $r = .41$, $p < .05$; alliteration: $r = .55$, $p < .01$; letter-sound identification: $r = .39$, $p < .05$) as well as the rise-time discrimination variable ($r = –.36$, $p < .05$).

To explore the relationship between the psychoacoustic and psychometric measures furthermore, a series of fixed-order multiple regressions were computed. For each regression, the Cook's distance metric was calculated. No data points had a Cook's distance score of greater than 1.0, and thus no participants were excluded from the regressions (Tabachnik & Fidell, 2001). The intensity measure was used as a control measure for the attentional demands of the psychoacoustic procedures. However, this measure could only provide an estimate of children's attention to task.

The five dependent variables were the phonological awareness measures (rhyme awareness, syllable segmentation, alliteration awareness, sound isolation) and letter-sound knowledge. The independent variables in each regression were (in a fixed order) (1) age, (2) nonverbal IQ, (3) intensity discrimination (attentional control), and (4) an additional psychoacoustic measure (rise time discrimination, frequency discrimination). The resulting parameter estimates are displayed in Tables 5 through 7 along with the unique variance accounted for by each variable (showing the change in R^2). Only unique variance that was significant after Bonferroni corrections were applied is indicated; however, before applying Bonferroni corrections, changes in R^2 of 3% or greater were significant.

Inspection of Table 5 reveals that the rise time and frequency sweeps measures were consistent predictors of unique variance in the rhyme awareness measure, with rise time also predicting unique variance in the alliteration awareness and sound isolation measures. The psychoacoustic measures did not predict unique variance on the syllable segmentation and letter-sound awareness tasks. For rhyme awareness, as much as 16% of unique variation was explained by individual differences in rise time processing and 7% was explained by frequency sweeps processing. For alliteration awareness, as much as 14% of unique variance was accounted for by differences in rise time processing.

The results of the regression equations show that individual differences in auditory processing of rise time explained between 6% and 16% of unique variance in rhyme awareness, alliteration awareness, and sound isolation. It is important to recall that rise time was a unique predictor of these prereading abilities even after IQ and an estimate of children's attention to task were controlled for in these analyses.

Longitudinal Results

Children's mean performance in the phonological awareness and letter-sound knowledge tasks by time point

Table 5. Stepwise Regressions of the Unique Variance in Rhyme Awareness, Syllable Segmentation, Alliteration Awareness, Sound Isolation, and Letter-Sound Knowledge Accounted for by the Psychoacoustic Variables (n = 88)

		Rhyme Awareness		Syllable Segmentation		Alliteration Awareness		Sound Isolation		Letter-Sound Knowledge	
Step (Model)		1	2	3	4	5	6	7	8	9	10
1. Age	β	.59***	.61***	.51***	.41***	.53***	.28**	.55***	.57***	.67***	.59***
	ΔR^2	.35	.34	.26	.26	.36	.21	.35	.31	.36	.28
2. Full Scale IQ	β	.17	.26*	.28	.15	.25**	.27	.15	.22	.15	.24
	ΔR^2	.04	.06	.08	.03	.07	.09	.03	.04	.02	.05
3. Intensity	β	.21*	.29	.11	.11	.01	.01	.03	.18	.08	.19
	ΔR^2	.03	.01	.00	.01	.00	.02	.00	.01	.01	.01
4. Rise Time	β	−.44***		−.17		−.46**		−.17*		.05	
	ΔR^2	.16		.02		.14		.06		.03	
5. Frequency	β		−.33*		−.12		−.19		−.27		−.13
	ΔR^2		.07		.01		.03		.05		.01

***Change in R^2 significant using a Bonferroni-corrected alpha (α/10, $p < .005$).

Table 6. Mean (Standard Deviation) Participant Characteristics for the Standardized Phonological Awareness Tasks, Letter-Sound Knowledge, and Experimental Psychoacoustic Measures by Time Point

	Time 1 (4;5)	Time 2 (4;11)	Time 3 (5;5)	$F(2, 72)$
Rhyme^{a,f}	6.4 (2.7)	7.4 (2.8)	9.0 (2.9)	4.14*
Syllable^{b,f}	5.9 (2.9)	6.8 (2.9)	8.4 (2.4)	5.14*
Alliteration^{c}	5.6 (2.9)	2.9 (2.8)	8.6 (3.2)	0.77
Isolation^{d,f}	6.8 (3.5)	9.3 (2.9)	10.6 (1.7)	3.59*
Letter^{e,f}	14.2 (8.6)	14.4 (9.6)	23.2 (6.9)	8.19***
Rise time, ms^{f}	34.50 (18.48)	54.08 (45.17)	87.07 (84.6)	8.87***
Intensity^{g}	15.6 (7.8)	8.9 (6.3)	7.6 (4.7)	11.26***
Frequency, Hz^{f}	808 (111)	803 (113)	749 (85)	3.37*

[a] Pre-Reading Inventory of Phonological Awareness (PIPA) Rhyme Awareness subtest raw score (max = 12).
[b] PIPA Syllable Segmentation subtest raw score (max =12).
[c] PIPA Alliteration Awareness subtest raw score (max = 12).
[d] PIPA Sound Isolation subtest raw score (max = 12).
[e] PIPA Letter-Sound Knowledge raw score (max = 32).
[f] Time 1 < Time 3.
[g] Time 1 < Time 2 < Time 3.
*$p < .05$. ***$p < .001$.

(time 1: mean age 4;5; time 2: mean age 4;11; time 3: mean age 5;5) for the 25 children who were tested longitudinally is displayed in Table 6. One-way between-subjects ANOVAs by time point were conducted for all of the tasks given. The ANOVAs revealed significant group differences for all phonological and psychoacoustic measures, with the exception of alliteration awareness, as shown in Table 6. Post hoc Bonferroni tests revealed that scores increased significantly between times 1 and 3 for rhyme awareness, syllable segmentation, sound isolation, letter-sound knowledge, rise time discrimination, and frequency discrimination (*p*s < .05). Scores increased significantly between times 1 and 2 and again between times 2 and 3 for intensity discrimination (*p*s < .001).

To further evaluate the relationship between the psychoacoustic and phonological awareness measures, a series of multilevel regression models were computed. We chose to compute multilevel models instead of repeated-measures ANOVA for two reasons. First, classical methods using repeated-measures ANOVA take into account the variability by individual time point but do not account for the fact that individual scores over time are correlated within the individual students (Singer & Willett, 2003). Second, repeated-measures ANOVA aggregates individual scores at each time point. Because we were interested in the individual-level variability in the development of phonological skills, we chose to use multilevel regression models. According to Hox (1995),

Table 7. Multilevel Regression Models Exploring Change in Rhyme Awareness Over Time (n = 25)

		Parameter	Model A	Model B	Model C	Model D
Fixed effects initial status, π_{0i}	Intercept	γ_{00}	6.26***	6.67***	8.92***	8.04***
	Rise time	γ_{01}			–0.20**	–0.16*
	FSIQ	γ_{02}				0.07
Rate of change, π_{1i}	Intercept	γ_{10}		0.80**		1.08
	Rise time	γ_{11}				0.01
	FSIQ	γ_{12}				0.02

Note: FSIQ = Full-scale IQ standardized score from Kaufman Brief Intelligence Test–2.
*$p < .05$. **$p < .01$. ***$p < .001$.

models with sample sizes greater than 20 yield adequate power.

Based on the cross-sectional results, rhyme awareness was most strongly correlated to the auditory measures across age groups. Thus, we chose rhyme awareness as our dependent variable and explored the following predictors: time point, Rise time discrimination (Time 1), and full-scale IQ (Time 1). These models are shown in Table 7.

The first two models in Table 7 partition the variation in rhyme awareness both across students only (Model A) and across both students and time point (Model B). Because the parameter estimates in both models are significant, this suggests that there is systematic variation both between students (Model A: Fixed Effects) and within students over time, controlling for the variation between students (Model B: rate of change). Model C includes our predictor of interest, rise time discrimination (Time 1). Here only the fixed effects parameter estimate is statistically significant, suggesting that controlling for individual variation over time, the differences in rise time discrimination across students are significantly predictive of rhyme awareness ability. Finally, Model D includes full-scale IQ to control for individual variability in intelligence. Controlling for intelligence, we see the same finding as in Model C: Rise time discrimination across students is predictive of rhyme awareness ability.

We confirmed the effects found in Model D through inspection of the fixed-effects variance component (Level 1: σ_e^2) and the two rate of change variance components (Level 2: σ_0^2, σ_1^2). The estimated Level 1 variance component, σ_e^2 was 1.85, which is significant at the $p < .001$ level, confirming that the between-person variation was significantly predictive of rhyme awareness. Both Level 2 variance components were statistically significant ($\sigma_0^2 = 2.94$, $p < .05$, $\sigma_1^2 = 3.06$, $p < .05$), suggesting that, taken together as a group, the time-variant portion accounted for unique variation in rhyme awareness.

To determine the amount of variation in rhyme awareness accounted for by our final model (Model D) we conducted pseudo-R^2 statistics for the fixed effects and rate of change portions of our model. Pseudo-R^2 statistics are the proportional reduction in residual variance as predictors are added (Singer & Willett, 2003). For Model D, the pseudo-R^2 explained by including between-person variables (pseudo-R_e^2 was .61, indicating that 61% of the between-person variation in rhyme awareness was explained by Model D. The two pseudo-R^2s for the within-person variation (pseudo-R_0^2 and pseudo-R_1^2) were .06 and .10, respectively, indicating that only 6% and 10% of the within-person variation in rhyme awareness was explained by this model. Thus, inspection of the pseudo-R^2 statistics confirms that, controlling for FSIQ, rise time explains a considerable amount of between-person variation in rhyme awareness ability.

Discussion

This study explored both concurrent and predictive relationships between preschoolers' amplitude rise time sensitivity and their emerging phonological and literacy skills. The cross-sectional results supported the hypothesis that auditory processing skills, especially those that focus on sensitivity to the speech envelope, are strongly correlated to reading precursor skills between the ages of 3 and 6 years. In correlations controlling for age, performance on the rise time discrimination task was strongly associated with rhyme awareness ($r = –.51$) as well as significantly associated with initial phoneme detection (the alliteration task, $r = –.27$) and identification (the sound isolation task, $r = –.23$). Equally, a measure of frequency sweep discrimination was significantly correlated to the alliteration task ($r = –.43$) and to rhyme awareness ($r = –.26$). The psychoacoustic control measure of intensity discrimination had a significant relationship with rhyme awareness only ($r = –.21$). Regression analyses controlling for age, IQ, and the demands of the psychoacoustic assessment itself (using the intensity discrimination variable) confirmed these relationships, with rise time and frequency discrimination predicting 16% and 7% of the unique variance respectively in rhyme awareness and rise time predicting unique variance in alliteration and sound isolation ability. This relationship was confirmed through a more powerful longitudinal design with a subset of children assessed at three 6-month intervals. Children's initial rise time discrimination ability at mean age 4;5 was able significantly to predict interindividual growth in rhyme awareness between ages 4;5 and 5;5.

The strongest relationships in this study were between both rise time and frequency discrimination and rhyme awareness. This fits with the developmental framework proposed here, whereby auditory processing influences reading acquisition through its effects on a child's ability to extract phonological information from the speech stream. It also extends the many studies involving older children that have found associations between phonological awareness and rise time (Goswami et al., 2002; Hämalainen et al., 2005; Muneaux et al., 2004; Richardson et al., 2004) or frequency discrimination (Talcott et al., 2000). Relationships between rise time and another skill related to reading, letter-sound knowledge, were present, but only within the older age group (5-6 years) of this study. Studies with older children who have received formal literacy instruction have found relationships with reading and/or spelling as well as phonological awareness for both rise time (Goswami et al., 2002; Hämalainen et al., 2005; Muneaux et al., 2004; Richardson et al., 2004) and frequency discrimination (Talcott et al., 2000; Witton et al., 1998). The lack of relationship when including 3- to 4-year-olds in the analysis may reflect the relatively underdeveloped letter-sound knowledge of the younger age group. There results are also consistent with the only other preschool longitudinal study to explore relationships between envelope-level auditory processing and early literacy (Boets et al., 2008). In the study by Boets et al., a link with rhyming ability was also salient: Slow-varying frequency discrimination was related to speech perception in noise, which itself was related to phonological awareness measured using a rhyme task and three sound identity tasks (first-sound, end-sound, rhyme). Boets et al. also found that phonological awareness measured this way was a unique predictor of reading and spelling. Taken together, auditory processing in these studies, although not predicting decoding skills per se, is predicting an important precursor to decoding, phonological awareness of intrasyllabic structure. This ability to extend our powers of prediction to developmentally earlier precursors of reading is crucial as practitioners increasingly try to determine a child's risk for reading failure, even before kindergarten.

This study explored longitudinal relationships between prereading skills and auditory processing in the immediate preschool period. It will also be important to understand and replicate these results in the context of the longitudinal studies of reading risk that have looked for markers of risk at even earlier ages, for example, the Jyvaskyla Longitudinal Study of Dyslexia (Lyytinen et al., 2004). Such studies highlight the developmental significance of auditory processing for later reading ability, with auditory responses in response to a synthetic syllable /ga/ measured using electrophysiology even in the first week of life able to differentiate the genetically at-risk versus not-at-risk newborns (Guttorm, Leppanen, Richardson, & Lyytinen, 2001; Guttorm, Leppanen, Tolvanen, & Lyytinen, 2003) as well as predict reading-related skills such as receptive language at 2.5 years and verbal memory skills at 5 years (Guttorm et al., 2005).

The relationships found here between auditory processing skills and precursor reading skills in preschoolers also have implications for early intervention. In a recent study involving a group of school-age children with dyslexia (Thomson, Cheah, & Goswami, in prep.), a 6-week intervention program was administered that aimed singularly at improving rise time discrimination. The intervention had significant, direct effects upon the children's rhyming skills in comparison to a no-intervention control group. Because rhyme awareness has been demonstrated to predict subsequent reading ability (Maclean et al., 1987), it is likely that the intervention group will also exhibit an increase in reading ability. Moreover, this type of intervention may be even more effective at a preschool age. Rhyming skills are the most developmentally advanced stage of phonological awareness prior to reading exposure. Therefore, an intervention targeting rhyming could bolster prereading skills even before a child is exposed to reading instruction and potential failure.

Acknowledgments

We thank Bethany Colavincenzo, Rachel Currie-Rubin, Hadas Eidelman, Wendy Israel, and Jennifer Worden for help with data collection. Sincere thanks are also extended to the children, families, and school staff who participated in this study.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interests with respect to the authorship and/or publication of this article.

Financial Disclosure/Funding

The authors received no financial support for the research and/or authorship of this article.

References

Anthony, J., & Francis, D. (2005). Development of Phonological Awareness. *Current Directions in Psychological Science, 14*(5), 255–259.

Astrom, R., Wadsworth, S. J., & DeFries, J. (2007). Etiology of the stability of reading difficulties: The longitudinal twin study of reading disabilities. *Twin Research and Human Genetics, 10*(3), 434–439.

Blumstein, S. E., & Stevens, K. N. (1981). Phonetic features and acoustic invariance in speech. *Cognition, 10*(1), 25–32.

Boets, B., Wouters, J., van Wieringen, A., De Smedt, B., & Ghesquire, P. (2008). Modelling relations between sensory processing, speech perception, orthographic and phonological ability, and literacy achievement. *Brain and Language, 106*, 29–40.

Choi, Y. C., Hasegawa-Johnson, M., & Cole, J. (2005). Finding intonational boundaries using acoustic cues related to the voice source. *Journal of the Acoustical Society of America, 118*(4), 2579–br2587.

Corriveau, K, Pasquini, E., & Goswami,U. (2007) Basic auditory processing skills and Specific Language Impairment: A new look at an old hypothesis. *Journal of Speech Language and Hearing Research, 50*, 647–666.

De Martino, S., Espesser, R., Rey, V., & Habib, M. (2001). The "temporal processing deficit" hypothesis in dyslexia: new experimental evidence. *Brain and Cognition, 46*(1–2), 104–108.

Dodd, B., Crosbie, S., McIntosh, B., Teitzel, T., & Ozanne, A. (2003). *The Pre-Reading Inventory of Phonological Awareness.* San Antonio, TX: Psychological Corporation.

Dunn, L. M., & Dunn, L. M. (1997). *Peabody Picture Vocabulary Test*. Circle Pines, MN: American Guidance Service.

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

Francis, D. J., Shaywitz, S. E., Stuebing, K. K., Shaywitz, B. A., & Fletcher, J. M. (1996). Developmental lag versus deficit models of reading disability: A longitudinal, individual growth curves analysis. *Journal of Educational Psychology, 88*(1), 3–17.

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

Greenberg, S. (1999). Speaking in shorthand—A syllable-centric perspective for understanding pronunciation variation. *Speech Communication, 29*, 159–176.

Guttorm, T. K., Leppanen, P. H., Poikkeus, A. M., Eklund, K. M., Lyytinen, P., & Lyytinen, H. (2005). Brain event-related potentials (ERPs) measured at birth predict later language development in children with and without familial risk for dyslexia. *Cortex, 41*(3), 291–303.

Guttorm, T. K., Leppanen, P. H., Richardson, U., & Lyytinen, H. (2001). Event-related potentials and consonant differentiation in newborns with familial risk for dyslexia. *Journal of Learning Disabilities, 34*(6), 534–544.

Guttorm, T. K., Leppanen, P. H., Tolvanen, A., & Lyytinen, H. (2003). Event-related potentials in newborns with and without familial risk for dyslexia: Principal component analysis reveals differences between the groups. *Journal of Neural Transmission, 110*(9), 1059–1074.

Hamalainen, J., Leppanen, P. H., Torppa, M., Muller, K., & Lyytinen, H. (2005). Detection of sound rise time by adults with dyslexia. *Brain and Language, 94*(1), 32–42.

Heath, S. M., & Hogben, J. H. (2004). Cost-effective prediction of reading difficulties. *Journal of Speech, Language, and Hearing Research, 47*(4), 751–765.

Heiervang, E., Stevenson, J., & Hugdahl, K. (2002). Auditory processing in children with dyslexia. *Journal of Child Psychology and Psychiatry, 43*(7), 931–938.

Ho, C. S.-H., & Bryant, P. (1997). Phonological skills are important in learning to read Chinese. *Developmental Psychology, 33*(6), 946–951.

Holliman, A. J., Wood, C., & Sheehy, K. (2008). Sensitivity to speech rhythm explains individual differences in reading ability independently of phonological awareness. *British Journal of Developmental Psychology, 26*(3), 357–367.

Hood, M., & Conlon, E. (2004). Visual and auditory temporal processing and early reading development. *Dyslexia, 10*(3), 234-252.

Hox, J.J. (1995). *Applied multilevel analysis*. Amsterdam: TT-Publikaties.

Kaufman, A. S., & Kaufman, N. (1997). *Kaufman Brief Intelligence Test* (2nd ed.). Minneapolis, MN: Pearson Assessments.

Kochanski, G., Grabe, E., Coleman, J., & Rosner, B. (2005). Loudness predicts prominence: Fundamental frequency adds little. *Journal of the Acoustical Society of America, 118*(2), 1038–1054.

Konold, T. R., Juel, C., & McKinnon, M. (2003). A multivariate model of early reading acquisition. *Applied Psycholinguistics, 24*(1), 89–112.

Lyytinen, H., Ahonen. T., Eklund, K., Guttorm, T., Kulju, P., Laakso, M-L., Leiwo, M., Leppänen, P., Lyytinen, P., Poikkeus, A.-M., Richardson, U., Torppa, M., & Viholainen, H. (2004). Early development of children at familial risk for dyslexia - follow-up from birth to school age. *Dyslexia, 10*(3), 146–178.

Maclean, M., Bryant, P., & Bradley, L. (1987). Rhymes, nursery rhymes, and reading in early childhood. *Merrill-Palmer Quarterly, 33*(3), 255–281.

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, and Hearing Research, 44*(4), 925–940.

Muneaux, M., Ziegler, J. C., True, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: Evidence from French. *Neuroreport, 15*(8), 1255–1259.

Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems? *Journal of Speech, Language, and Hearing Research, 42*(4), 925–942.

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

Pasquini, E. S., Corriveau, K. H., & Goswami, U. (2007). Auditory processing of amplitude envelope rise time in adults diagnosed with developmental dyslexia. *Scientific Studies of Reading, 11*(3), 259–286.

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. *Journal of Experimental Child Psychology, 48*(2), 270–292.

Rey, V., De Martino, S., Espesser, R., & Habib, M. (2002). Temporal processing and phonological impairment in dyslexia: Effect of phoneme lengthening on order judgment of two consonants. *Brain and Language, 80*(3), 576–591.

Richardson, U., Thomson, J. M., Scott, S. K., & Goswami, U. (2004). Auditory processing skills and phonological representation in dyslexic children. *Dyslexia, 10*(3), 215–233.

Rosen, S., & Manganari, E. (2001). Is there a relationship between speech and nonspeech auditory processing in children with dyslexia? *Journal of Speech, Language, and Hearing Research, 44*(4), 720–736.

Scanlon, D. M., & Vellutino, F. R. (1996). Prerequisite skills, early instruction, and success in first-grade reading: Selected results from a longitudinal study. *Mental Retardation and Developmental Disabilities Research Reviews, 2*(1), 54–63.

Scarborough, H. (1998). Early identification of children at risk for reading disabilities: Phonological awareness and some other promising predictors. In B. K. Shapiro, P. Accardo, & A. J. Capute (Eds.), *Specific reading disability: A view of the spectrum* (pp. 75–119). Timonium, MD: York Press.

Scott, S. K. (1998). The point of P-centres. *Psychological Research/Psychologische Forschung, 61*(1), 4–11.

Shannon, R. V., Zeng, F.-G., Kamath, V., & Wygonski, J., & Ekelid, M. (1995). Speech recognition with primarily temporal cues. *Science, 270*(5234), 303–304.

Share, D. L., Jorm, A. F., Maclean, R., & Matthews, R. (1984). Sources of individual differences in reading acquisition. *Journal of Educational Psychology, 76*(6), 1309–1324.

Share, D. L., Jorm, A. F., Maclean, R., & Matthews, R. (2002). Temporal processing and reading disability. *Reading and Writing, 15*(1), 151–178.

Singer, J. D., & Willett, J. B. (2003). *Applied longitudinal data analysis: Modeling change and event occurrence.* . New York, NY: Oxford University Press.

Smith, Z. M., Delgutte, B., & Oxenham, A. J. (2002). Chimaeric sounds reveal dichotomies in auditory perception. *Nature, 416*(6876), 87–90.

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.

Suranyi, Z., Csepe, V., Richardson, U., Thomson, J. M., Honbolygo, F., & Goswami, U. (in press). Sensitivity to rhythmic parameters in dyslexic children: A comparison of Hungarian and English. *Reading & Writing*.

Tabachnik, B. G., & Fidell, L. S. (2001). *Using multivariate statistics* (4th ed.). Boston, MA: Allyn & Bacon.

Talcott, J. B., Witton, C., McLean, M. F., Hansen, P. C., Rees, A., Green, G. G. R., Stein, J. F. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences of the United States of America, 97*, 2952-2957.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language, 9*(2), 182–198.

Tallal, P., & Piercy, M. (1973). Defects of non-verbal auditory perception in children with developmental aphasia. *Nature, 241*(5390), 468–469.

Tallal, P., & Piercy, M. (1974). Developmental aphasia: Rate of auditory processing and selective impairment of consonant perception. *Neuropsychologia, 12*(1), 83–93.

Thomson, J. M., Cheah, V., & Goswami, U. (in prep.). *Auditory processing intervention for school-age children with developmental dyslexia: A comparison of speech and non-speech approaches.* Boston, MA: Harvard University.

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*(3), 334–348.

Thomson, J. M., & Goswami, U. (2008). Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *Journal of Physiology (Paris), 102*, 120–129.

Waber, D. P., Weiler, M. D., Wolff, P. H., Bellinger, D., Marcus, D. J., Ariel, R., Forbes, P., & Wypij, D.. (2001). Processing of rapid auditory stimuli in school-age children referred for evaluation of learning disorders. *Child Development, 72*(1), 37–49.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). Development of reading-related phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology, 30*(1), 73–87.

Whalley, K., & Hansen, J. (2006). The role of prosodic sensitivity in children's reading development. *Journal of Research in Reading, 29*(3), 288–303.

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

Wood, C. (2004). Do levels of pre-school alphabetic tuition affect the development of phonological awareness and early literacy? *Educational Psychology, 24*(1), 3–11.

Woodcock, R. W. (1987). *Woodcock Reading Mastery Tests–Revised*. Circle Pines, MN: American Guidance Service.

Ziegler, J. C., & Goswami, U. (2006). Becoming literate in different languages: similar problems, different solutions. *Developmental Science, 9,* 429–436.

Ziegler, J., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131,* 3–29.

About the Authors

Kathleen H. Corriveau, MPhil, Ed.M, is an advanced doctoral student at the Harvard Graduate School of Education. She studies early social and cognitive development.

Usha Goswami, D.Phil, is Director of the Centre for Neuroscience in Education and Professor of Education at the University of Cambridge. Her current research focuses on the neural basis of rhythm perception and implications for language development and literacy.

Jennifer M. Thomson, PhD, is an assistant professor at the Harvard Graduate School of Education. She studies specific learning disabilities and their neurological underpinnings.