Basic Auditory Processing Skills and Specific Language Impairment: A New Look at an Old Hypothesis

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Purpose: To explore the sensitivity of children with specific language impairment (SLI) to amplitude-modulated and durational cues that are important for perceiving suprasegmental speech rhythm and stress patterns.
Method: Sixty-three children between 7 and 11 years of age were tested, 21 of whom had a diagnosis of SLI, 21 of whom were matched for chronological age to the SLI sample, and 21 of whom were matched for language age to the SLI sample. All children received a battery of nonspeech auditory processing tasks along with standardized measures of phonology and language.
Results: As many as 70%–80% of children diagnosed with SLI were found to perform below the 5th percentile of age-matched controls in auditory processing tasks measuring sensitivity to amplitude envelope rise time and sound duration. Furthermore, individual differences in sensitivity to these cues predicted unique variance in language and literacy attainment, even when age, nonverbal IQ, and task-related (attentional) factors were controlled.
Conclusion: Many children with SLI have auditory processing difficulties, but for most children, these are not specific to brief, rapidly successive acoustic cues. Instead, sensitivity to durational and amplitude envelope cues appear to predict language and literacy outcomes more strongly. This finding now requires replication and exploration in languages other than English.

KEY WORDS: phonology, auditory processing, speech and language

Children with specific language impairment (SLI) have expressive and receptive oral language deficits that interfere with their educational achievements and their communicative abilities. These difficulties are exhibited in the presence of normal nonverbal intelligence and hearing ability, along with an apparent absence of neurological dysfunction. Although the general profile of children with SLI is well established, the underlying cause or causes of the disorder have been the subject of much debate. A prominent low-level causal theory is that children with SLI have difficulties in processing brief, rapidly successive acoustic stimuli and that these difficulties lead directly to their language problems (Tallal & Piercy, 1973a). Higher level theories fall into two broad categories. One category includes theories that assume specific deficits in language knowledge—for example, knowledge of implicit rules for marking tense, number, and person (e.g., Gopnik & Crago, 1991), or an extended period during which children believe that finiteness-marking is optional (Rice & Wexler, 1996). The second category includes theories that assume deficits in language processing—for example, the *surface deficit hypothesis* proposed by Leonard (1995). According to this hypothesis, children with SLI may have difficulties in acquiring grammatical morphemes with low phonetic substance (i.e., morphemes with short-duration, low-intensity acoustics). Both language knowledge and language processing accounts expect that the hypothesized deficits will characterize children with SLI across the world's languages.

The potential role of auditory processing difficulties in explaining SLI has been explored in depth by Tallal and her colleagues (Benasich & Tallal, 2002; Spitz, Tallal, Flax, & Benasich, 1997; Tallal & Piercy, 1973a, 1973b, 1974, 1975). They have proposed a rapid temporal processing deficit account of SLI. Difficulties in rapid temporal processing are thought to explain language problems "as speech occurs at roughly 80 ms per phoneme" (Tallal & Piercy, 1973a, p. 397). The original *rapid temporal processing hypothesis* was based on a landmark series of studies by Tallal and Piercy (1973a, 1973b, 1974, 1975; see also Efron, 1963). Tallal and Piercy administered a temporal order judgment (TOJ) task to twelve 8- to 12-year-old children with language impairments and 12 control participants matched for age and nonverbal IQ. In the TOJ task, the children had to learn to associate a button press with a particular tone (high or low). They were then asked to listen to two tones and to respond by pressing the correct buttons in the appropriate order. Children with SLI were found to be impaired in this task when stimuli were brief (75 ms) and were separated by short interstimulus intervals (ISIs). The children with SLI did not differ from the control participants when ISIs were longer (>150 ms or >305 ms, depending on the study). Although difficulties in rapid auditory processing have subsequently been reported in some studies of children with SLI (Alexander & Frost, 1982; Frumkin & Rapin, 1980), they have not been found in others (Bishop, Carlyon, Deeks, & Bishop, 1999; Helzer, Champlin, & Gillam, 1996; Norrelgen, Lacerda, & Forssberg, 2002). Some now argue that although children with SLI may show auditory processing deficits, these deficits are not characterized by the rapidity of the stimuli (see McArthur & Bishop, 2001, and Rosen, 2003, for reviews). Others have argued that when children with SLI show difficulties in perceptual tasks, this may arise from auditory immaturity (Bishop, Adams, Nation, & Rosen, 2005) or from task artifacts (Coady, Kluender, & Evans, 2005). The role of auditory perceptual deficits in explaining the etiology of SLI is thus strongly debated.

Auditory processing of cues related to speech prosody has not been widely investigated in children with SLI. This is surprising because recent work in infant language acquisition has shown that prosody plays an important role in word learning. For example, prosodic cues (in particular, changes in duration and stress) carry important information about how sounds are ordered into words when the words are multisyllabic. It is estimated that 90% of English bisyllabic content words follow a strong–weak syllable pattern, with the stress on the first syllable (e.g., *monkey, bottle, doctor, sister*). Jusczyk, Houston, and Newsome (1999) were able to show that 7.5-month-old infants can learn that word onsets are aligned with strong (stressed) syllables and that this guides them in picking out words in speech. The infants tended to mis-segment words with an atypical weak–strong syllable pattern, such as *guitar* and *surprise*. More recently, Curtin, Mintz, and Christiansen (2005) demonstrated that stress was an integral part of the phonological representations developed by 7-month-old infants. They first analyzed a corpus of phonologically transcribed speech directed to British infants between 6 and 16 weeks old to see whether a connectionist model would be able to learn word representations better when stress provided an additional cue. The addition of stress to the syllable representations led to better segmentation performance by the model. Curtin et al. suggested that lexical stress makes it easier to distinguish transitional probabilities in the speech stream. To test this idea, they familiarized 7-month-old infants with novel words presented in real English sentences. The novel words either had the lexical stress typical of English (*DObita*) or atypical stress (*doBIta*). The question was whether the two types of word, which contained the same phonemes and transitional probabilities, would be represented as distinct by the infants on the basis of whether they contained initial or medial stress. The results showed that the infants preferred the sentences that contained the words with initial stress. Curtin et al. concluded that lexical stress is retained in the protolexical representation. Indeed, in natural language, lexical forms with identical phonemes but differential stress patterns may be different words (as in *CONtent* and *conTENT*; Fry, 1954). Experiments such as these suggest that an early insensitivity to auditory prosodic cues to speech rhythm and stress could have profound effects on the development of the language system.

In this study, we therefore set out to explore the possibility that children with SLI might have basic auditory processing impairments to suprasegmental cues to speech rhythm and syllable stress. Recent theories of stress perception give central importance to the cues of amplitude and duration (e.g., Greenberg, 1999, 2006; Greenberg, Carvey, Hitchcock, & Chang, 2003; Kochanski, Grabe, Coleman, & Rosner, 2005). For example, Greenberg (1999) described an automatic prosodic algorithm developed to label stressed and unstressed syllables in a corpus of spontaneous speech. The algorithm depends on three separate parameters of the acoustic signal: (a) duration, (b) amplitude, and (c) fundamental frequency. In contrast to classic accounts, Greenberg (1999) reported that "fundamental frequency turns out to be relatively unimportant for distinguishing between the presence and absence of prosodic prominence . . . the results indicate that the product of amplitude and duration . . . yields the performance closest to . . . linguistic transcribers" (p. 172). Kochanski et al. (2005) reached similar conclusions in an investigation of a large corpus of natural speech covering seven English dialects. They concluded that "Contrary to textbooks and common assumption, fundamental frequency played a minor role in distinguishing prominent syllables from the rest of the utterance . . . speakers primarily marked prominence with patterns of loudness and duration" (p. 1038). Choi, Hasegawa-Johnson, and Cole (2005) also demonstrated a greater role for amplitude and duration cues in detecting stressed syllables in comparison to pitch cues in their study of machine detection of prosodic boundaries in the Boston University Radio Speech Corpus. Amplitude and duration also played a key role in detecting intonational boundaries, the detection of which is particularly likely to be related to grammatical acquisition by children. It is very notable that grammatical deficits in SLI tend to vary across languages (e.g., Bedore & Leonard, 2000; Bortolini & Leonard, 2000; Leonard & Bortolini, 1998; Roberts & Leonard, 1997). The reason may be that different languages use different prosodic cues to highlight different aspects of syntax. In the present study, we focused on children's sensitivity to amplitude envelope rise time and duration.

The hypothesis underlying the present studies—that grammatical deficits in SLI may be linked to the perception of amplitude and duration cues that signal stressed and unstressed parts of words and sentences—is similar in principle to the position long advocated by Leonard (e.g., Leonard, Eyer, Bedore, & Grela, 1997; McGregor & Leonard, 1994). Leonard has also proposed that difficulties with prosody may underlie many of the impairments noted in the grammatical morphology of children with SLI. However, Leonard's perceptual hypothesis is framed in terms of phonetic substance. It is hypothesized that syllables that are shorter, of lower amplitude, and of lower pitch cause particular difficulties. For example, children with SLI show problems with nonfinal weak syllables across languages (Bedore & Leonard, 2000; Bortolini & Leonard, 2000; Leonard & Bortolini, 1998; Roberts & Leonard, 1997). The hypothesis is that processing limitations are the key to this pattern of data. Processing speed in children with SLI is hypothesized to be slow, and consequently it is argued that processing limitations are exacerbated when morphemes are brief. In contrast, we propose that children with SLI do not have a problem with processing speed, per se; instead, they are expected to have difficulties when acoustic cues are extended over time. Hence, it is longer duration rather than shorter duration that should be problematic, particularly if amplitude changes with duration. Extended amplitude envelope onsets or cues with longer durations should be particularly difficult to distinguish. This alternative prosodic hypothesis argues that the variation in children's grammatical errors across languages and contexts is related to the temporal integration of changes in amplitude across duration—that is, amplitude envelope onset cues—rather than to slower processing of briefer cues.

The purpose of this study was, therefore, to examine basic auditory processing abilities related to perceiving stress and syllable prominence in a sample of children diagnosed as having SLI. The rise time and duration tasks used were drawn from prior studies of children with developmental dyslexia. These studies have reported impaired sensitivity to rise time and duration in such samples (Goswami et al., 2002; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Richardson, Thomson, Scott, & Goswami, 2004). Dyslexia is a developmental language disorder that is sometimes comorbid with SLI (Catts, Adlof, Hogan, & Weismer, 2005). In the present study, comparisons were made between a sample of children diagnosed with an SLI and samples of typically developing children matched for age and language abilities. If a specific deficit in sensitivity to rise time and duration were to be found in children diagnosed with SLI, this would be a first step in investigating whether developmental speech and language deficits arise, in part, from a relative insensitivity to stress cues to syllable prominence that may carry grammatical information.

Method

Participants

Sixty-three children aged between 7 and 11 years participated in this study. Only children who had no diagnosed additional learning difficulties (e.g., dyspraxia, attention-deficit/hyperactivity disorder, autistic spectrum disorder, dyslexia[1]), a nonverbal IQ above 80, and English as the first language spoken at home were included. All participants received a short hearing screen via an audiometer. Sounds were presented in both the left and right ear at a range of frequencies (250, 500, 1000, 2000, 4000, and 8000 Hz), and all participants were sensitive to sounds at the 20 dB HL level.

Twenty-one of the children (13 boys and 8 girls; M = 10;2 [years;months], SD = 0;11) had a statement of SLI from their local education authority and were drawn from school language support units or referred by local speech-language therapists (SLI group). They were assessed experimentally using two expressive and two receptive subtests of the Clinical Evaluation of Language Fundamentals—3 (CELF–3; Semel, Wiig, & Secord, 1995)

[1]No children in the sample had a diagnosis of dyslexia. However, when tested for the study, 5 children in the SLI sample were found to have standardized single-word reading scores that were more than 1.5 *SD*s below the population mean.

and were included in the study if they scored below 1.5 *SD*s on two or more of these subtests. Individual standard scores of the children in the SLI group for the four CELF subtests administered—the expressive and receptive vocabulary measures, nonverbal IQ, and single-word reading scores—are shown in Table 1. Note that in our prior studies of dyslexia, only children with a clinical diagnosis of dyslexia and no history of speech or language impairments were studied. Here, we studied children with a clinical diagnosis of SLI and no diagnosis of reading impairments; hence, the overlap between this population and the children in our prior studies is small (although note that 5 of the 21 children in the sample with SLI did score poorly on the test of single-word reading that we administered experimentally—namely, Participants 5, 6, 7, 16, and 18).

Forty-two control children from a local school were included. Of these, 21 were chronological-age-matched controls (CA group; 9 boys, 12 girls; M = 9;9, SD = 2;4), and 21 were language-ability-matched controls (LA group; 11 boys, 10 girls; M = 7;8, SD = 8 months). The LA group was matched to the children with SLI through use of raw scores on the tests of expressive vocabulary (Wechsler Intelligence Scale for Children, Vocabulary subtest; Wechsler, 1974) and receptive vocabulary (British Picture Vocabulary Scale [BPVS]; Dunn, Dunn, Whetton, & Pintilie, 1982). Raw scores were matched to within 5 points (± 2 *SE*). Participant characteristics are shown in Table 2.

Tasks

Psychometric Tests

The children received psychometric tests of IQ, language, reading, rapid naming ability, and working memory. Language abilities in the SLI group were checked through the use of two receptive subtests (Concepts and Directions, Semantic Relations) and two expressive subtests (Formulating Sentences, Sentence Assembly) of the CELF–3. For all children, receptive vocabulary was measured through use of the BPVS. All children were also given standardized tests of single-word and nonword reading (Test of Word Reading Efficiency [TOWRE]; Torgesen, Wagner, & Rashotte, 1999), reading comprehension (Wechsler Objective Reading Dimensions [WORD], Comprehension subtest; Rust, Golombok, & Trickey, 1992), spelling (British Ability Scales; Elliott, Smith, & McCulloch, 1996), rapid color naming (CELF–3 Rapid Color Naming subtest; Semel et al., 1995), word recall

Table 1. Individual scores for the language measures in the group of children with specific language impairment (SLI).

Participant	Receptive vocabulary[a]	Expressive vocabulary[b]	CELF Expressive[c]		CELF Receptive		Nonverbal IQ[d]	Single-word reading[e]
			FS	SA	SR	CD		
1	88	8	3	3	3	3	82	116
2	69	3	3	3	3	3	92	94
3	88	9	3	4	3	4	88	117
4	95	7	3	6	4	3	85	112
5	81	7	3	7	5	3	107	71
6	90	5	3	6	5	6	85	63
7	90	7	3	4	3	4	85	71
8	92	10	3	3	4	4	125	83
9	81	8	3	7	5	9	95	91
10	75	7	3	3	3	3	85	96
11	78	6	3	3	4	3	103	87
12	74	7	3	3	3	3	99	96
13	73	5	5	3	4	3	80	89
14	77	6	3	3	3	3	101	91
15	84	4	3	4	5	3	85	96
16	83	6	3	3	3	3	80	67
17	76	6	5	4	3	3	88	90
18	85	5	3	3	5	3	85	64
19	90	6	3	5	5	3	110	92
20	82	8	3	3	4	3	95	82
21	79	6	3	6	4	6	80	97

Note. FS = Formulating Sentences; SA = Sentence Assembly; SR = Semantic Relationships; CD = Concepts and Directions.

[a]British Picture Vocabulary Scale standard score (M = 100, SD = 15). [b]Wechsler Intelligence Scale for Children (WISC) Vocabulary standard score (M = 10, SD = 3). [c]Clinical Evaluation of Language Fundamentals (CELF) Expressive and Receptive subtests (M = 10, SD = 3). [d]WISC Performance IQ (M = 100, SD = 15). [e]Test of Word Reading Efficiency Sight Word subtest (M = 100, SD = 15).

Table 2. Mean (standard deviation) participant characteristics for the standardized tasks.

Group	SLI	CA match	LA match	*F*(2, 60)
N	21	21	21	
Age[a,b]	10;2	9;9	7;8	66.69***
SD	0.94	2.38	0.67	
Nonverbal IQ[c]	92.14	97.29	104.09	1.37
SD	11.75	10.08	8.67	
BPVS raw[b,d,e]	78.43	104.19	79.19	50.76***
SD	7.48	8.89	11.39	
WISC Vocab. raw[b,d,f]	20.15	28.7	20.67	23.10***
SD	2.64	6.33	4.15	

[a]SLI > language-ability-matched (LA) participants, $p < .001$. [b]chronological-age-matched (CA) participants > LA, $p < .001$. [c]Nonverbal IQ was estimated from the WISC Block Design and Picture Arrangement subtests (M = 100, SD = 15). [d]CA > SLI, $p < .001$. [e]Raw score was calculated using standard ceiling-to-floor guidelines of the British Picture Vocabulary Scale (BPVS; maximum = 144). [f]Raw score was calculated using the WISC vocabulary (Vocab.) procedures (maximum = 40).

***$p < .001$.

(Working Memory Test Battery for Children; Pickering & Gathercole, 2001), and nonword repetition (Children's Test of Nonword Repetition; Gathercole & Baddeley, 1996). Finally, all children received four subtests of the Wechsler Intelligence Scale for Children (WISC–III; Wechsler, 1974): (a) Block Design, (b) Picture Arrangement, (c) Similarities, and (d) Vocabulary. IQ scores were then prorated for each child from these subtests following the procedure adopted by Sattler (1982).

Experimental Phonological Tasks

Phoneme deletion task. This task was a shortened form of a similar task described by McDougall, Hulme, Ellis, and Monk (1994). Children heard 18 nonwords (15 test words and 3 practice words) presented orally by the experimenter and were asked to delete a particular phoneme, or phoneme cluster and to repeat the words without that phoneme or phoneme cluster; for example, "Say *bice* without the /b/." "Say *splow* without the /p/." Phonemes and phoneme blends were deleted at various points throughout the word (initial, medial, final). The maximum score possible on this task was 15. After piloting, a live voice task was selected over a synthetic speech task because the children were more engaged by the former.

Rime oddity task. In this task, children heard 24 triplets of words (20 test triplets and 4 practice triplets) presented on the computer using digitized speech created from a native female speaker of British English. Ten of the experimental word triplets came from dense rime neighborhoods (mean number of rime neighbors = 24.33, *SD* = 3.13), and the remaining 10 triplets came from sparse rime neighborhoods (mean number of rime neighbors = 8.63, *SD* = 3.20). All 60 experimental words were matched for frequency, and triplets were matched for the difference in rime neighborhood density between the odd word out and the two rhyming words. The maximum score possible in this task was 20. The stimuli were presented in a random order through headphones at 73 dB SPL using E-Prime 1.0 (Psychology Software Tools, Pittsburgh, PA). Three different orders of trial presentation were used, counterbalanced across children. After each triplet, the child was asked to say the word that did not sound the same as the other two, and his or her response was recorded on the keyboard by the experimenter.

Psychoacoustic Tasks

All psychoacoustic stimuli were presented binaurally through headphones at 73 dB SPL. Earphone sensitivity was calculated using a Zwislocki coupler in one ear of a KEMAR manikin (Burkhard & Sachs, 1975). Children's responses were recorded on the keyboard by the experimenter. Many of the psychoacoustic measures used the "dinosaur" threshold estimation program created by Dorothy Bishop (Oxford University), which used a two-interval forced-choice paradigm with a 500-ms ISI. In all tasks using the dinosaur program, the child heard each dinosaur make a sound and was asked to choose which dinosaur produced the target sound. Feedback was given online throughout the course of the experiment. The dinosaur program used the more virulent form of Parameter Settings by Sequential Estimation (PEST; Findlay, 1978) to staircase adaptively through the stimulus set on the basis of the participant's previous answer. Therefore, the number of trials completed by individual participants varied slightly (maximum number of trials = 40). The threshold score achieved was based on the 75% correct point for the last four reversals. In ongoing work with children with dyslexia, we are investigating the effects of attentional lapses in the PEST procedure used here and are finding that it is robust in terms of thresholds achieved.

Intensity discrimination. This dinosaur task was modeled after the loudness perception task as described by Ivry and Keele (1989) and was intended as a control task for the attentional demands of the psychoacoustic procedures.[2] A continuum of 31 stimuli was created using half of the stimuli used by Ivry and Keele. The stimuli ranged in loudness from 73 to 81.1 dB SPL, with 0.27 dB SPL between each step. Only half of the original Ivry and Keele stimuli were used because this task was also presented in the dinosaur format and, therefore, could take only a single adaptive staircase procedure. Each pure tone was presented at 1000 Hz for 50 ms. The

[2]To date, participants in our studies of developmental dyslexia have not had any difficulties in intensity discrimination.

level of the standard tone was 73 dB SPL. Children were asked to choose the dinosaur that made the loudest sound.

Amplitude envelope onset rise time (one-ramp rise time task). For this dinosaur task, a continuum of 40 stimuli was created from a 500-Hz sinusoid. The linear rise time envelope 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 heard the stimulus with the longest rise time (300 ms) as the standard sound and were asked to choose the dinosaur that made the sound that was sharpest at the beginning. Examples of the stimuli are shown in Figure 1.

Rise time from a carrier (two-ramp rise time task). In this dinosaur task, a continuum of 40 stimuli was created using a sinusoidal carrier at 500 Hz amplitude-modulated at the rate of 0.7 Hz (depth of 50%). Each stimulus was 3,750 ms long (2.5 cycles). Rise time was again varied logarithmically from 15 ms to 300 ms, and the fall time was fixed at 350 ms. Children always heard the longest rise time sound as the standard sound and were asked to choose the dinosaur that made the sound that had the sharpest beat. Examples of the stimuli are shown in Figure 2.

Temporal order judgment (TOJ) task. This task was modeled after similar tasks used by Tallal and colleagues (Tallal & Piercy, 1973a, 1973b) but avoided the additional cognitive demands introduced by their button-press procedure and used more ecologically valid stimuli. It was intended to examine children's sensitivity to brief consecutive sounds presented rapidly in time. Two sounds readily identifiable as a dog bark and a car horn with a fundamental frequency of 400 Hz and a duration of 115 ms were used as the stimuli in this task. A continuum of 40 sounds was created with variable stimulus onset asynchrony (SOA) from −405 ms (dog first, SOA = 405 ms) to 405 ms (car first, SOA = 405 ms) with a step

Figure 1. Schematic depiction of the stimulus wave form for the one-ramp task with (a) 15-ms rise time and (b) 300-ms rise time.

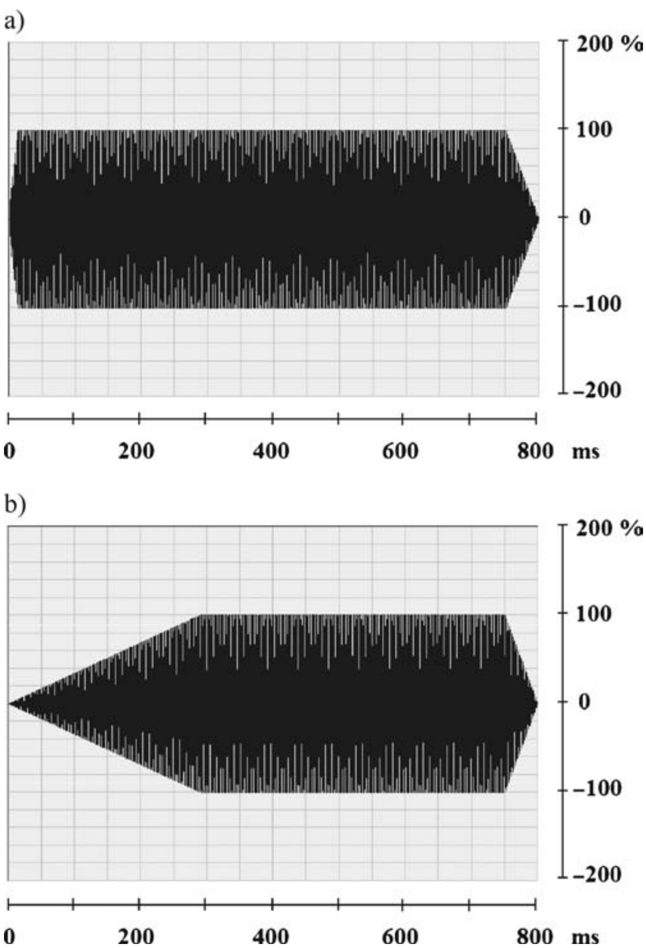
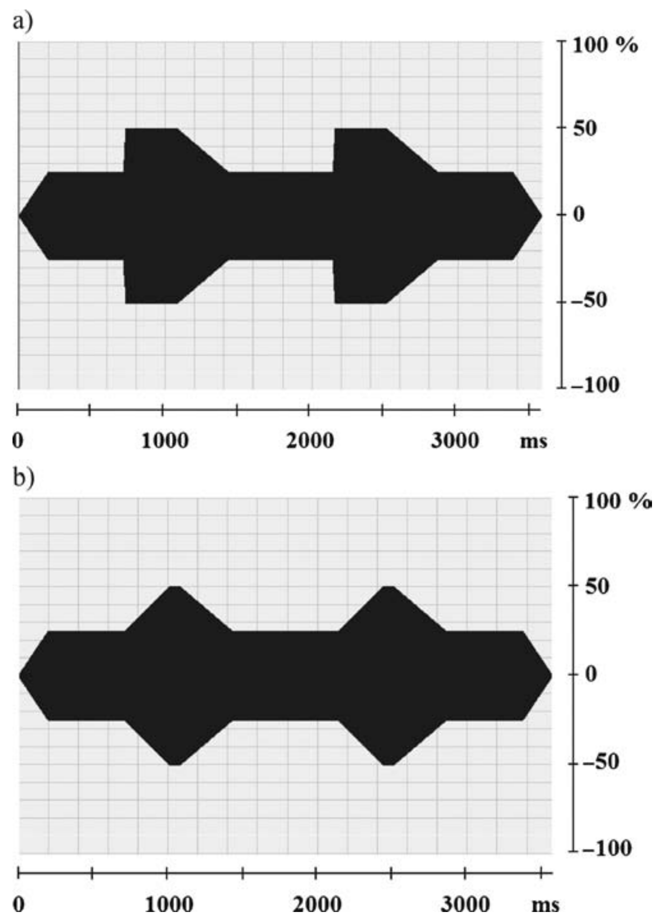


Figure 2. Schematic depiction of the stimulus wave form for the two-ramp task with (a) 15-ms rise time and (b) 300-ms rise time.



size of about 20 ms. Stimuli were allowed to overlap to the degree necessary to present the specified SOA. The stimuli were presented using a Speech Pattern Audiometer II, a C++ derivative of a categorical perception procedure created by Stuart Rosen (UCL, London, England). Before the test block, participants were given six practice stimuli, which represented the most extreme dog–car and car–dog SOA (405 ms), a middle SOA (237 ms), and a very difficult SOA (74 ms). Before beginning the test trials, each participant was required to give the correct answer for all 6 practice trials. A maximum of 40 experimental trials were then presented to each participant. Each subsequent trial was determined using a modification of Levitt's (1971) procedure created by Stuart Rosen. Summary statistics for the categorization slope and category boundary were derived using probit analysis (Finney, 1971). For all trials, children were asked to choose the sound (dog bark or car horn) that was perceived first. Note that because environmental noises were used, this task is not directly comparable to the TOJ task of Tallal and Piercy. However, the auditory characteristics of our stimuli probably make them more appropriate to use when examining the influence of auditory perception on speech perception.

Duration Discrimination Task 1 (briefer sounds duration task). This dinosaur task was modeled after the time perception task described by Ivry and Keele (1989). A continuum of 31 stimuli was created using pure tones. The stimuli ranged in duration from 400 ms to 640 ms, with 8 ms between each step. Each pure tone was presented at 1000 Hz. The duration of the standard tone was 400 ms. Children were asked to choose the dinosaur that made the longest sound.

Duration Discrimination Task 2 (longer sounds duration task). This task used the exact parameters of the time estimation task used by Ramus, Pidgeon, and Frith (2003), which was modeled after Nicolson, Fawcett, and Dean (1995). Twenty-three pure-tone stimuli with a frequency of 800 Hz were created with respective durations of 400, 700, 800, 900, 950, 1000, 1050, 1100, 1140, 1160, 1180, 1200, 1220, 1240, 1260, 1300, 1350, 1400, 1450, 1500, 1600, 1700, and 2000 ms. The ISI between the two tones was 1,000 ms. Each trial was repeated three times, amounting to 66 test trials, presented randomly. The test block was preceded by a practice block of the eight most extreme stimulus pairs, presented randomly. Feedback was given in the practice block but not in the test block. The stimuli were presented in E-Prime 1.0 using a nonadaptive paradigm. The duration of the standard tone was 1,200 ms. The child was asked to determine if the second tone was longer or shorter than the first tone. Although this procedure differs from that used in Duration Discrimination Task 1, it was followed in order to be consistent with prior studies of durational processing of tones by children with dyslexia.

Procedure

The children were assessed individually in a quiet room within their school. Children first received the WISC–III, BPVS, CELF–III (if applicable), and the audiometer screening tasks. The remaining tasks were presented in the following fixed order: one-ramp rise time, rapid color naming, Duration Discrimination Task 1, TOJ, rime oddity, working memory, phoneme deletion, nonword repetition, two-ramp rise time, Duration Discrimination Task 2, single-word reading, nonword reading, intensity discrimination, spelling, reading comprehension. Session lengths varied on the basis of children's attentiveness; sessions were terminated as soon as children exhibited attentional lapses. On average, children completed the tasks in four sessions of approximately 40 min. However, session lengths for children with SLI were usually shorter than for children in the two control groups, and some children with SLI were seen for five sessions.

To ensure that all children understood the directions for the computer tasks, a rigorous practice procedure was applied before the presentation of the experimental tasks. For the dinosaur tasks, children were required to answer four of five practice trials correctly. For all other computer tasks, children were required to answer all practice trials correctly. Practice trials were repeated until children were able to complete the requisite number of trials correctly. Both verbal and nonverbal (pointing) responses were accepted; many children in all three participant groups chose to point to the pictures on the computer screen instead of giving a verbal response.

Results

Children's performance in the reading, memory, and phonological awareness measures is displayed in Tables 3 and 4. One-way between-subjects analyses of variance (ANOVAs) by group (SLI, CA, LA) were conducted for all of the tasks given. The ANOVAs revealed significant group differences for all psychometric measures, as shown in Table 3. Post hoc Bonferroni tests revealed that children with SLI were significantly impaired compared with their CA and LA control groups on every measure except for CELF Rapid Color Naming. For this task, the children with SLI were only impaired compared with the CA control participants.

Children's mean performance in the experimental measures is displayed in Table 4. For the intensity and amplitude envelope tasks, children's performance was measured in terms of the threshold at which they were able to detect reliably the difference between the two sounds (75% of the time). For example, an intensity threshold of 76 dB would indicate that the person can detect a difference between the standard stimulus (73 dB SPL)

Table 3. Mean performance (standard deviation) in the reading, memory, and rapid naming tasks by group (SLI, CA, LA).

Group	SLI	*SD*	CA match	*SD*	LA match	*SD*	*F*(2, 60)	Effect size (η^2)
Working memory[a,b]	77.43	9.52	94.24	13.37	103.00	13.56	14.23***	.44
Nonword repetition (max = 30)[a,b]	18.28	3.30	25.42	4.11	22.62	4.54	16.81***	.36
TOWRE word[a,b]	88.81	15.51	107.91	11.37	114.95	9.45	25.09***	.46
TOWRE nonword[a,b]	85.09	11.23	104.47	13.65	109.85	12.34	30.31***	.50
BAS spelling[a,b]	84.09	14.04	113.43	11.10	118.05	12.14	39.76***	.56
Reading comprehension[a,b]	76.52	8.51	96.95	11.02	105.57	9.78	48.36***	.61
CELF rapid color naming (s)[a]	32.15	11.92	22.19	3.77	26.25	6.07	8.24***	.22

Note. TOWRE = Test of Word Reading Efficiency; BAS = British Ability Scales; s = seconds.

[a]CA > SLI, $p < .001$. [b]LA > SLI, $p < .001$.

***$p < .001$.

and a test stimulus with 75% accuracy as long as these two stimuli differ by 3 dB. An amplitude envelope threshold of 190 ms would indicate that the person can detect a difference between the standard stimulus (300 ms) and a test stimulus with 75% accuracy when the test stimulus has a rise time of 110 ms. An amplitude envelope threshold of 265 ms would indicate that the person can detect a difference between the standard stimulus (300 ms) and a test stimulus with 75% accuracy when the test stimulus has a rise time of 35 ms. Children's 75% correct threshold was also calculated in the two duration tasks; these scores were then log-transformed following customary practice. For the TOJ task, performance was measured in terms of slope, boundary, and threshold. The slope is a measure of the child's consistency in categorizing the sounds as either "dog first" or "car first," regardless of accuracy. A more negative slope indicates more consistent categorization than a less negative slope. The boundary is a measure of the difference between the point at which the stimuli shifted from "dog first" to "car first" and the point at which children judged this shift to occur. Children with lower boundary scores were more accurate in judging this shift than were children with higher boundary scores. The mean TOJ threshold is the average SOA at which children correctly judged the temporal order of the stimuli with 75% accuracy. Recall that the length of the dog/car sounds was 115 ms. Thus, a child with a threshold of 130 ms would accurately judge the order of the two sounds with 75% accuracy as long as they were separated by an interval of at least 15 ms (130 ms minus 115 ms).

One-way between-subjects ANOVAs by group (SLI, CA, LA) were conducted for all experimental measures. Significant group differences were revealed on all tasks except for the intensity task, TOJ slope, TOJ boundary, and TOJ threshold. Post hoc Bonferroni tests indicated that the SLI group was significantly impaired with respect to the CA control participants in the one-ramp rise time, two-ramp rise time, and Duration Discrimination

Table 4. Mean performance (standard deviation) in the experimental phonological and psychoacoustic measures by group (SLI, CA, LA).

Group	SLI	*SD*	CA match	*SD*	LA match	*SD*	*F*(2, 60)	Effect size (η^2)	Standard tone	Range of tones
Phoneme deletion (max = 15)[a,c]	4.90	2.09	10.67	2.37	8.95	2.87	30.19***	.50	—	—
Rime oddity (max = 20)[a,b,c]	10.43	3.09	15.95	2.01	13.71	2.95	21.79***	.42	—	—
Intensity threshold (dB)	76.14	1.80	75.48	1.41	76.02	2.12	0.78	.02	73 dB SPL	73.0–81.1 dB SPL
One-ramp threshold (ms)[a,b]	264.19	154.27	191.78	139.92	254.28	130.93	11.39***	.27	300 ms	15–300 ms
Two-ramp threshold (ms)[a]	267.51	147.1	239.89	153.94	242.30	142.42	3.93*	.12	300 ms	15–300 ms
Ln Duration 1 threshold (ms)[a,b]	2.50	0.49	1.90	0.38	2.38	0.52	9.16***	.25	400 ms	400–640 ms
Ln Duration 2 threshold (ms)[a,c]	5.58	0.51	4.94	0.19	5.19	0.34	15.47***	.34	1,200 ms	400–2,000 ms
TOJ slope	−.136	.104	−.237	.159	−.189	.138	2.85	.08	—	—
TOJ boundary[d] (ms)	19.48	4.99	17.89	5.32	20.08	3.81	1.20	.04	—	—
TOJ threshold[e] (ms)	127.00	95.2	82.4	58.2	130.2	118.8	1.70	.04	—	0–405 ms

Note. Ln = log; TOJ = temporal order judgment. Em dashes indicate that data are not applicable.

[a]CA > SLI, $p < .001$. [b]CA > LA, $p < .001$. [c]LA > SLI, $p < .001$. [d]True boundary = 0 ms. [e]Dog/car tone = 115 ms.

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

Task 1 (briefer sounds) tasks and that the group with SLI was impaired relative to both the CA and the LA control participants in the Duration Discrimination Task 2 (longer sounds) task and the phoneme deletion and rime oddity tasks. Note that administration of the phoneme deletion task used a live voice procedure, and so the possibility of inadvertent cueing by the experimenter cannot be ruled out. Nevertheless, results by group were identical in the two different phonological awareness tasks.

To determine whether the group-level auditory processing deficits found for rise time and duration were, in fact, due to a subset of the children with SLI, the performance of the CA control group was used to calculate performance levels falling below the 5th percentile. This was computed following the criteria suggested by Ramus et al. (2003) and used by Richardson et al. (2004). Children falling below the 5th percentile typical for their age can be considered to have a processing deficit. The percentage of SLI children with performance levels below the 5th percentile was then examined for all the auditory tasks. To examine the full extent of individual differences in duration discrimination, the untransformed version of these tasks was examined (a scatter plot is also provided for the log data of Duration Discrimination Task 2 for comparison). For the rise time tasks, 15 children in the SLI group fell below the 5th percentile of the CA control participants in the one-ramp rise time task (71.4%), but no child fell below this criterion in the two-ramp task. However, the majority of the children with SLI (52%) fell below the 25th percentile of control performance in the two-ramp task, and 76% fell below the 50th percentile. For the duration measures, 10 of 21 (47.6%) children with SLI fell below the 5th percentile of the CA control participants using the untransformed Duration Discrimination Task 1 (briefer sounds) measure, 17 of 20 (85%) fell below criterion using the untransformed Duration Discrimination Task 2 (longer sounds) measure, and 9 of 20 (45%) fell below criterion in the log Duration Discrimination Task 2 (longer sounds) measure. For the rapid auditory processing measure, 9 of 21 (38.1%) children with SLI were below criterion (using the TOJ threshold measure). Figure 3 shows the performance of individual children with SLI compared with CA control participants for the one-ramp rise time, untransformed Duration Discrimination Task 1, untransformed Duration Discrimination Task 2, log Duration Discrimination Task 2, and TOJ threshold measures.

Of the 17 children with SLI who fell below the 5th percentile in the untransformed Duration Discrimination Task 2 (longer sounds), 15 also fell below the 5th percentile in the amplitude envelope onset (one-ramp rise time) task, 10 also fell below the 5th percentile in judging sounds with briefer durations (untransformed Duration Discrimination Task 1), and 8 also fell below the 5th percentile in their TOJ thresholds. Thus, the children exhibiting difficulty with the duration discrimination tasks were the same children who had difficulty with the amplitude envelope rise time task, consistent with the developmental dyslexia literature. Furthermore, 8 of the 9 children who could be said to have a rapid processing deficit for environmental sounds also had difficulties in processing auditory cues of longer durations. To date, this overlap has not been found in children with developmental dyslexia (see Richardson et al., 2004).

Exploration of simple correlations controlling for age showed that nonverbal IQ was not related to any of the measures of interest (see Table 5). To explore the relationships between the psychoacoustic tasks and the vocabulary, phonological, working memory, and reading measures, 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 above 1.0, and thus no participants were excluded from the regressions (Tabachnik & Fidell, 2001). Because the groups did not differ in the intensity measure, and because this measure used the same psychoacoustic procedure as most of our other auditory tasks, the intensity measure was used as a control measure for the attentional demands of the psychoacoustic procedures. However, it should be noted that this measure can provide only an estimate of children's attention to task.

Four composite variables were created for the regressions: (a) vocabulary (including WISC Vocabulary and BPVS), (b) phonological awareness (including phoneme deletion and rime oddity), (c) reading and spelling (including TOWRE Sight Word Efficiency, TOWRE Phonemic Decoding Efficiency, WORD Reading Comprehension, and British Ability Scales Spelling), and (d) working memory (Nonword Repetition and Working Memory Test for Children, Word subtest). These four composite variables were used as the dependent variables along with rapid color naming. The independent variables in each regression were (in a fixed order): (a) age, (b) WISC Performance IQ,[3] (c) intensity discrimination (attentional control), and (d) an additional psychoacoustic measure (two-ramp rise time, one-ramp rise time, log Duration Discrimination Task 1 (shorter sounds), log Duration Discrimination Task 2 (longer sounds), TOJ threshold. The resulting parameter estimates are displayed in Tables 6 through 10 along with the unique variance accounted for by each variable (showing ΔR^2). Only unique variance that was significant after Bonferroni corrections were applied is indicated; however, before applying Bonferroni corrections, changes in R^2 of 6% or greater were significant.

Inspection of Tables 6–10 reveals that the duration measures and the single-ramp amplitude rise time measure were consistent predictors of unique variance in the

[3]Because a language deficit is the defining criterion of having a speech or language impairment, we did not control for verbal IQ in these regressions.

Figure 3. Scatter plots showing deviance as compared to CA controls for the (a) one-ramp rise time, (b) Duration Discrimination Task 2 (longer sounds), (c) Duration Discrimination Task 1 (shorter sounds), (d) ln duration 2 (longer sounds), (e) TOJ threshold, and (f) two-ramp measures. ln = log.

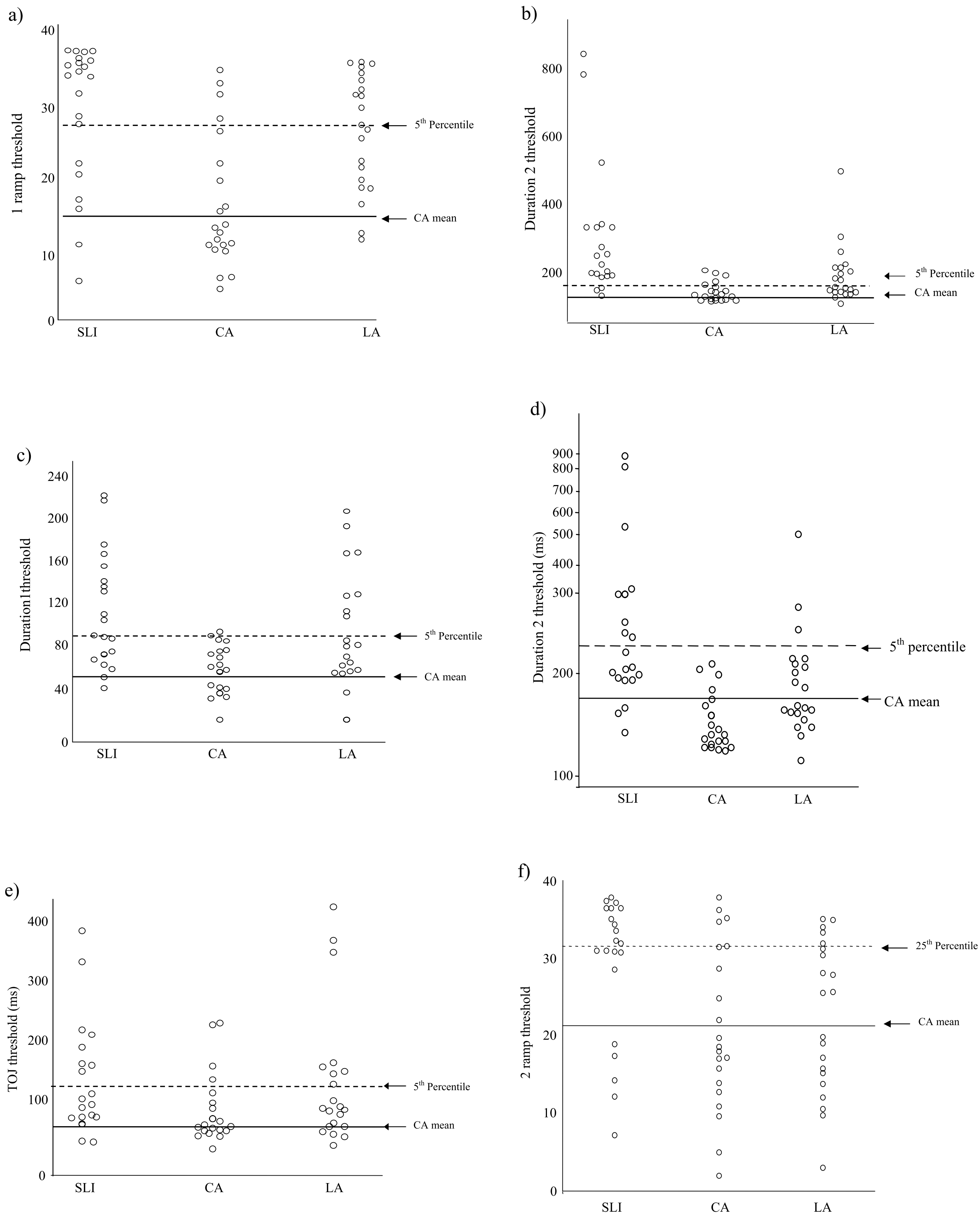


Table 5. Partial correlations (*r*s) of intelligence, language, reading, and psychoacoustic measures, controlling for age (months).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Nonverbal IQ[a]	—	.134	.183	.041	.105	.076	.073	.051	.098	.124	.028	−.030	.001	.047	−.108
2. Verbal IQ[b]		—	.719***	.593***	.553***	.351**	.388**	.453***	.631***	−.050	−.336*	−.377**	−.370**	−.110	−.265*
3. Receptive vocabulary[c]			—	.605***	.637***	.393**	.364**	.485***	.639***	−.040	−.461***	−.402**	−.427**	−.211	−.165
4. Phoneme deletion				—	.701***	.631***	.638***	.691***	.622***	−.148	−.440**	−.560***	−.527***	−.308*	−.399**
5. Rime oddity					—	.477***	.400**	.527***	.637***	−.074	−.455***	−.498***	−.517***	−.264*	−.322*
6. Word reading[d]						—	.844***	.827***	.530***	−.182	−.404**	−.373**	−.401**	−.198	−.272*
7. Nonword reading[e]							—	.825***	.481***	−.188	−.312*	−.363**	−.396**	−.239~	−.275*
8. Spelling[f]								—	.494***	−.235~	−.311*	−.426**	−.503***	−.319*	−.351**
9. Reading comprehension[g]									—	−.013	−.441**	−.372**	−.440**	−.175	−.148
10. Intensity discrimination										—	.160	.279*	.349**	.423**	.101
11. Duration 1 discrimination											—	.338**	.439**	.362**	.164
12. Duration 2 discrimination												—	.551***	.401**	.282*
13. One-ramp discrimination													—	.586***	.233~
14. Two-ramp discrimination														—	.211
15. TOJ threshold															—

[a]Nonverbal IQ was estimated from the Block Design and Picture Arrangement subtests (M = 100, SD = 15). [b]Verbal IQ was estimated from the Similarities and Vocabulary subtests (M = 100, SD =15). [c]British Picture Vocabulary Test (M =100, SD = 15). [d]Test of Word Reading Efficiency, Sight Word subtest (M = 100, SD = 15). [e]Test of Word Reading Efficiency, Non-Word subtest (M = 100, SD = 15). [f]British Ability Scales, Spelling subtest (M = 100, SD = 15). [g]WORD Reading Comprehension subtest (M = 100, SD = 15).

*p < .05. **p < .01. ***p < .001.

Table 6. Stepwise regressions of the unique variance in vocabulary ability accounted for by the psychoacoustic variables.

	Vocabulary ability				
Step	Model 1	Model 2	Model 3	Model 4	Model 5
1. Age					
β	.532[a]	.370[a]	.431[a]	.513[a]	.493[a]
ΔR^2	.243	.243	.243	.251	.243
2. Performance IQ					
β	.122	.114	.132	.151	.106
ΔR^2	.014	.014	.014	.019	.014
3. Intensity					
β	.082	.134	.053	.061	.005
ΔR^2	.000	.000	.000	.001	.000
4. Two-ramp rise time					
β	−.212				
ΔR^2	.024				
4. One-ramp rise time					
β		−.465[a]			
ΔR^2		.169			
4. Duration 1					
β			−.456[a]		
ΔR^2			.195		
4. Duration 2					
β				−.341**	
ΔR^2				.107	
4. TOJ threshold					
β					−.157
ΔR^2					.024

Note. $n = 63$. The composite vocabulary score includes the WISC Vocabulary subscale and the BPVS.

[a]Change in R^2 significant using a Bonferroni-corrected alpha ($\alpha/25$, $p < .002$).

language, reading, and phonology measures. For the vocabulary composite (see Table 6), as much as 19% of unique variation was explained by these auditory processing measures. For the phonological awareness composite (see Table 7), up to 31% of unique variance was accounted for by individual differences in rise time and duration processing. For the working memory composite (see Table 8), rise time and Duration Discrimination Task 2 both contributed 17% additional variance. All three measures were able to account for significant additional variance in the reading and spelling composite variable (see Table 9). The Duration Discrimination Task 1 (briefer sounds) task accounted for the most additional variance, explaining 21% of the variance in the reading composite variable.

The results of the regression equations show that individual differences in auditory processing of rise time and duration explained between 10.7% and 31.2% of unique variance in vocabulary attainment, phonological awareness, and reading. It is important to recall that IQ and an estimate of children's attention to task were controlled in these analyses. In contrast to the results obtained for the amplitude envelope onset and duration measures, the measures of rapid auditory processing and intensity discrimination that we included showed no significant relationships. This mirrors the developmental dyslexia literature. Intensity discrimination has not been found to be impaired in groups of children with dyslexia. Even when group differences have been found in the TOJ task used here, individual differences in TOJ rarely predict unique variance in phonological awareness and literacy (Goswami et al., 2002; Muneaux et al., 2004; Ramus et al., 2003; Richardson et al., 2004).

As an additional measure of whether the poor performance of children with SLI in the psychoacoustic tasks was due to a subgroup of children with especially severe language, working memory, or literacy difficulties, a series of good–poor splits were applied to the sample. Children with SLI were divided into "good" and "poor" groups for each

Table 7. Stepwise regressions of the unique variance in phonological awareness ability accounted for by the psychoacoustic variables.

	Phonological awareness ability				
Step	Model 6	Model 7	Model 8	Model 9	Model 10
1. Age					
β	−.050	−.272	−.155	−.082	−.126
ΔR^2	.006	.006	.004	.006	.006
2. Performance IQ					
β	.083	.084	−.117	.054	.044
ΔR^2	.005	.005	.006	.006	.005
3. Intensity					
β	.016	.052	−.071	.041	−.093
ΔR^2	.017	.017	.016	.018	.017
4. Two-ramp rise time					
β	−.335				
ΔR^2	.091				
4. One-ramp rise time					
β		−.615[a]			
ΔR^2		.296			
4. Duration 1					
β			−.482[a]		
ΔR^2			.218		
4. Duration 2					
β				−.586[a]	
ΔR^2				.312	
4. TOJ threshold					
β					−.387
ΔR^2					.145

Note. $n = 63$. The composite phonological awareness score includes Phoneme Deletion and Rime Oddity.

[a]Change in R^2 significant using a Bonferroni-corrected alpha ($\alpha/25$, $p < .002$).

of the vocabulary, working memory, reading, and spelling tasks, making a total of 8 good–poor splits. "Poor" performance was judged to be below 1 *SD* of the standardized mean (below 85) or the standard mean (below 7), depending on the test. Each of the pairs of groups yielded by the vocabulary, working memory, spelling, and reading good–poor splits was entered into a series of one-way between-group ANOVAs, with each of the psychoacoustic measures as the dependent variable. This resulted in 56 one-way ANOVAs. No significant main effect of group was found for any of the psychoacoustic measures. Hence, in no case did the "poor" group appear to be carrying the auditory processing deficits found in the whole-sample analyses, even when working memory was the subgrouping variable.

Discussion

The ongoing debate concerning whether children with SLI can be characterized by a rapid auditory processing deficit (e.g., Rosen, 2003; Tallal, 2004) has obscured the possibility that these children could have a range of auditory processing difficulties. Ours is the first study of which we are aware that examines the amplitude rise time and duration processing abilities of children with SLI. The deficits that we have documented are remarkably consistent across children with SLI. The majority (70%–80%) of children in our sample performed below the 5th percentile of performance achieved by control participants for detecting both amplitude envelope rise time and the duration of simple tones. A minority also had a rapid auditory processing deficit. Individual differences in the rise time and duration processing measures accounted for a significant amount of variability in standardized measures of language and reading and in experimental measures of phonological awareness; individual differences in rapid auditory processing did not. The data indicate that the auditory processing difficulties that are most strongly predictive of language and phonology in children

Table 8. Stepwise regressions of the unique variance in reading and spelling awareness ability accounted for by the psychoacoustic variables.

	Reading and spelling ability				
Step	Model 11	Model 12	Model 13	Model 14	Model 15
1. Age					
β	.207	.017	.117	.197	.141
ΔR^2	.039	.039	.044	.047	.039
2. Performance IQ					
β	.051	.052	.073	.078	.017
ΔR^2	.001	.001	.001	.006	.001
3. Intensity					
β	−.039	−.013	−.106	−.088	−.136
ΔR^2	.028	.028	.024	.045	.028
4. Two-ramp rise time					
β	−.297				
ΔR^2	.071				
4. One-ramp rise time					
β		.523[a]			
ΔR^2		−.214			
4. Duration 1					
β			−.420[a]		
ΔR^2			.166		
4. Duration 2					
β				−.421[a]	
ΔR^2				.161	
4. TOJ threshold					
β					−.332
ΔR^2					.100

Note. $n = 63$. The composite reading score includes TOWRE Sight Word Efficiency, TOWRE Phoneme Decoding Efficiency, WORD Reading Comprehension subtest, and British Ability Scales Spelling subtest.

[a]Change in R^2 significant using a Bonferroni-corrected alpha ($\alpha/25$, $p < .002$).

with SLI are found in tasks requiring the integration of temporal information over relatively long temporal windows.

As noted earlier, there was no overlap in terms of sampling between the children included in this study and the children tested in our studies of developmental dyslexia (Goswami et al., 2002; Muneaux et al., 2004; Richardson et al., 2004; see also Rocheron, Lorenzi, Fullgrabe, & Dumont, 2002). The children in the present study were referred by speech-language therapists and had a statement of SLI from their local education authorities. No child had a diagnosis of dyslexia. The children with developmental dyslexia in our previous studies had no diagnosis of speech and language impairments and no history of developmental language problems, but they did have a specific impairment in reading. Nevertheless, it is of interest to compare the pattern of results found here with those found in prior studies of children diagnosed with developmental dyslexia. The most comparable study is that reported by Richardson et al. (2004). In that study, the two-ramp rise time task used here accounted for 13% of unique variance in a rime oddity task after controlling for age, verbal and nonverbal IQ, and vocabulary ($p < .01$), and for 8% and 11% of unique variance in reading and spelling, respectively (ps $< .05$). In the current study, the two-ramp rise time task accounted for 9% of unique variance in the phonological composite, 7% of unique variance in the reading/spelling composite, and 7% of variance in the rapid naming task (all nonsignificant). The stimuli used here for the one-ramp rise time task were used in an AXB task format with children with developmental dyslexia (Richardson et al.). Individual differences in this AXB task accounted for 9% of unique variance in rime oddity after controlling for age, IQ, and vocabulary ($p < .05$) and accounted for 8% of unique variance in reading and 13% of unique

Table 9. Stepwise regressions of the unique variance in working memory ability accounted for by the psychoacoustic variables.

Step	Working memory ability				
	Model 16	Model 17	Model 18	Model 19	Model 20
1. Age					
β	−.065	−.224	−.136	−.075	−.117
ΔR^2	.003	.003	.002	.002	.003
2. Performance IQ					
β	.076	.076	.092	.069	.040
ΔR^2	.003	.003	.003	.005	.003
3. Intensity					
β	−.152	−.081	−.195	−.107	−.186
ΔR^2	.048	.048	.053	.054	.048
4. Two-ramp rise time					
β	−.160				
ΔR^2	.021				
4. One-ramp rise time					
β		−.469[a]			
ΔR^2		.172			
4. Duration 1					
β			−.337		
ΔR^2			.107		
4. Duration 2					
β				−.429[a]	
ΔR^2				.167	
4. TOJ threshold					
β					−.344
ΔR^2					.115

Note. $n = 63$. The composite working memory score includes Nonword Repetition and Working Memory Scales for Children Word subtest.

[a]Change in R^2 significant using a Bonferroni-corrected alpha ($\alpha/25$, $p < .002$).

variance in nonword reading (ps < .01). In the current study, the one-ramp rise time task accounted for 30% of unique variance in the phonological awareness composite and 21% of unique variance in the reading composite (ps < .002 using Bonferroni corrections). The duration task used by Richardson et al. used speechlike VCV syllables ("ata," "atta"), and the children with developmental dyslexia had to decide which syllable was longer. Individual differences in duration detection accounted for 10% of unique variance in real word reading after controlling for age, IQ, and vocabulary ($p < .01$), for 8% of unique variance in spelling ($p < .05$), and for 12% of unique variance in nonword reading ($p < .01$). In the current study, the tone duration tasks accounted for 22% and 31% of unique variance in the phonological awareness composite (shorter vs. longer sounds, respectively), 17% and 16% of unique variance in the reading/spelling composite, and 13% and 18% of unique variance in rapid naming (all ps < .002). The TOJ threshold measure did not account for any significant unique variance in phonological awareness or literacy in the current sample. This replicates the findings for children with developmental dyslexia using the same dog/car TOJ task reported by Richardson et al. (2004). Overall, therefore, the relationships among auditory processing, phonological awareness, and literacy are very similar in both samples of children with a developmental language disorder. However, the relationships appear stronger in terms of absolute variance accounted for in the sample of children with SLI.

One explanation for the apparent severity of the difficulties experienced by the current sample of children with SLI is that task complexity and attentional factors might be especially problematic for such children. To attempt to control for attentional factors, we tested our sample on auditory variables that we either did or did not expect to show a deficit, using the same psychoacoustic

Table 10. Stepwise regressions of the unique variance in rapid color naming ability accounted for by the psychoacoustic variables.

	Rapid color naming ability				
Step	Model 21	Model 22	Model 23	Model 24	Model 25
1. Age					
β	−.040	.094	.041	−.103	.021
ΔR^2	.000	.000	.001	.000	.000
2. Performance IQ					
β	−.166	−.168	−.200	−.153	−.140
ΔR^2	.022	.022	.025	.124	.022
3. Intensity					
β	.071	.105	−.156	.080	.177
ΔR^2	.041	.041	.039	.045	.041
4. Two-ramp rise time					
β	.302				
ΔR^2	.073				
4. 1-ramp rise time					
β		.333			
ΔR^2		.087			
4. Duration 1					
β			.382[a]		
ΔR^2			.138		
4. Duration 2					
β				.447[a]	
ΔR^2				.181	
4. TOJ threshold					
β					.269
ΔR^2					.070

Note. $n = 63$.

[a]Change in R^2 significant using a Bonferroni-corrected alpha ($\alpha/25$, $p < .002$).

paradigm. As expected on the basis of prior work with children with dyslexia (Richardson et al., 2004), no impairments were found in the two-interval forced-choice psychoacoustic procedure for intensity discrimination, but significant impairments were found using the same procedure for rise time and duration. It could, nevertheless, be argued that the PEST procedure used was vulnerable to lapses in attention, as indeed all such procedures are. However, this should have affected all tasks equally, rather than selected tasks only. As a further control, when exploring relationships between the auditory variables and the outcome measures using multiple regression techniques, we used performance in the intensity task as an estimate of the children's attention to task before investigating specific relations between auditory processing, language, reading, and phonology. The relations reported were those remaining after controlling for age, nonverbal IQ, and this estimate of attention to task. The same logic applies to alternative objections that our findings may reflect working memory deficits in the sample of children with SLI. If problems with working memory in the children with SLI explain our auditory findings, then the children should have been impaired in all of the psychoacoustic tasks. They were not. Also, it could be argued that the Duration Discrimination 2 task should have been significantly more difficult than the Duration Discrimination 1 task, because the stimuli were longer (creating a larger memory load). It was not. Finally, it could be that we are demonstrating differences in learning rather than underlying differences in basic auditory processing abilities. Because each auditory task was given only once, it is impossible to separate learning of the task from underlying auditory capabilities. Nevertheless, because performance remained poor in tasks received later (e.g., Duration Discrimination Task 2), learning effects across auditory tasks appears unlikely.

We submit that these auditory data are interesting for a number of reasons. First, they provide converging evidence for the view that quite low-level processes might be important in explaining the etiology of developmental language disorders. Certainly, lower level processes are an important determinant of language acquisition. Recent studies show that abilities as diverse as tracking the conditional probabilities in auditory sequences at 8 months of age, discriminating between two synthesized vowels at 6 months of age, and distinguishing syllable stress at 5 months of age, are related to language development (Saffran, Aslin, & Newport, 1996; Tsao, Liu, & Kuhl, 2004; Weber, Hahne, Friedrich, & Friederici, 2004). Electrophysiological studies also suggest that children with SLI differ from CA peers in peripheral and central neurological processing of nonspeech acoustic signals (e.g., Marler & Champlin, 2005; Marler, Champlin, & Gillam, 2002; McArthur & Bishop, 2005). The data presented here support the possibility that SLI could be caused by lower level processing difficulties in the auditory domain. With respect to our focus on the auditory cues of amplitude rise time and duration, it seems plausible that early difficulties, present from infancy, in accurately processing these cues to prosody could impair the acquisition of language via impaired word segmentation and the development of degraded phonological representations (Curtin et al., 2005; Juscyzk et al., 1999). An early insensitivity to auditory cues to rhythm and stress could have profound and lasting consequences on word segmentation and the development of the language system.

At the biological level, the recent work of Heil and colleagues is relevant. Biermann and Heil (2000) reported neurons in the auditory cortex of the cat that are specialized to detect the slopes of amplitude envelope onsets. The neurons respond selectively at different points of the amplitude onset slopes. Comparable response patterns were reported for humans in a parallel study using magnetoencephalography. This postulated neuronal mechanism should be activated by the rise-time-varying stimuli being used here. Neubauer and Heil (2004) considered the ability of the human auditory system to integrate sound over time and pointed out that classic accounts assume that the quantity ultimately integrated is sound intensity (e.g., Plomp & Bouman, 1959). Heil and Neubauer (2001, 2003) argued that their experiments suggested a different model of temporal integration, based on the integration of the sound's pressure envelope rather than its intensity. When stimuli of different durations and of different envelopes were used to characterize thresholds independent of envelope shape, temporal summation was found to depend on the pressure envelope and not on intensity. In terms of patients with hearing loss, Heil and Neubauer suggested that the effective portion of the stimulus changes as a consequence of hearing loss. There is an elevation in the baseline above which sound pressure is effective in driving the auditory system. A similar mechanism could be at work in the children being studied here. Auditory thresholds could be elevated in these children because of inefficient processing at the neuronal level, which could affect the effective portion of the stimulus.

The data also speak to the importance of cross-language studies when trying to understand etiology. For example, testing the phonological deficit hypothesis of developmental dyslexia across languages has been extremely fruitful in terms of refining our understanding of the developmental links between phonological representation and literacy (Ziegler & Goswami, 2005). Studies of basic auditory processing in dyslexia across languages are also finding consistent lower level deficits, notably in sensitivity to rise time and durational cues (Hamalainen, Leppanen, Torppa, Muller, & Lyytinen, 2005; Muneaux et al., 2004; Richardson, Leppänen, Leiwo, & Lyytinen, 2003). One possibility is that the different grammatical deficits found in samples of children with SLI across languages could reflect the ways in which stress is used to mark grammatical constructions in the languages that they are learning. To understand possible developmental links among syntax, rhythm, and stress, a good starting point would be a systematic analysis in different languages of the types of grammatical construction that should be impaired if the processing of stress cues were compromised. Children with SLI in languages other than English could then be studied to see whether they also lack sensitivity to rise time and durational cues and whether this insensitivity is linked in predictable ways to their ability to acquire particular grammatical distinctions in their language.

Finally, the data are more consistent with the view that there is a continuum of developmental language disorder (Catts, 1996) than with the view that SLI and developmental dyslexia are distinct syndromes (Bishop & Snowling, 2004). Although some studies have put the comorbidity for dyslexia and SLI as high as 50% (e.g., McArthur, Hogben, Edwards, Heath, & Mengler, 2000), other estimates of comorbidity are as low as 10% (Bishop & Snowling, 2004). Recently, Catts et al. (2005) reported only limited (but significant) overlap between dyslexia and SLI in a population-based sample of 527 school-age children. They concluded that the two disorders were distinct but were comorbid in some children. They also noted that a problem in phonological processing did not appear to be a major factor in SLI when it occurred in isolation from dyslexia. Nevertheless, the auditory processing deficits found in the children with SLI studied here were the same deficits found in previous studies of children with developmental dyslexia, only more severe (see Goswami et al., 2002; Muneaux et al., 2004; Richardson et al., 2004). Although it does not necessarily follow that similar performance is evidence of a shared root cause, it makes biological sense that language development and audition should be linked. An intriguing possibility is that the majority of children with developmental language disorders have auditory processing deficits that are brain based. However, the developmental trajectory of a core auditory deficit may vary depending on the severity of the deficit; the types of auditory processing most affected; reciprocal developmental interactions with phonology, semantics, and syntax; the language being learned by the child; and social cognition and environmental factors that lie outside the core language domain. Pinpointing etiology in developmental disorders is a very difficult task. Nevertheless, studies across languages that measure the lowest level deficits that can be discovered and then track developmental trajectories offer one of the best ways of uncovering the causal basis of speech and language disorders (Goswami, 2003; Tsao et al., 2004).

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