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Examining the nature of lexical processing in children with specific language impairment: Temporal processing or processing capacity deficit?

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ABSTRACT
The real-time lexical processing of children with specific language impairment (SLI) was examined, and the focus was to determine whether a temporal processing deficit or a general processing capacity deficit disrupts these children's lexical processing. A group of SLI children (mean age 8;3), a group of age-matched children (CA, mean age 8;1), and a group of receptive syntax-matched children (RS; mean age 6;7) completed a sentence processing task in which they monitored sentences for a target word appearing at the beginning, middle, or end of sentences. Sentences systematically varied with respect to containing either a high proportion of stop consonants (stop-loaded sentences) or a high proportion of nonstop consonants (nonstop-loaded sentences). Children also completed the Identification (ID) Speech Perception Task. On the sentence processing task, SLI children yielded significantly slower word recognition reaction time (RT) overall than both CA and RS controls. Sentence type had no effect on any subject group's RT. No Group × Sentence Type interaction was found. On the ID task, SLI children performed significantly worse than CA controls but similarly to RS children. No correlation was found between temporal processing and lexical processing (for either sentence type or sentences combined) for any group. The findings are interpreted to suggest that a general processing capacity limitation was responsible for the poor ID task performance and slower lexical processing of SLI children.

The comprehension of spoken language occurs in real time and requires the immediate processing and construction of meaning. Children with specific language impairment (SLI) have been shown to process spoken language more slowly than their typically developing age peers (Montgomery, 2000; Montgomery & Leonard, 1998; Stark & Montgomery, 1995) and some of their younger counterparts (Montgomery, 2000). In particular, these children demonstrate slower lexical processing (i.e., word recognition). The nature of this processing

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inefficiency, however, is not yet well understood. Montgomery and colleagues have proposed that these children's slower processing reflects less efficient linguistic operations (e.g., lexical retrieval, lexical integration). However, because of the temporal processing difficulties common to many of these children (e.g., Tallal et al., 1996; Tallal & Stark, 1981; Tallal, Stark, & Mellits, 1985a, 1985b), it is also possible that poor temporal processing may be a contributing factor. Although Stark and Montgomery (1995) examined the effects of both temporal and spectral properties of input on SLI children's lexical processing, their study yielded equivocal results regarding any specific temporal effects (see below for details). Another potential contributing factor is diminished general processing capacity. Children with SLI may have trouble handling the various demands of on-line processing tasks, in addition to being slower linguistic processors. In the present study, we investigate these two possibilities.

A MODEL OF WORD RECOGNITION: THE REVISED COHORT MODEL

Recent models of spoken language comprehension (Frauenfelder & Tyler, 1987; Gaskell, & Marslen-Wilson, 1997; Marslen-Wilson & Zwiterslood, 1989; McQueen, Cutler, Briscoe, & Norris, 1995; Pitt & Samuel, 1995), especially those pertaining to auditory word recognition, appear to be well suited to help us characterize the real-time lexical processing abilities of SLI children. Most current models regard word recognition as an automatic, data-driven process that is facilitated by context. An especially important feature of many of these models is that they provide for the interaction of perceptual processes with the various sources of language knowledge (i.e., phonological, syntactic, morphological, semantic). It is at the level of word recognition where this interaction has been studied, because it is here that a listener's linguistic knowledge presumably interfaces with acoustic–phonetic input (Marslen-Wilson & Tyler, 1980; Marslen-Wilson & Welsh, 1978; Pisoni & Luce, 1987; Salasoo & Pisoni, 1985).

Many word recognition theories assume there are several identifiable stages, the degree of modularity or interactivity of these stages varying from one theory to another. One influential model is the revised cohort theory (Frauenfelder & Tyler, 1987; Marslen-Wilson & Zwiterslood, 1989), which is regarded as an "interactive" staged model of word recognition. The theory details several hypothesized stages and their relationship to one another. Figure 1 is a schematic representation of the presumed stages of word recognition according to this model.

According to the revised cohort model, word recognition comprises various stages, including lexical contact, activation, retrieval and access, selection, and recognition and integration. Lexical contact and activation is assumed to operate as an autonomous prelexical stage of processing, in that the sensory form of the input word undergoes an acoustic–phonetic analysis prior to a linguistic analysis. During lexical contact, listeners synthesize several form-based representations from the sensory input and then match them to lexical items stored in long-term memory. Those words that match the contact representations then become activated. This initial set of activated words is referred to as the word-initial cohort. For this study, we will refer collectively to these stages as the

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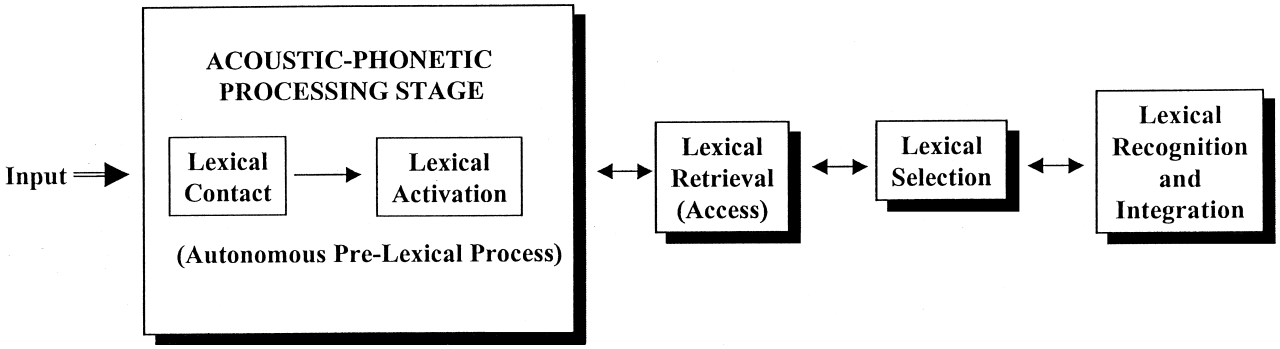


Figure 1. A schematic representation of the putative stages of word recognition according to the revised cohort theory.

acoustic–phonetic processing stage. Our primary focus on this stage is on the sensory processing of the signal, not the establishment of the word-initial cohort per se.

It is during the acoustic–phonetic processing stage that listeners continually and rapidly process the intake of acoustic–phonetic information of a word. Experimental evidence reveals that listeners have the ability to use subphonetic cues (i.e., temporal and/or spectral) of prior speech segments to help predict and identify an upcoming phonetic segment and facilitate word recognition (Lahiri & Marslen-Wilson, 1990; Warren & Marslen-Wilson, 1988). It has been further argued that word-onset information, in particular, holds special status and priority in the word recognition system. This is because it is on the basis of word-initial information (i.e., about the first 150 ms) that listeners presumably are able to align the stimulus with possible word candidates in the mental lexicon and activate a word-initial cohort.

During lexical access and retrieval, the linguistic properties (e.g., syntactic, morphological, semantic) that are functionally associated with the set of activated words are retrieved and made available to the rest of the language processing system. The linguistic properties of the competing word candidates are then assessed for syntactic and semantic appropriateness relative to prior context. Activated words that are inconsistent with subsequent sensory information and prior context become inhibited. The remaining lexical entry best matching both sources of constraint is finally selected, recognized, and integrated into context. The interactivity of the model is reflected in the fact that listeners often can recognize words in context before their acoustic offset. (However, see Pisoni, Nusbaum, Luce, & Slowiaczek, 1985, and Wingfield, Goodglass, & Lindfield, 1997, for findings related to recognition after word offset.) Although the acoustic–phonetic processing stage initiates the word recognition process, "later" stages may influence the sensory processing of the signal to the extent that word recognition may be derived from less than full acoustic specification of the word.

LEXICAL PROCESSING IN SLI CHILDREN

Few studies have examined the real-time processing of spoken language in SLI children in general, and fewer still have investigated the potential role of perceptual/temporal processes on lexical processing specifically. Most of these studies have employed a word recognition reaction time (RT) task within the context of a sentence processing paradigm (Montgomery, 2000; Montgomery & Leonard, 1998; Montgomery, Scudder, & Moore, 1990; Stark & Montgomery, 1995). Real-time language processing studies allow investigators to examine the unconscious mental representations and operations that are automatically invoked during the course of comprehension (Tyler, 1992) and the interaction of perceptual and linguistic processes. In addition, investigators also can examine the effects of various linguistic and acoustic modifications on listeners' lexical processing. This paradigm has proved to be a sensitive measure of both lexical processing (Montgomery, 2000; Montgomery et al., 1990; Stark & Montgom-

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ery, 1995) and the processing of bound grammatical morphemes by SLI and control children (Montgomery & Leonard, 1998).

The results of the few word recognition studies indicate that SLI children are slower to recognize sentence-embedded words compared to age-matched (CA) (Montgomery, 2000; Montgomery & Leonard, 1998; Stark & Montgomery, 1995) and younger, receptive syntax-matched (RS) children (Montgomery, 2000). Based on the overall pattern of results from each study, less efficient linguistic processing (e.g., lexical retrieval, integration) has been asserted as the main culprit in these children's slower lexical processing, not faulty acoustic–phonetic processing. The results of the Stark and Montgomery (1995) study are especially intriguing because they show that the processing of acoustic–phonetic content (i.e., temporal and spectral cues) interacts in complex ways with semantic and syntactic processes. These investigators examined the effects of time compression and low-pass filtering on children's word recognition during sentence processing. Relative to both the filtered and unaltered conditions (i.e., sentences that were not manipulated by low-pass filtering or time compression), all of the children showed faster word recognition RT in the time compression condition. By contrast, compared to the time compression sentences, all of the children demonstrated slower word recognition RT in the filtered condition. These investigators suggested that reduced access to spectral cues, and not the temporal character of the input, leads to greater difficulty in lexical processing for both SLI and control children. Also, regardless of condition, the SLI group demonstrated slower RT than their age peers. These results, coupled with the absence of a Group × Sentence Condition interaction, were interpreted to suggest that the slower RT of the SLI children was attributed to slower linguistic processing, not to acoustic–phonetic processing difficulties. However, this conclusion must be interpreted with caution. First, no independent measure of temporal processing was reported. Second, the phonetic content of the sentences was not controlled. Third, and most important, because the time compression algorithm used to speed up the sentences decreased *all* pitch period segments by a proportional amount, it is impossible to ferret out what the specific differential effects of temporal versus spectral cues might have had on the children's lexical processing. The question thus remains whether a temporal processing problem (i.e., difficulty in processing brief-duration speech segments) might contribute to these children's slower lexical processing.

TEMPORAL PROCESSING IN SLI CHILDREN

Many SLI children are thought to suffer from a primary temporal processing deficit (e.g., Stark & Tallal, 1988; Tallal & Piercy, 1975; Tallal & Stark, 1981; Tallal et al., 1985a, 1985b, 1996; Wright, Lombardino, King, Puranik, Leonard, & Merzenich, 1997). According to Tallal's notion of temporal processing, SLI children have particular trouble processing rapidly presented information, whether linguistic or nonlinguistic, and this difficulty directly hinders their language processing and subsequent language learning. In the present study, we focus on the temporal speech processing abilities of SLI children, heretofore referred to only as temporal processing.

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The view that SLI children suffer from a temporal processing deficit derives from findings reported by Tallal and colleagues showing that SLI children, relative to CA peers, have markedly greater difficulty processing (i.e., identifying, discriminating, remembering, sequencing) speech containing rapid consonant–vowel (CV)/vowel–consonant formant transitions (i.e., brief duration stop consonants). When these brief-duration segments are lengthened, SLI children and their CA peers demonstrate comparable performance. The general conclusion advanced by Tallal and her collaborators is that it is the brevity of the information, and not the character of the formant transition per se, that gives rise to imparied speech perception by SLI children. Moreover, Tallal and associates have argued that the receptive language impairment of these children, in particular, is secondary to a temporal processing deficit. In support of this interpretation, these researchers have reported that performance on rapid rate perception tasks by SLI children is highly correlated with the level of receptive language impairment ($r = +.83$) but not expressive language (Tallal et al., 1985b). However, not all investigators have shown SLI children to have temporal processing problems. For instance, Bishop and colleagues (Bishop, Carlyon, Deeks, & Bishop, 1999) reported that their SLI children performed no worse than their CA peers across a variety of nonlinguistic auditory processing tasks. In a study by Nittrouer (1999), reading disordered children showed no evidence of temporal processing difficulties compared to a control group on several tasks using synthesized brief-duration speech stimuli, despite the reading impaired children showing a variety of phonological and linguistic processing deficits.

Although the evidence for temporal processing difficulties in SLI children is mixed, their "causal" significance to the condition of SLI is highly controversial (e.g., Johnston, 1994; Leonard, McGregor, & Allen, 1992). Most pertinent to the present study is that research to date has been concerned exclusively with the association between temporal processing and performance on "off-line" language (comprehension) tasks (e.g., Fellbaum, Miller, Curtiss, & Tallal, 1995; Nittrouer, 1999; Tallal et al., 1996). Equally important is whether and how the temporal processing abilities of these children relate to their slower language processing. Because language processing is dependent on the immediate conversion of a transient acoustic signal into linguistic meaning, examining such a relation would provide us with a better understanding of the nature of the interaction of perceptual and linguistic processes as they operate in the moment in SLI children. Examining this interaction is important because it has been proposed by some researchers (e.g., Dorman, Cutting, & Raphael, 1975; Phillips, 1999) that formant transitions might play an important integrating function regarding the perception of phonetic segments, thereby helping to preserve the perceived temporal order of speech. Difficulty in tracking rapidly occurring formants in running speech might cause some SLI children to confuse the order of segments within words or the order of words within larger units, as suggested by Kamhi, Lee, and Nelson (1985). Finally, it is important to point out that the temporal processing deficit claim has been based primarily on SLI children's difficulty in processing synthetic speech. An important question is whether such findings translate into less efficiency in processing natural running speech.

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PROCESSING CAPACITY LIMITATIONS IN SLI CHILDREN

A number of researchers have proposed that SLI children possess less general processing capacity than typically developing peers (e.g., Bishop, 1994; Ellis Weismer & Hesketh, 1996; Johnston, 1994; Kail, 1994; Leonard et al., 1992; Montgomery, 1995, 2000; Windsor & Hwang, 1999). The basic idea is that SLI children have fewer cognitive resources to allocate to any given task and when task demands exceed these resources poor performance occurs. Limitations in processing capacity have been conceptualized in different ways by different investigators. In models that regard capacity from a more functional point of view (e.g., Kail & Bisanz, 1982; Kail & Salthouse, 1994), capacity represents the amount of work performed within a given unit of time, where speed, efficiency, and the power of processing routines or schemes are of the essence. The generalized slowing hypothesis proposed by Kail and colleagues (Kail, 1994; Miller, Kail, Leonard, & Tomblin, 2001) is an example of such a model. According to this model, regardless of task nature and modality, many SLI children, compared to CA control children, are slower to perform all tasks by a proportional amount. By contrast, structural models view capacity primarily as a function of the amount of work space (e.g., working memory) available to perform complex mental tasks requiring both information storage and processing (e.g., Baddeley, 1986; Just & Carpenter, 1992). Relative to typically developing peers, SLI children have been shown to have less phonological working memory capacity or storage (Dollaghan & Campbell, 1998; Gathercole & Baddeley, 1990; Montgomery, 1995) and functional working memory capacity (Ellis Weismer, Evans, & Hesketh, 1999; Montgomery, 2000). Although the emphasis of structural models is on available work space, processing speed is implicit, because all processing is time dependent. Kail's generalized slowing hypothesis would appear to be the most applicable model to the present study, but our tasks (and analyses) were not specifically designed to test the model; therefore, a structural view of processing capacity will be taken.

Especially relevant to the present study is the potential relation between the temporal processing difficulties and processing capacity limitations of SLI children. Some researchers have interpreted SLI children's poor performance on various speech perception tasks, including the identification (ID) task to be used here, to reflect not a temporal processing problem, but rather a limitation in general processing capacity (Hanson & Montgomery, in press; Leonard et al., 1992; Sussman, 1993). In Tallal and Stark's ID task, during training, children learn to associate one syllable (e.g., [*ba*]) with a particular button and a second syllable (e.g., [*da*]) with another button. During the experiment proper, children are presented with one of the syllables and asked to point to the corresponding button. A processing capacity account assumes that SLI children do not have special difficulty perceiving the difference between brief-duration syllables. Their difficulty lies with handling the various processing demands of the task. Such a task presumably incorporates such demands as attending to the stimuli, establishing and storing a template or representation of each syllable in short-term memory, learning to associate each syllable with a specific dot, identifying

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or classifying the input syllable correctly by comparing it with the stored template, deciding which dot to point to, and making a motor response. Successful task performance also ultimately hinges on the child's ability to identify or classify the input stimulus in a timely fashion, before it fades from short-term memory. Supporting evidence for such a view is provided by the results of a study by Hanson and Montgomery (in press). They compared SLI and CA children's performance on the same ID task to be used in this study with their performance on a standard discrimination task. It was reasoned that the discrimination task entailed fewer cognitive demands than the ID task. Children only had to listen to syllable pairs and push a response pad as quickly as they could on all "same" stimulus pairs. Thus, children simply judged whether two syllables were the same; no ID or classification was required. It was hypothesized that if the SLI children had a basic temporal processing deficit they should show poor performance on both tasks. The dependent variables for the discrimination task were accuracy and RT. The results revealed a significant group difference on the ID task but no group difference in accuracy or RT in the discrimination task. These findings were taken to suggest that the SLI and control children indeed had comparable temporal processing abilities and that the SLI children's trouble on the ID task was due to difficulty managing the multiple processing demands in a timely manner. In the present study, if the SLI children perform worse than control children, it will maintain a processing capacity limitation interpretation.

The construct of limited processing capacity may also have relevance to SLI children's on-line language processing. Although word recognition tasks are designed to minimize extraneous, off-line processing requirements (Tyler, 1992), it is possible that SLI children's slower lexical processing is a reflection of diminished processing capacity, and not just slower linguistic processing. In addition to being slower to invoke various linguistic operations, SLI children may also be inefficient at managing the various other demands of the task, which presumably include sustaining focused attention, remembering the target word, and remembering to push the button immediately upon recognizing the target but withholding a response on all other words.

The purpose of the present study was to examine whether poor temporal processing or diminished general processing capacity better accounts for the slower lexical processing of SLI children. To address this issue, children monitored sentences of two sorts (stop-loaded sentences and nonstop-loaded sentences) for a target word located at the beginning, middle, or end of a sentence. Children also completed the ID task (Tallal & Stark, 1981), which has been used as an index of children's temporal processing by Tallal and colleagues (e.g., Tallal & Stark, 1981).

PREDICTIONS

If Tallal's temporal processing deficit hypothesis is valid, our primary prediction would be that the SLI children should yield slower word recognition RT for stop-loaded sentences versus nonstop-loaded sentences. These predictions derive from the logic that a temporal processing difficulty should disrupt the earliest

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Table 1. *Chronological age, PPVT standard score, receptive language score (RLS), and expressive language score (ELS) on the CELF–R; mean number of blocks passed (and standard score) on the Test of Reception of Grammar (TROG); and mean mental quotient (IQ) on the Test of Nonverbal Intelligence for the SLI, CA, and RS children*

Group	Age (months)	PPVT	CELF–R RLS	CELF–R ELS	TROG	IQ
SLI						
M	99.3	89.7	77.5	71.9	12.4 (81)	102.6
SD	14.9	15.1	4.8	7.5	1.8	10.7
Range	82–125	61–108	70–82	54–81	9–15	89–125
CA						
M	97.1	110.5	108.8	106.6	17.1 (106)	106.5
SD	15.6	9.8	10.7	8.9	1.6	7.6
Range	79–127	89–128	89–122	95–124	13–19	95–121
RS						
M	78.9	106.6	101.8	100.8	12.5 (97)	105.7
SD	9.5	10.4	6.9	7.6	1.8	6.6
Range	66–96	83–126	91–115	88–118	9–15	94–116

stage of word recognition (i.e., the acoustic–phonetic processing stage) and that this disruption should reveal itself in those sentences presumably entailing the greatest temporal processing load. The control children's lexical processing should be unaffected by the nature of input and be faster than the SLI children's. We also would predict a positive correlation between performance on the ID task and the word recognition task in the SLI children. If diminished general processing capacity undermines SLI children's word recognition, the primary prediction would be that no Group × Sentence Type interaction should emerge; SLI children (who should yield overall slower RT than control children) should perform equally poorly in each sentence condition.

METHOD

Participants

Recruited for this study were 21 SLI children (mean age 8 years;3 months), 21 with normal language matched for CA (mean age 8;1), and 21 with normal language matched for levels of RS knowledge (mean age 6;7). Descriptive summary data for each group appear in Table 1. All of the SLI children met the following language-specific criteria. First, they performed greater than −1 *SD* from the mean on at least two of the three receptive subtests and more than −1 *SD* on two of three expressive subtests on the Clinical Evaluation of Language Fundamentals–Revised (CELF–R, Semel, Wiig, & Secord, 1987). Second, they attained an overall receptive language score and an overall expressive langauge score that fell at a minimum more than −1 *SD* from the mean. Third, they

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performed greater than 1 *SD* below the mean on the Test of Reception of Grammar (TROG, Bishop, 1989). The CA and RS children performed at or above −1 *SD* from the mean on the same language measures. Children's single word receptive vocabulary knowledge was also assessed using the Peabody Picture Vocabulary Test–Revised (PPVT–R, Dunn & Dunn, 1981), although no performance critierion was set to be eligible for the study. Using raw score as the dependent variable, the groups were found to differ on PPVT, $F(2, 60) = 17.72$, $p < .001$; the SLI children attained a significantly lower score, Tukey honestly significant difference (HSD), $p \leq .05$, than either the CA or RS children and the RS group attained a lower score than the CA children. Each SLI child was matched with a same-gender CA child (±3 months) and a same-gender RS child on the number of blocks passed on the TROG. A significant group difference was found for the number of blocks passed, $F(2, 60) = 49.42$, $p < .00$, and the CA children passed more blocks than both RS and SLI groups, Tukey HSD, $p \leq .05$, who did not differ.

All children demonstrated normal-range nonverbal IQ (85–125) on the Test of Nonverbal Intelligence (TONI; Brown, Sherbenou, & Johnsen, 1990), normal-range hearing sensitivity as determined by audiometric pure-tone screening at 20-dB HL (ANSI, 1989), and no oral structural or motor impairments affecting speech or nonspeech movements of the articulators (Robbins & Klee, 1987). None of the children were judged to have any difficulty sustaining different vowels or rapidly producing various syllables in isolation or in combination (e.g., [ma], [ba], [ta], [ka]). They also demonstrated normal or corrected vision and articulation abilities that fell at or above the 67th percentile on the Goldman–Fristoe Test of Articulation (1986). Also, all of the children were judged to produce intelligible conversational speech, demonstrating few, if any, phonological problems. The groups did not differ on the TONI, $F(2, 60) = 1.87$, $p > .05$. The children had no history of frank neurologic impairment, psychological and emotional disturbance, or attention deficit disorder (from parent report). For each child, the number of years of education attained by the mother was also obtained. No significant differences emerged across groups with respect to the number of mothers who attained a college education, $\chi^2(2) = 1.76$, $p > .05$. Each group included 13 boys and 8 girls. Within the SLI group, 5 children were Black or of Hispanic or Asian descent. In the CA and RS groups combined, 5 children were Black or of Hispanic or Asian descent. To adjust for potential dialectical variations of the Black children, responses on each of the expressive subtests of the CELF–R were evaluated relative to the dialectical variations outlined by Washington and Craig (1994).

Sentence processing and word recognition RT task

Sentence type conditions. Two sentence type conditions were created to test the hypothesis that sentences requiring "heavy" temporal processing should pose greater lexical processing difficulties for SLI children than sentences requiring fewer such demands. Forty-two sentence pairs were created for a stop-loaded condition and 42 sentence pairs for a nonstop-loaded condition. Stop-loaded

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sentences contained a high proportion (84%) of brief-duration stop consonants. Nonstop-loaded sentences included a high proportion (79%) of nonstop consonants (e.g., fricative, nasal, liquid, glide).

From a high quality tape of the experimental sentences, two independent listeners transcribed all of the stimuli using broad phonetic transcription to identify all stop segments in the stop sentences and all nonstop segments in the nonstop sentences. A point to point intertranscriber agreement of greater than 95% was obtained for each sentence type. Both sentence types included a similar range of constructions and vocabulary appropriate to 5-year-olds' comprehension and production abilities (e.g., Miller, 1981). No differences were found between sentence types for such features as number of clauses, $t(41) = .374$, $p > .02$, total number of words, $t(41) = 1.49$, $p > .02$, or mean length of utterance, $t(41) = 2.77$, $p > .02$, across stimulus sentence pairs. The rationale for using familiar syntactic structures was to control for potential group differences in syntax knowledge, thereby isolating potential temporal and lexical processing differences between the SLI and control children. The first sentence in each pair ranged from 4 to 12 words and served as a topic sentence. The second sentence ranged from 11 to 14 words. All words preceding the target were acoustically dissimilar to the target, thereby preventing acoustically based false alarms. Twelve catch trials per sentence condition were constructed in which a target word did not appear in the second sentence. Catch trials were included to identify children with an impulsive response style.

Target words. Target words included 42 highly familiar monosyllabic words (e.g., duck, fish, dad, milk, bike; e.g., Moe, Hopkins, & Rush, 1982). Target words appeared in the 5th, 7th, or 10th word position of the second sentence of each sentence pair. The purpose of varying word position was to prevent the children from guessing the location of the target.

The 84 experimental sentences (and 24 catch trials) were arranged into four sets of equal numbers of sentences. Each set contained approximately equal numbers of stop and nonstop sentences arranged in random order. Three orders of the four sets were created.

Target word and sentence generation procedures

A list of individual target words corresponding to the target words appearing in the sentences and the stimulus sentences were read aloud by an adult male native speaker of American English. High quality recordings of all materials were made in a sound treated booth. Individual target words were read in list fashion. The sentences were read at a normal rate with normal prosodic variation. Prior to waveform editing, each recorded sentence was low-pass filtered (4.5 kHz), digitized (10 kHz), and stored on a disk. Each digitized audio waveform was edited interactively using the ASYST software package to identify the acoustic onsets and offsets of each sentence-embedded target word. The edited stimuli were stored on a disk, later played out (10 kHz), and low-pass filtered (4.5 kHz) from a PC laboratory computer to the subject. A 500-Hz timing pulse was synchronized to begin at sentence-one onset. The timing tone, inaudible to

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the subject, was used during the experiment to trigger an external clock that was used to capture subjects' word recognition RT. For each sentence, its corresponding isolated target word was low-pass filtered (4.5 kHz), digitized (10 kHz), and stored on a disk. Each target word was later played out (10 kHz) and low-pass filtered (4.5 kHz) to the subject 1 s prior to its corresponding stimulus sentence.

Procedure. Children were tested individually in an acoustically isolated booth over three or four testing sessions. A trained graduate student (second experimenter) sat with the child in the testing booth while the experimenter (J.W.M.) sat in an adjoining control room delivering the stimuli. All sentence stimuli were delivered to the child binaurally via headphones at a comfortable listening level.

Four live-voice practice items and 12 computer practice items preceded the experimental items. Children were told to listen to some "short stories" and to push a response pad as quickly as they could as soon as they heard the target word in the "story." Again, both response accuracy and speed were stressed to the children in the instructions and practice trials, as well as during the experimental task. Prior to stimulus presentation, children were shown a picture of the target word by the second experimenter and heard the target word presented in isolation via the computer.

Throughout testing, children received constant encouragement and praise and, as needed, reminders to "stay focused." These forms of nonspecific feedback were intended to maximize both motivation and RT performance. Children also received a small toy after each testing session, with the intent of providing further motivation to perform well on the tasks. The children's responses (pad press) stopped the clock. Responses occurring prior to target word onset (i.e., negative RT) were scored as false alarms, and failures to respond were scored as misses. Children's RTs were computed by a custom-written program and stored on the computer. The RT was automatically calculated by the computer as the difference between the target word onset and the time the child pressed the response pad.

Auditory detection RT task

Because some SLI children show slower RT than CA controls on a variety of tasks having little to do with language (e.g., Hughes & Sussman, 1983; Nichols, Townsend, & Wulfeck, 1995), we included a simple auditory detection RT task to serve as an index of motor response and auditory reception or sensation time, independent of linguistic processing. Children were instructed to press the response pad as quickly as possible in response to the onset of an imperative stimulus (1-s 2-kHz pure tone), which followed a warning tone (500-ms 500-Hz tone). Again, both response accuracy and speed were stressed to the subject. Following five live-voice practice trials (i.e., examiner producing a "low beep" followed by a "high beep" and demonstrating the button press on the high beep) and 15 computer-delivered practice trials, 36 experimental RT trials (interstimulus interval [ISI] between warning and test tones varying randomly between 1.5 and 3 s) were presented. Children received constant encouragement and praise,

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as well as necessary reminders "to stay alert" or "focused" during the task. A mean auditory detection RT was calculated for each subject. This task also provided children with practice and familiarity with the word recognition RT task and enhanced intrasubject RT stability. This task always preceded the word recognition task. Each RT was automatically calculated by the computer as the difference between the onset of the imperative stimulus (high tone) and the time the child pushed the response pad.

Temporal processing task

To obtain a measure of children's ability to identify and respond to brief-duration speech segments, subjects were administered the ID Speech Perception Task by Tallal and Stark (1981). The stimulus contrast included the two-formant CV pair /ba/ and /da/, because this stimulus pair has consistently distinguished SLI children from CA control children and it contains the brief-duration acoustic properties relevant to the focus of this study. The stimuli were generated using a cascade software synthesizer (Klatt, 1980), implemented on a PDP 11/23 laboratory computer and later transferred to a CompuAdd 316 computer. Stimuli were synthesized at a sampling rate of 10 kHz. The stimulus characteristics were as follows: (a) the total syllable duration was 250 ms and the F_0 was 115 Hz until the last 50 ms, during which it fell linearly to 75 Hz; (b) the amplitude was 70 dB, dropping by 25 dB over the last 50 ms; (c) there was a /b/ and /d/ burst in the first 10 ms, after which the formants moved toward the steady-state portion of the vowel, which was 200 ms; (d) the formant transition durations were fixed at 40 ms; and (e) the syllables contained two formants. High quality training and experimental stimulus tapes were created.

Children were taught the task in three phases. First, following a six-trial demonstration by the experimenter instructing the subject to tap a yellow dot in response to the syllable /ba/, the child was encouraged to tap the yellow dot to 12 presentations of /ba/. Second, the same procedures were repeated for teaching the child to tap a green dot for /da/. Third, following the experimenter's demonstration of the appropriate alternating responses to 6 random trials of /ba/ and /da/, subjects heard 18 trials during which /ba/ and /da/ were presented randomly (ISI = 1.5 s). They were encouraged to tap the appropriate dot corresponding to each CV. Feedback was given after the first 6 trials. On the next 12 trials, children received no assistance or feedback but did receive constant encouragement and praise. If the children performed below 75% (9/12) on this phase, each of the three training phases was repeated once. Following this second training set, regardless of performance, the children completed the experiment proper, which entailed the presentation of 32 random trials of /ba/ and /da/.

Two counterbalanced orders containing the ID and word recognition tasks were developed. These counterbalanced orders were then presented across the children.

Data analysis

Prior to the analyses of each RT task, all outlying responses from a child's mean RT were eliminated from his or her data set (e.g., Fazio, 1990; Kail, 1991). In

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Table 2. *Mean number correct on the ID task (total possible = 32) and mean RT (ms) for the auditory detection RT task for the SLI, CA, and RS children*

	ID task	Auditory detection task
SLI	22.3	385
	(5.6)	(118)
CA	28.0	321
	(4.4)	(75)
RS	24.8	369
	(5.4)	(93)

Note: The numbers in parentheses are standard deviations.

each RT task, an outlier was defined as any RT ± 2 *SD* from a child's mean RT. In the word recognition task, outliers were identified according to word type, sentence type, and word position. For any child with missing RTs (i.e., false alarms, no responses, or outliers), an appropriate mean RT was calculated and then inserted into his or her data set and a new mean RT was then derived (Fazio, 1990) in order to yield a complete data set for each child for each task.

RESULTS

ID task

Results of a 1-way analysis of variance (ANOVA) revealed a significant group effect for the number of correct identifications, $F(2, 60) = 6.50$, $p < .01$. A post hoc Tukey analysis ($p < .05$) showed that SLI children performed worse relative to CA children but comparably to RS children. The CA and RS children did not differ. It should be noted that seven of the SLI children failed the initial training portion of the task, whereas four RS children and just two CA children failed. Table 2 displays group means and standard deviations for this task.

Auditory detection RT task

Less than 2% of each group's responses were eliminated because of outlying responses. No group differences emerged with respect to hit rates, $F(2, 60) = 2.66$, $p > .05$. The SLI children achieved a hit rate of 96%, CA controls achieved a hit rate of 95%, and RS children achieved a hit rate of 93%. A 1-way ANOVA indicated that the groups yielded a comparable mean RT, $F(2, 60) = 2.51$, $p > .05$. Because the groups did not differ in simple RT, this variable was not used as a covariate in the following analyses. Group means and standard deviations are displayed in Table 2.

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Table 3. *Mean number of false alarms and no responses in the word recognition RT task by the SLI, CA, and RS children*

	SLI	CA	RS
Number of false alarms	4.2 (2.1)	5.4 (3.0)	6.1 (2.8)
No responses	3.4 (2.3)	2.6 (2.1)	3.9 (2.5)

Note: The numbers in parentheses are standard deviations.

Table 4. *Mean word recognition RT (ms) by sentence type for the SLI, CA, and RS children*

	Stop sentences	Nonstop sentences	Grand mean
SLI	376 (122)	397 (139)	387 (131)
CA	295 (77)	305 (78)	300 (78)
RS	351 (96)	349 (89)	350 (92)

Note: The numbers in parentheses are standard deviations.

Word recognition RT task

Prior to the ANOVA, a power analysis was computed to ensure the detection of at least a moderate group difference, which revealed a power of .81. Less than 2% of each group's responses were eliminated as outliers. The groups yielded similar hit rates, $F(2, 60) = 2.99$, $p > .05$. The SLI and CA groups attained a hit rate of 95% and the RS children a hit rate of 93%. The groups did not differ with respect to either number of false alarms, $F(2, 60) = 2.83$, $p > .05$, or number of no responses, $F(2, 60) = 1.78$, $p > .05$. Table 3 shows false alarm and no response data for each group.

The results of a Group (SLI, CA, RS) × Sentence Type (stop-loaded, nonstop-loaded) repeated measures ANOVA revealed only a main effect for group, $F(2, 720) = 44.288$, $p < .001$. No significant effect for sentence type or a Group × Sentence Type interaction emerged. A post hoc 1-way ANOVA with Tukey HSD analysis, $p < .05$, indicated that the SLI children yielded significantly slower word recognition RT overall than either the CA or RS children. The CA children demonstrated faster RT than the RS children. Group means and standard deviations appear in Table 4.

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Table 5. *Correlation between ID task performance (using total number correct) and word recognition RT for stop-loaded sentences, nonstop-loaded sentences, and sentence conditions combined (using grand mean RTs) for the SLI, CA, and RS groups*

Sentences	SLI	CA	RS
Stop loaded	−.248	.074	−.216
Nonstop loaded	−.196	.019	.288
Combined	−.227	.074	−.216

Note: All correlations are nonsignificant, $p > .01$.

Relation between temporal processing and lexical processing

Next, we assessed the potential relation between temporal processing and lexical processing. For each group, we computed three Pearson Product Moment correlations ($p < .01$) between performance on the ID task (using total score) and performance on the (a) stop-loaded sentences (using grand mean RT), (b) nonstop-loaded sentences (using grand mean RT), and (c) both sentence conditions combined. For all groups, no significant correlations were found. The results of the correlational analyses are presented in Table 5.

DISCUSSION

We investigated whether the documented slower language processing of SLI children might be attributable to a basic temporal processing deficit or to a limitation in general processing capacity. We hypothesized that if poor temporal processing is a factor, this limitation should exert a local and specific influence on the acoustic–phonetic processing stage of word recognition. This prediction follows from the claim that it is here that listeners perform an immediate sensory analysis of input, prior to any linguistic analysis. We thus reasoned that SLI children, relative to control children, should have particular difficulty processing sentences incorporating high temporal processing demands (i.e., stop sentences) compared to sentences requiring less temporal processing. We also predicted a positive correlation between performance on the ID task and word recognition in the SLI children. On the contrary, a limited processing capacity account would predict SLI children should have no particular difficulty processing stop sentences; however, they should yield overall slower lexical processing than control children. Before discussing these possibilities, we first consider the results of the ID task.

ID task: Temporal processing

Consistent with many previous reports (e.g., Tallal et al., 1985a, 1985b; Tallal & Stark, 1981), the SLI children performed significantly worse than their CA counterparts in identifying stop CV syllables; however, they performed compa-

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rably to their RS peers. Viewed within a temporal processing deficit framework, the poor performance of the SLI children would be interpreted to represent a basic temporal processing deficit. On this view, the SLI children had trouble identifying or classifying [ba] and [da] because they had difficulty processing the brief-duration formant transition cue responsible for helping to distinguish the two stimuli. Moreover, such a temporal processing deficit would be regarded as causal to the observed slower lexical processing of the SLI children (Merzenich et al., 1996; Wright et al., 1997), a possibility that will be addressed shortly.

The poor performance of the SLI children could be explained in other ways, however. One possibility relates to the fact that SLI children show marked practice or learning effects across a variety of tasks and task domains, including speech perception tasks (Stark & Heinz, 1996; Tomblin & Quinn, 1983). These SLI children simply may have needed a greater number of trials before learning and reliably using the formant transition cue to help them distinguish the two stimuli. The fact that 7 of the 21 SLI children (33%) but only 2 of the CA children (10%) failed the initial training phase lends some credence to this possibility.

The other possibility, and the one outlined earlier and favored here, is that the SLI children had diminished general processing capacity relative to the CA children (Hanson & Montgomery, in press; Leonard et al., 1992; Sussman, 1993), which hindered their ability to perform the task. Recall that according to this view SLI children have trouble handling the various processing demands of the task, such as attending to the stimuli, establishing and storing a template or representation of each syllable in short-term memory, learning to associate each syllable with a specific dot, identifying or classifying the input syllable correctly by comparing it with the stored template, deciding which dot to point to, and making a motor (pointing) response. Moreover, SLI children must complete these mental operations or responses in a timely fashion, before the input stimulus fades from short-term memory. The findings from Hanson and Montgomery (in press), showing that SLI and CA children perform similarly on a discrimination task but more poorly on the same ID task, support this interpretation. In short, when having to rapidly identify one of two similar sounding stimuli, SLI children's processing capacity may well be exceeded.

Word recognition task: Lexical processing

No support was found for the prediction that the slower lexical processing of SLI children is attributable to poor temporal processing. This interpretation is supported on several grounds. First, like their CA and RS peers, these SLI children demonstrated no disadvantage when processing stop sentences versus nonstop sentences. The SLI children did not yield significantly slower RT for stop sentences compared to nonstop sentences, as was predicted. Also, the absence of a Group × Sentence Type interaction indicates that sentence type had no differential influence on the SLI children. Second, if the poorer lexical processing of the SLI children was adversely affected by a temporal processing problem, a significant and positive correlation between performance on the ID task and word recognition RT should have been seen. However, this was not the

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case, suggesting that the temporal and lexical processing limitations of the SLI children were unrelated. Third, although the SLI and RS children performed comparably on the ID task, the SLI children yielded significantly slower lexical processing than the RS children. These findings, too, suggest that temporal processing had little or no effect on the SLI children's lexical processing. Thus, when viewed within the context of the revised cohort theory (Figure 1), the temporal processing abilities of these SLI children had no detrimental effect on the earliest stage of lexical processing (i.e., the acoustic–phonetic processing stage).

It is then evident that the SLI children's slower lexical processing at least reflects inefficient lingusitic processing. Consistent with our previous studies (e.g., Montgomery, 2000; Stark & Montgomery, 1995), these SLI children were slower to retrieve the linguistic properties (i.e., syntactic, morphological, semantic) of incoming words once an acoustic–phonetic analysis of input had been completed. They may also have possessed less efficient and/or less powerful lexical integration routines (i.e., routines responsible for generating phase- or clause-level thematic representations). In short, the linguistic processes in these SLI children appeared to operate in a more rate-limited fashion than in typically developing children. A particularly striking feature of the findings is that, despite having comparable syntactic knowledge to their younger RS peers, these SLI children still evidenced significantly slower language processing, a finding that accords well with our previous findings (Montgomery, 2000; Montgomery & Leonard, 1998). At the same time, it is reasonable to believe that the SLI children were also less adept at managing the overall information processing requirements of the RT task. Children needed to remember the target word, remember to push the response button immediately when recognizing the target but to withhold a response if the target was not heard, and sustain focused attention over the course of the task. Thus, it is highly likely that the demands for immediate language processing, coupled with the need to allocate or coordinate mental resources across the various dimensions of the task, stretched the limits of these SLI children's processing capacity.

If we are appealing to a processing capacity limitation to explain our findings, why then are SLI children, relative to RS children, impaired in lexical processing yet comparable to ID task performance? The answer lies in the nature of the interaction between task demands and child processing abilities. Although it could safely be assumed that the ID task entailed even greater working memory demands than the word recognition task, the ID task did not require a speeded response, whereas the word recognition task did. Recall that structural models of processing capacity also include the construct of processing speed. Even though the SLI and RS children's processing capacities apparently were affected similarly by the working memory demands of the ID task, it is highly likely that a group difference would have emerged had we required a timed response. This interpretation thus suggests that it is the dual requirements of working memory and speed of processing that determine whether the processing system of SLI children, even relative to younger peers, reaches its limits.

It might be argued that we did not find a sentence type effect or a Group × Sentence Type interaction because our sentence conditions did not really entail different phonetic processing requirements. For instance, because voiceless fric-

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atives, if of relatively short duration, can be perceived as voiceless stop consonants during running speech (e.g., Weismer, 1980), it is possible that the nonstop and stop sentences resembled each other with respect to temporal processing requirements. If it could be shown that the nonstop sentences comprised primarily voiceless fricatives, this possibility might have some merit. However, this was not the case. These sentences contained a significantly greater number of voiced fricatives (M = 19.28, SD = 2.6) per sentence than voiceless fricatives (M = 7.42, SD = 1.4), $t(13) = 19.73$, $p < .001$. Second, stop sentences included significantly greater numbers of voiced stops (M = 8.85, SD = 2.6) than voiceless stops (M = 7.07, SD = 2.0), $t(13) = 2.95$, $p < .01$. Importantly, there are other reasons to believe that stop sentences entailed greater temporal processing. Although it is true that in some instances voiceless fricatives might be perceived as voiceless stops, it is also true that the transition duration in voiced fricative words and other voiced nonstop words (e.g., nasals, glides) tends to be longer than in voiced stop words (Pickett, 1999). In addition, the extent or rate of overall spectral change associated with the transition is typically different in stop versus nonstop words (e.g., Pickett, 1999). In glides the spectral change is more gradual and smooth compared to the more abrupt change seen in voiced stops. In voiced fricatives the spectral change from periodic to random turbulence generally appears to be more gradual (e.g., Pickett, 1999). Although the focus of the present study was on formant transition duration, in keeping with Tallal's notion of temporal processing, there are other important acoustic cues that are clearly temporal in nature that can help distinguish stops and nonstops. Stop consonants include, for example, a very brief-duration noise burst or transient that is no longer than about 5–40 ms just prior to the onset of the formant transition. Relative to a noise burst, fricatives contain a much longer noise segment preceding or following a vowel whereas nasals generally contain a longer murmur segment (Kent & Read, 1992). It is reasonable to believe, then, that, relative to nonstop sentences, the collection of brief-duration temporal cues inherent in stop sentences indeed demanded greater temporal processing than the temporal cues contained in nonstop sentences.

Despite our best efforts to create phonetically distinct sentence types, we may have failed. The two sentence types simply may have had poor reliability to detect group differences in phonetic processing. To test this possibility, we first computed separate split-half reliability coefficients on children's word recognition RT for stop and nonstop sentences to determine the internal consistency for each sentence type. Correlations were computed between all even numbered and odd numbered items. A significant correlation for each sentence type obtained (Stop, $r = .75$, $p < .01$; Nonstop, $r = .66$, $p < .01$), indicating that each sentence type indeed possessed strong internal stability. Next, to determine whether the manipulation of phonetic content yielded two distinct sentence types, a correlation between stop and nonstop sentences was computed. A significant ($p <$ .01), although moderate, correlation of .38 was found. That a modest correlation emerged should not be surprising because the sentence types were matched on a variety of linguistic parameters. Given that phonetic content accounted for a substantial portion of the variance between the sentence types, we might thus conclude that the manipulation of phonetic content was successful.

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Finally, it is possible that we missed a developmental period during which the SLI (and control) children might have shown optimal sensitivity to phonetic content during language processing. Bernstein and Stark (1985), for example, found that by 9 years old the SLI children tend to perform like their CA peers on various temporal processing tasks, whereas 4 years earlier they demonstrated poor performance. It is important that these investigators also showed that even though the SLI children no longer evidenced poor temporal processing, they remained language impaired. Like Bernstein and Stark (1985), the present results suggest that many SLI children may "outgrow" an earlier temporal processing deficit (as measured by the ID task). An inspection of individual subject data supports their developmental findings. For instance, three out of nine 6- to 8-year-old SLI children performed below 50% correct, whereas none of the 9- to 10-year-old SLI children did so. The majority of 6- to 8-year-old SLI children (6/9) performed between 50 and 74% correct, whereas considerably fewer (3/9) 9- to 10-year-old SLI children performed within this range. Finally, just three 6- to 8-year-old SLI children performed at or above 75% correct, while six 9- to 10-year-olds did. By contrast, for the CA children, the large majority of 6- to 8-year-olds (9 out of 11) performed at or above 75% correct, and all ten 9- to 10-year-olds did so. Thus, the SLI-CA group difference appears to be largely attributable to the younger SLI children's poor performance. At the same time, our findings do not necessarily rule out the possibility that some older SLI children's language problems are not a reflection of residual effects of an earlier temporal processing problem (Bernstein & Stark, 1985). Although it is impossible to evaluate this scenario, we did examine the relation between ID task performance and word recognition RT (using grand mean RT) for the younger and older SLI children and CA children separately. No significant ($p < .01$) correlation was found at either age for either group, thus providing further support for the view that the SLI children's poor temporal and lexical processing were unrelated.

In conclusion, findings from this study offer further evidence of processing capacity limitations in SLI children and a parsimonious attempt to account for these children's performance deficits on two very different sorts of tasks. The findings also suggest that SLI children are unusually sensitive to task complexity, even relative to their younger, language-matched peers. As we begin to better understand these children's processing constraints, more sensitive and effective assessment and treatment approaches may be developed.

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APPENDIX

EXAMPLE OF STOP-LOADED AND NONSTOP-LOADED SENTENCE PAIRS

The target words are in italics.

Stop-loaded sentences

1. Pete reads a lot. Today Pete got a *book* about wild dogs and cats.
2. Doug got hurt today. He tripped onto his *bike* and broke a leg.
3. Anton tried to fix his bike. But he couldn't fix the back *wheel* because it was bent.
4. Ted likes to eat weird food. Ted even likes eating *cheese* on his breakfast cereal.
5. Dad gets up late most mornings. At bedtime each night Dad forgets to set the *clock* for the next day.
6. Kurt and Bob were playing catch. Kurt accidentally hit Bob in the *face* with the ball.

Nonstop-loaded sentences

1. Jenny loves her science class. She read about the *moon* and the different planets this week.
2. Anthony loves to go to the river. He loves to catch *fish* and crabs by the riverbank.
3. Shane's little sister is always thirsty at bedtime. Shane always gives his sister a *cup* of juice before bed.
4. Jenny was goofing around in art class. She ended up spilling *paint* all over the table and floor.
5. Jessie loves to do weird things. She just put orange and green paint in her *hair* and on her face.
6. Johnny is always losing his stuff. Just the other day he lost his new winter *coat* at school.

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