Simulating SLI: General Cognitive Processing Stressors Can Produce a Specific Linguistic Profile

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This study attempted to model specific language impairment (SLI) in a group of 6-year-old children with typically developing language by introducing cognitive stress factors into a grammaticality judgment task. At normal speech rate, all children had near-perfect performance. When the speech signal was compressed to 50% of its original rate, to simulate reduced speed of processing, children displayed the same pattern of errors that is reported in SLI: good performance on noun morphology (plural *-s*) and very poor performance on verb morphology (past tense *-ed* and 3rd-person singular *-s*). A similar pattern was found when memory load was increased by adding redundant verbiage to sentence stimuli. The finding that an SLI-like pattern of performance can be induced in children with intact linguistic systems by increasing cognitive processing demands supports the idea that a processing deficit may underlie the profile of language difficulty that characterizes SLI.

KEY WORDS: specific language impairment, simulation, inflectional morphology, speed of processing, verbal short-term memory

One of the key questions in the study of specific language impairment (SLI) is whether there is a primary representational deficit in the grammar module or whether more general-purpose processing mechanisms can account for the linguistic deficits, without invoking an independent module for grammar. If it were possible to demonstrate that the specific profile of language difficulties seen in language-impaired individuals does not depend on impaired linguistic representations, this would provide strong support for a processing explanation of SLI. Such a demonstration has been reported in the adult aphasia literature.

By means of a variety of cognitive stressors, a number of studies have been able to simulate the agrammatic language profile reported in Broca's aphasia, in individuals with unimpaired language skills. One possible type of stressor is peripheral: a degradation of the signal. Kilborn (1991) compared performance of German- and English-speaking participants on a sentence-interpretation task, in which participants had to decide which of two nouns was the actor in the sentence. Under normal conditions, English speakers relied heavily on word order, while German speakers relied more on morphological information. However, when a low-level noise mask was introduced into the sentence stimuli, the two language groups were differentially affected. English speakers were unaffected by the stimulus degradation, while German speakers made much less use of grammatical morphology and compensated by increasing reliance on word order information. Thus, "a global reduction in processing capacity can affect some aspects of language more than others" (Kilborn, 1991, p. 275).

A second possible type of processing stressor is central: Instead of degrading the input, the load on cognitive resources is increased. Participants in a study by Blackwell and Bates (1995) had to remember a string of digits at the same time that they did a grammaticality judgment task. Increasing the number of digits to remember produced the same profile of difficulty as that seen in Broca's aphasia: Agreement errors were the most vulnerable (hardest to detect under stressed conditions), while omission and particularly transposition errors were robust (easy to detect even under stressed conditions).

The idea of memory as an important factor in aphasia-like language processing was also explored by Miyake, Carpenter, and Just (1994), using a rapid serial visual presentation paradigm. Miyake et al. found that under speeded but not normal-rate presentation of stimuli, participants with normal language skills showed the same gradient of difficulty across sentence types of differing syntactic complexity as individuals with Broca's aphasia. The effect was exaggerated for individuals with low working memory capacity.

Most recently, a study by Dick et al. (2001) directly compared the effects of a number of peripheral, as well as central, stressors on a sentence-comprehension task. The peripheral stressors used in this study were a noise mask (at 50% of maximum signal-to-noise ratio) and a low-pass filter (at 600 Hz). The central stressors were speech rate compression (to 50% of the original signal) and a visual and auditory version of a six-digit load (participants had to judge whether the same string of six digits was presented before and after the comprehension task). Each of these was tested independently, as well as in dual-stressor combinations. Apart from the two digit-load conditions, all stressors independently induced a profile of difficulty similar to that seen in patients with aphasia, in which passive and object-cleft sentences were much more problematic than active and subject-cleft sentences. Further, combining the speech compression with the low-pass filter manipulation had dramatic effects, producing not only a qualitative (similar pattern of errors) but also a quantitative (similar number of errors) simulation of aphasic performance on the comprehension task.

Given the increasing amount of evidence suggesting that a general processing mechanism may be able to account for an acquired, adult grammar-specific deficit, it seems reasonable that a similar explanation might be appropriate for what is often described as a developmental grammar-specific deficit: SLI. What types of general processing mechanisms might be involved in SLI? Two candidates that appear fairly consistently in the literature are speed of processing and verbal short-term memory.

Speed of Information Processing

There is a substantial amount of research showing that children with SLI tend to be slower (generally gauged using a reaction time [RT] measure) than their peers on a wide range of tasks, both verbal and nonverbal (Johnston & Ellis Weismer, 1983; Lahey & Edwards, 1996; Wulfeck & Bates, 1995). To account for this type of finding, the generalized slowing hypothesis (Kail, 1994) suggests that children with SLI are slower than their language-normal peers at processing each component of any given task by a constant proportion. For example, picture naming may be broken down into a number of different steps: recognizing the picture, retrieving its name, producing the phonological output. Each step will be slower than normal by a constant proportion, resulting in an RT for children with SLI that is a function of the RT of typically developing children: $RT_{SLI} = m \times RT_{normal}$. Kail (1994) used a meta-analysis of five studies to test this hypothesis and showed that a proportional function could account for 96% of the variance in RT data from children with SLI, for a range of different linguistic and nonlinguistic tasks. He estimated that the general slowing was approximately 30%. Windsor and Hwang (1999) found further support for this model with a meta-analysis of three studies; they too were able to account for 96% of the variance with the proportional function, although their estimate of the proportion of slowing was slightly lower than Kail's at 20%.

More recently Miller, Kail, Leonard, and Tomblin (2001) directly compared RT data across a range of linguistic and nonlinguistic tasks, for the same group of children. They found a generalized proportion of slowing of about 20% across tasks for most of the children with SLI, particularly those who had both production and comprehension difficulties.

Verbal Short-Term Memory

Another frontline candidate for a deficient processing mechanism in SLI is verbal short-term memory. Gathercole and Baddeley (1990) showed that children with SLI had greater difficulty repeating three- and four-syllable nonwords compared with one- and two-syllable nonwords, while mental-age- and vocabulary-matched controls did not show this length effect. This was interpreted as demonstrating that children with SLI have impaired phonological memory. It was further suggested that this may account for their below-age vocabulary ability, because word learning requires access to stable and distinct phonological representations.

Nonword repetition has since received substantial attention as an important marker for SLI: It has been found to have high heritability (Bishop et al., 1999; Bishop, North, & Donlan, 1996) and to discriminate between children with and without language impairment with a high degree of accuracy (Dollaghan & Campbell, 1998; Ellis Weismer et al., 2000). Recent work by Botting and Conti-Ramsden (2001) showed that children who scored highly on a nonword repetition task performed significantly better on a wide range of language measures than children who did poorly on nonword repetition. Although the nonword repetition paradigm is usually discussed in terms of phonological working memory, it should be borne in mind that phonological analysis, articulatory output processes, and long-term lexical knowledge can also affect performance on this task (Snowling, Chiat, & Hulme, 1991). In particular, there is some evidence suggesting that difficulty on a nonword repetition task may be partially attributable to poor phonological discrimination rather than a memory deficit (James, van Steenbrugge, & Chiveralls, 1994). However, whatever its other demands, nonword repetition undoubtedly does tap processes associated with verbal short-term memory and has been consistently shown to be associated with SLI.

An impairment in short-term verbal memory may be able to explain not only lexical but also syntactic and even morphological difficulties. Many sentence types that prove problematic in SLI, including passive constructions, center-embedded clauses, and semantically reversible sentences, have a high memory load (Gathercole & Baddeley, 1993). *The dog was bitten by the cat*, for example, cannot be fully analyzed without maintaining in memory information about the object until the end of the utterance, when it can be matched up with the subject.

Montgomery (1995, 2000) reported that children with SLI performed poorly relative to language-matched controls on a sentence-comprehension task, when the sentences contained redundant information. Thus, while children with normally developing language found *The dirty little boy climbs the great big tall tree* no more difficult than *The little boy climbs the tree*, children with SLI found the longer sentence significantly more difficult. Importantly, there was a strong correlation between performance on the redundant sentence condition and performance on a task tapping working memory capacity (a nonword repetition task and real-word free-recall task) indicating that sentence-comprehension difficulties are very likely to be due to reduced phonological memory capacity.

Rationale for the Current Study

Taking into account the evidence for general processing deficits in SLI, in the form of memory and speed-of-processing constraints, we set out to explore whether SLI could be simulated in young children with typically developing language, when demands on memory and speed of processing were increased. The obvious question was on which area of language processing to focus and how to define an SLI profile of performance.

Children with SLI are notoriously bad at inflectional morphology; it seems to be an area of disproportionate difficulty even relative to their generally poor grammatical and lexical skills. A plethora of studies has shown that compared with younger children with a similar mean length of utterance (MLU controls), children with SLI produce far fewer inflectional morphemes in both spontaneous and elicited speech samples. There is also a handful of studies showing that this weakness is present in receptive as well as expressive language (Felbaum, Miller, Curtiss, & Tallal, 1995; van der Lely & Ullman, 1995; Wulfeck & Bates, 1995).

Furthermore, there seem to be areas of disproportionate difficulty even within inflectional morphology; in English, at least, verb-phrase morphology is generally found to be more problematic than noun-phrase morphology. For example, in a discriminant function analysis, Gavin, Klee, and Membrino (1993) found that frequency of verb-phrase errors was the variable that discriminated best between children with SLI and typically developing peers in a preschool sample. King, Schelletter, Sinka, Fletcher, and Ingham (1995) reported that at school age, children with SLI used third-person singular *-s* and past tense *-ed* less frequently than their peers. Rice, Wexler, and Cleave (1995) also found that these inflections were used far less frequently by 5- and 6-year old children with SLI than by MLU-matched controls. In the case of the third-person singular *-s*, the SLI group used the inflection appropriately in only 30% of obligatory contexts, compared with 45% for the MLU-matched group and 90% for the age-matched group. For regular past tense *-ed*, use was even lower in the SLI group, at 23%, compared with 53% in the MLU controls and 90% in the age-matched controls.

In the noun phrase, the most intensely examined inflection has been the plural *-s*, which is among the earliest morphemes to be acquired in normal language development (de Villiers & de Villiers, 1973). In a comparison with same-age peers, 3-year-old children with SLI were found to produce this inflection far less frequently: 68% versus 93% of obligatory contexts (Roberts, Rescorla, & Borneman, 1994). In comparison with MLU controls, 5-year-old children with SLI still produced plural *-s* less frequently (83% vs. 93%), but the disparity was much smaller than that for third-person singular *-s* (Rice &

Oetting, 1993). A further study by Oetting and Rice (1993) found no differences in use of the plural *-s* between children with SLI and MLU controls.

It seems fair to say that overall, greater difficulty does seem to appear in verb-phrase inflections, with regular past tense *-ed* being perhaps slightly more problematic than third-person singular *-s*, and that the noun-phrase plural *-s* inflection, while hardly robust, is less problematic than either of the verb inflections. It is worth bearing in mind that the third-person singular *-s* is very much rarer in spontaneous speech than the past tense *-ed* (Bishop, 1994), which makes it difficult to compare the two verb inflections directly.

The current study attempted to replicate this profile of difficulty in a group of 6-year-old children with normally developing language, by increasing memory and speed-of-processing loads within a grammaticality judgment paradigm. The predictions were that the speed-of-processing load (sentences presented at 50% speech rate compression) and memory load (sentences virtually doubled in length by the addition of redundant verbiage) would cause children to accept as correct ungrammatical sentences that were missing an obligatory inflection.

The number of errors was predicted to be greatest for the past tense *-ed* sentences, followed closely by the third-person singular *-s* and finally by the plural *-s*. A control condition involving the prepositions *in*, *on*, and *at* was also included, for which ceiling performance was expected for all children. *In* and *on* appear to be acquired relatively early by children with SLI (Albertini, 1980). In addition, a grammaticality judgment task using very similar stimuli to the current study found all three prepositions to be robust in a group of 8–12-year-old children with SLI (Hayiou-Thomas, 2002).

Method

Participants

In Oxfordshire, U.K., 138 children were recruited from Years 1 and 2 of local state primary schools. All participants had returned consent forms signed by their parents, agreeing to their participation in the study. All children were monolingual in English and had no history of hearing, speech, or language impairment, or general education difficulties, according to parental report.

Participants were screened for nonverbal ability (by means of Raven's Progressive Matrices; Raven, Court, & Raven, 1986) and vocabulary level (British Picture Vocabulary Scale; BPVS; Dunn, Dunn, Whetton, & Pintilie, 1982); criteria for inclusion in the study were age-appropriate scores on both these measures (i.e., a score no lower than 85 on the age-standardized scales). A binaural hearing screen (20 dB SPL, at 500, 1000, 2000, and 4000 Hz) was also administered to ensure that there was no peripheral hearing loss, at least at the time of testing. Eighteen children were excluded from the study on the basis of this screen. The profile of the remaining 120 children who participated is summarized in Table 1.

Stimuli: Grammaticality Judgment

Eight sets of 80-sentence stimuli were created to test the effects of sentence speed and length on sensitivity to grammatical inflections. These were divided into two versions for each of the following sentence conditions: short normal, short fast, long normal, and long fast. Within each sentence set, three types of grammatical inflection–plus the control prepositions condition—were tested (plural *-s*, third-person singular *-s*, regular past tense *-ed; in, on,* and *at*) with 20 sentences per inflection type. Half (10) of the sentences for each inflection type were well-formed; the other half (10) were ill-formed, so that they were missing an obligatory grammatical inflection (e.g., *We saw two bird in a tree*). The ill-formed prepositions sentences, likewise, were missing an obligatory preposition. The two versions for each sentence condition were created to counterbalance across well- and ill-formedness: Sentences that were well-formed in one version would appear in their ill-formed state in the other version. Examples of the sentence stimuli are presented in Appendix A. (The complete set of sentences can be obtained from Marianna E. Hayiou-Thomas on request.)

Table 1. Profile of participants for each sentence condition, on age, nonverbal ability, and receptive vocabulary.

	Short normal			Short fast			Long normal			Long fast		
	M	*SD*	Range	*M*	*SD*	Range	*M*	*SD*	Range	*M*	*SD*	Range
Age (years;months)	6;3	0;5	5;5–7;2	6;4	0;5	5;7–7;1	6;3	0;4	5;8–7;3	6;6	0;3	5;8–7;2
Raven's Matrices	119.80	8.64	100–130	119.00	8.57	100–130	120.07	9.78	96–130	123.27	7.56	100–130
BPVS	109.87	7.81	95–126	104.97	9.42	92–122	105.93	8.22	87–121	112.93	9.54	95–136

Note. Reported scores for these tests are age scaled, using the norms provided by the tests, with population *M* = 100, *SD* = 15. BPVS = British Picture Vocabulary Scale.

Sentences were in the active voice, with canonical subject, verb, object word order. Time was clearly marked by the opening phrase, which was always either *yesterday, last week, every day,* or *every week;* use of these phrases was counterbalanced across sentences. Plurality was marked where necessary by the use of *all* or a number (e.g., *two bird*). To avoid word-position effects, the target word was placed in the center of the sentence. The overall length of the sentence, as well as the number of phrases and the number of syllables before and after the target word, was counterbalanced across all sentences. Target words were followed by a vowel, to minimize interference with perception of the word ending (the inflection or lack thereof); target words were also counterbalanced for number of consonant clusters. Finally, sentences were counterbalanced with respect to the voicing of the target inflection, to control for any effect of phonological salience on sensitivity to grammatical inflections (/z/and /s/ allomorphs for plural and third-person singular *-s;* /d/ and /t/ allomorphs for past tense). The syllabic allomorphs for these inflections (/ɪz/ and /ɪs/ for plural and third-person singular and /ɪd/ and /ɪt/ for past tense) were not examined.

Long sentences were created by adding redundant verbiage to their short counterparts. For example, *Yesterday, we saw two birds in a tall tree* became *Yesterday, my little sister saw two birds in a big, tall, leafy, pretty, green tree.* As far as possible, the syntactic simplicity of the short sentences was maintained in the long, redundant sentences. Long sentences were roughly double the number of syllables of the short sentences (see Appendix B for details of sentence length).

Fast sentences were created by compressing duplicates of the normal-rate (approximately 225 syllables/min) sentences to 50% of their original length. This was done using SoundEdit 16 for Macintosh (Macromedia, 1996), with proprietary algorithms that excised redundant information in the 5–20-ms time range, thus altering the temporal but not spectral profile of the signal.

Recording and Editing

Sentences were spoken at a normal rate by an adult male native speaker of British English and were digitally recorded in a soundproof booth using a Tascam DAT DA-P1 recorder and Sennheiser ME65 microphone. The input-sampling rate was 44.1 kHz. The stimuli were downloaded to a Macintosh computer via a Sony DAT PCM-R300 player and converted to wav format using ProTools software (Digidesign, 2000). Two recordings of each sentence were made, and the best exemplar was used for the final stimuli.

Procedure

Children participated in a screening session in which Raven's Progressive Coloured Matrices, the BPVS, and the hearing screen were administered. If they met inclusion criteria, they participated in a second session in which they were randomly assigned to one of the four sentence conditions for the grammaticality judgment task. It is clear from Table 1 that the four groups of children were well matched on age and nonverbal ability. The matching on the vocabulary criterion was less clear-cut; this was partly but not entirely attributable to two high-scoring outliers in the long fast sentence group (with age-standardized BPVS scores of 132 and 136).

Sentence speed and length were between-subjects variables, and the inflection type was a within-subject variable; thus, any one child heard all four inflection types (20 sentences for each of four inflection types), in only one sentence condition (i.e., short normal, short fast, long normal, and long fast).

Children were instructed to listen to the monster say the sentences and were told that "Sometimes he will say sentences just right, and sometimes he will talk a bit funny and say the sentences wrong"; they were then asked to "Tell me if the monster said the sentence properly or not." Children were presented with three practice sentences to ensure they were making a grammaticality (rather than semantic) judgment. All participants were able to do this without any apparent difficulty. Sentence stimuli were presented by a cartoon monster, on a custom-built program, displayed on a Dell Latitude laptop, with stimuli presented monaurally over Sennheiser HD45 headphones. The experimenter wore a set of monitor headphones. All trials were initiated by the experimenter, and order of sentence presentation was automatically randomized by the computer program. Children responded verbally after hearing each sentence, indicating an acceptance with either "yes" or "right" and a rejection with "no" or "wrong." The experimenter recorded this response by entering a 1 for "yes" or a 0 for "no" on the computer keyboard, and these data were automatically saved in a text file. A 2 was entered for a "don't know" response or a request for repetition; in this case, the sentence was repeated later in the session, at a randomly assigned time. Children were encouraged to guess if they were not sure of the answer, but if they still didn't respond, the experimenter entered a 2 and the sentence was presented again at a later time. Each testing session lasted approximately half an hour and was carried out in a quiet room at school.

Results

Data Reduction

Data were analyzed by means of an A' measure of sensitivity, which adjusts for potential response bias by comparing the proportion of false alarms with the proportion of hits.[1] Perfect performance, accepting all grammatical sentences and rejecting all ungrammatical sentences, will give an A' of 1.00. Accepting all sentences, be they grammatical or ungrammatical, will give an A' of .50, that is, chance. An arcsine transformation was carried out to ensure equality of variances, as proportional data tend toward unequal variances, and all analyses reported use the transformed data. However, for the sake of clarity, graphs show untransformed data.

Overview of Data

Figure 1 depicts the mean A' scores for the different inflections, in each of the four sentence conditions. An initial examination of Figure 1 clearly shows that in all sentence conditions, performance on plurals was best, followed by third-person singular, followed by past tense. Performance on the prepositions (control inflection) was, contrary to experimental prediction, at roughly the level of third-person singular. Overall, the short normal sentence condition elicited the best performance, while the worst performance was in the long fast condition. Short fast and long normal sentences were intermediate, although of these two, there appeared to be better performance in the long normal sentence condition.

Within inflectional types, both plurals and prepositions seem to have been equally affected by speed and length; short fast and long normal sentences produced similar levels of performance.[2] Third-person singular and past tense seem to have been more affected by speed than length; there were lower A' scores for these inflection types in the short fast than in the long normal sentences. In fact, for third-person singular and past tense, performance in the short fast condition appeared to be almost identical to that in the long fast condition. This might explain why there appeared to be slightly more lower A' scores overall in the short fast than in the long normal condition; it also appeared that the past tense inflection was the most vulnerable to the cognitive load imposed by the speeded condition.

Statistical Analysis

A 2 (speed) × 2 (length) × 4 (inflection type) mixed analysis of variance confirmed many of these observations. Between-subjects factors were sentence speed (normal or fast) and sentence length (short or long); the within-subjects factor was inflection type (plural, third-person singular, past, or prepositions).

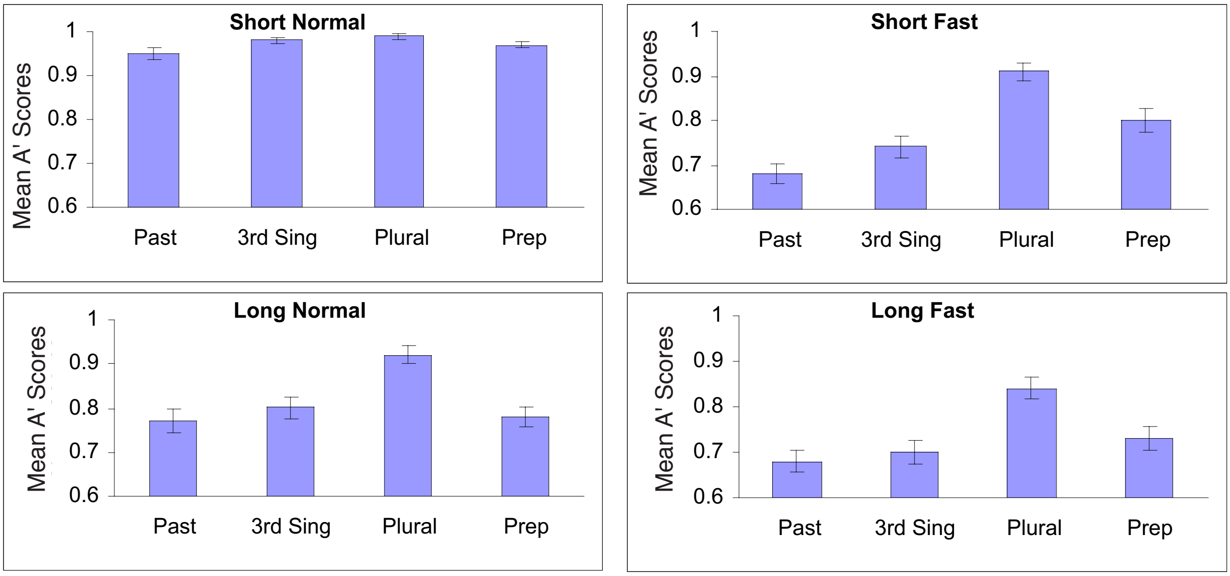
There were significant main effects for all three factors: speed, $F(1, 116) = 110.40$, $p < .001$, $\eta^2 = .49$; length, $F(1, 116) = 67.80$, $p < .001$, $\eta^2 = .37$; inflection type, $F(3, 348) = 68.02$, $p < .001$, $\eta^2 = .37$.

In addition to the main effects, there were several significant interactions: Inflection Type × Speed, $F(3, 348) = 4.82$, $p < .01$, $\eta^2 = .04$, and Length × Speed, $F(1,$

[1]The formula used was taken from Gelfand (1998): $A' = (0.5 * x * y) + [y * (1 - x)] + [0.5 * (1 - x) * (1 - y)]$, where x is the proportion of false alarms and y is the proportion of hits.

[2]Prepositions are included under the *inflectional types* umbrella, purely for purposes of brevity.

Figure 1. Mean A' scores (±*SE*) for each of the inflection types in each of the four sentence conditions. 3rd Sing = third-person singular; Prep = prepositions.



116) = 26.67, $p < .001$, $\eta^2 = .19$. Note that there was no significant interaction between inflection type and length, $F(3, 348) = 1.49$, $p > .05$. Finally, there was a significant three-way interaction between inflection type, speed, and length, $F(3, 348) = 7.35$, $p < .001$, $\eta^2 = .06$.

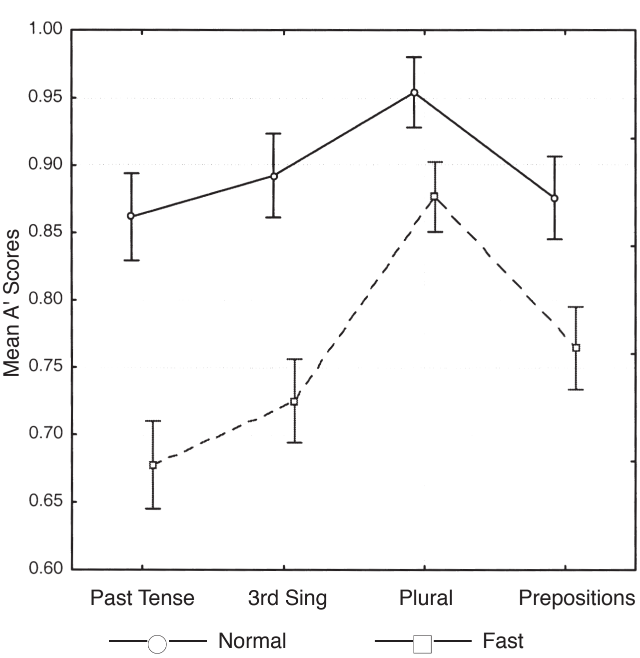
Inflection Type × Speed interaction. The interaction between inflection type and speed is illustrated in Figure 2. What is apparent from the figure is that the third-person singular and past tense inflections were affected by speed considerably more than the plural *-s* or prepositions.

A series of two-way mixed measures analyses of variance were carried out, to clarify what was driving the Inflection Type × Speed interaction. The between-subjects factor was speed; the within-subjects factor was inflection type. Two inflections were examined at a time.

The pattern of results suggests that the plural *-s* and prepositions were influenced in a similar way by speed. Although there were main effects of inflection type, $F(1, 118) = 58.67$, $p < .001$, $\eta^2 = .33$, and speed, $F(1, 118) = 37.53$, $p < .001$, $\eta^2 = .24$, there was no significant Inflection Type × Speed interaction when only plurals and prepositions were included in the analysis, $F(1, 118) = 0.01$, $p > .05$.

The third-person singular and past tense inflections seemed to be behaving in a similar way to each other as well, under the influence of speed. Here, too, there were

Figure 2. Speed × Inflection Type interaction. Mean *A*' scores for each of the four inflection types are plotted separately for normal and fast sentence conditions. 3rd Sing = third-person singular.



main effects of inflection type, $F(1, 118) = 17.91$, $p < .001$, $\eta^2 = .13$, and speed, $F(1, 118) = 70.92$, $p < .001$, $\eta^2 = .38$, but no interaction, $F(1, 118) = 0.16$, $p > .05$.

In contrast, there were significant interactions of Inflection Type × Speed when the plural inflection was compared with either the third-person singular, $F(1, 118) = 8.62$, $p < .01$, $\eta^2 = .07$, or the past tense, $F(1, 118) = 5.34$, $p < .05$, $\eta^2 = .04$. Similarly, the Inflection Type x Speed interaction was also significant when the prepositions were compared with either the third-person singular, $F(1, 118) = 8.88$, $p < .01$, $\eta^2 = .07$, or the past tense, $F(1, 118) = 6.26$, $p < .05$, $\eta^2 = .05$.

Finally, note that there was no main effect of inflection type when comparing third-person singular to prepositions, $F(1, 118) = 0.13$, $p > .05$, suggesting that although they were differently affected by speed, the number of errors made in both these sentence types was very similar. This is in contrast to every other comparison, in which the main effect of inflection was always significant.

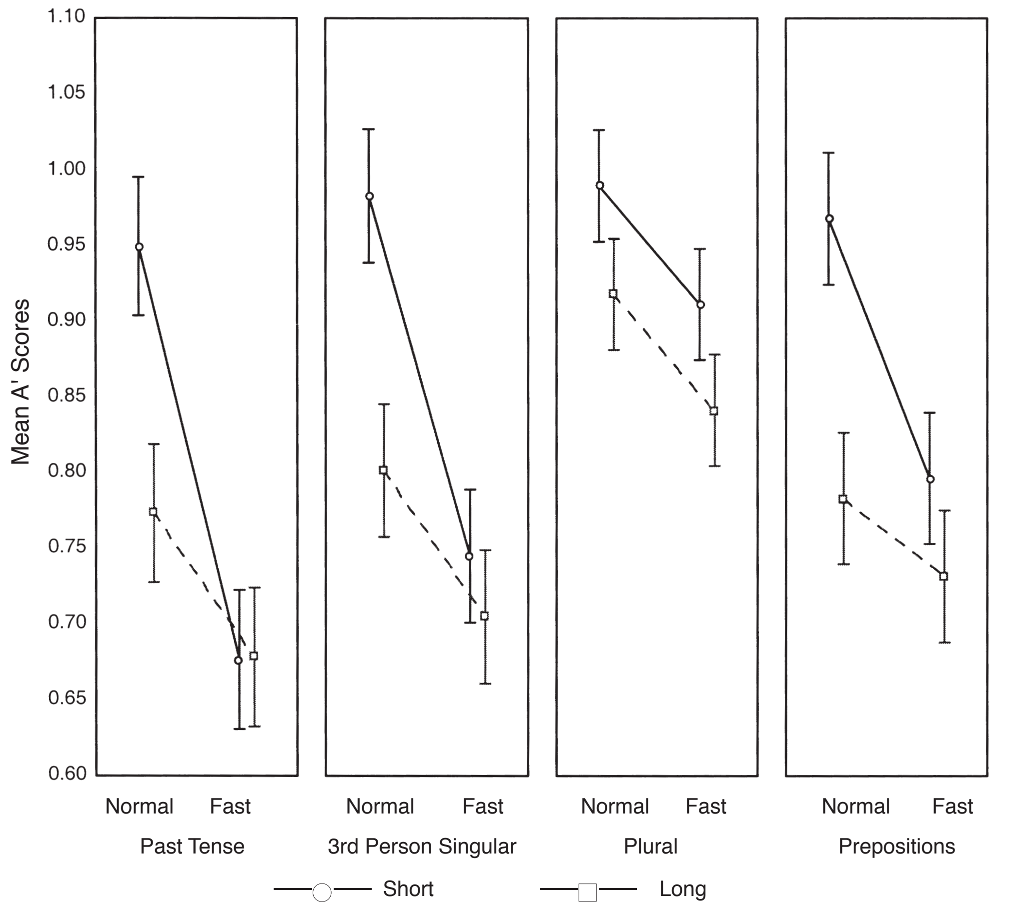
Inflection Type × Speed × Length interaction. The three-way interaction among inflection type, speed, and length is illustrated in Figure 3. This interaction appeared to be due to the fact that for every type of inflection apart from the plural, there was an interaction of speed with length, so that in the low-speed condition, length had great impact (substantially decreasing *A*' scores), but in the high-speed condition, the effect of length was negligible.

This interpretation was supported by a series of four 2 (speed) × 2 (length) analyses of variance, one for each inflection type. These confirmed a significant interaction between speed and length for prepositions, $F(1, 116) = 15.72$, $p < .001$, $\eta^2 = .12$, third-person singular, $F(1, 116) = 32.15$, $p < .001$, $\eta^2 = .22$, and past tense, $F(1, 116) = 27.20$, $p < .001$, $\eta^2 = .19$, but not for plural, $F(1, 116) = 0.21$, $p > .05$.

Further, looking within the long sentence conditions only, there was no significant Inflection Type × Speed interaction, $F(3, 174) = 1.35$, $p > .05$. That is, all four inflection types reacted similarly to speed when the sentences were long, although the actual level of performance differed among inflection types. When the sentences were short, however, there was more variability in the way speed affected different inflections; this was reflected in a significant Inflection Type × Speed interaction, $F(3, 174) = 12.02$, $p < .001$, $\eta^2 = .17$.

Effect of allomorph voicing. There was no effect of voicing on grammaticality judgment scores for the past tense inflection type (i.e., no difference for stimuli in which the verb took the /d/ or /t/ allomorph). A 2 (speed) × 2 (length) × 2 (voice) mixed measures analysis of variance showed no significant main effect of voicing, $F(1, 116) = 0.90$, $p > .05$ (/d/ mean *A*' = .78, *SD* = .17, /t/ mean

Figure 3. Speed × Length × Inflection Type interaction. Mean *A*' scores for each of the four inflection types are plotted separately for normal versus fast and short versus long sentence conditions.



A' = .76, *SD* = .18). There was also no significant interaction with either speed, $F(1, 116) = 1.46$, $p > .05$, or length, $F(1, 116) = 0.07$, $p > .05$. The equivalent analysis for the /z/ and /s/ plural inflection allomorphs also showed no main effect of voicing, $F(1, 116) = 1.14$, $p > .05$ (/z/ mean *A*' = .92, *SD* = .12; /s/ mean *A*' = .91, *SD* = .12) and no interaction with speed, $F(1, 116) = 0.23$, $p > .05$, or length, $F(1, 116) = 2.38$, $p > .05$.

Somewhat unexpectedly, there was a significant main effect of voicing for the third-person singular inflection, $F(1, 116) = 9.71$, $p < .01$, $\eta^2 = .08$, so that stimuli involving the /s/ allomorph elicited more accurate grammaticality judgments (mean *A*' = .83, *SD* = .17) than those with the /z/ allomorph (mean *A*' = .79, *SD* = .18). This pattern was consistent across sentence conditions, and there was no significant interaction with either sentence speed, $F(1, 116) = 0.60$, $p > .05$, or length, $F(1, 116) = 0.05$, $p > .05$.

The prepositions condition. The experimental prediction regarding the control condition, which involved the function morphemes *in*, *on*, and *at*, was that they would be robust and that near-ceiling performance would be maintained across all sentence conditions. This was not the case. Averaged across sentence conditions, the mean *A*' score for prepositions was .82, noticeably lower than the *A*' of .92 obtained for plurals.

Nor were all three prepositions equivalent: A mixed 2 (speed) × 2 (length) × 3 (preposition) analysis of variance revealed a main effect of preposition, $F(2, 232) = 8.88$, $p < .001$, $\eta^2 = .07$, so that *in* (mean *A*' = .80, *SD* = .16) was more problematic than *on* (mean *A*' = .84, *SD* = .18) or *at* (mean *A*' = .82, *SD* = .18). This pattern was consistent when looking at different sentence conditions, as there was no significant interaction between preposition and speed, $F(2, 232) = 1.02$, $p > .05$, or between preposition and length, $F(2, 232) = 1.59$, $p > .05$. Although *in* was more problematic than *on* or *at*, note that none of these prepositions elicited the ceiling performance that had been predicted for them.

Age effects. There was no overall effect of age on performance on the grammaticality judgment task, $r_s(120) = .12$, $p > .05$. However, on closer examination, it became apparent that there was a marked effect of age on grammaticality judgment scores (so that older children had higher A' scores) for normal-rate but not speeded sentences. The correlation between age and total A' scores was striking for both short normal sentences, $r_s(30) = .62, p < .001$, and long normal sentences, $r_s(30) = .62, p < .001$, but was nonsignificant for short fast sentences, $r_s(30) = .12, p > .05$, and was moderate for long fast sentences, $r_s(30) = .36, p < .05$.

Although there were no specific a priori predictions about how age and grammaticality judgment scores would be related, it was anticipated that in general older children would have higher A' scores and that this relationship would be strengthened in the more stressful sentence conditions. These expectations were only partially fulfilled. The dissociation between the effects of sentence speed and length was particularly interesting. Of the two stressors, speed appeared to induce more errors, so one might have predicted that children in the speeded sentence conditions would have benefited more from age effects. Instead, the reverse pattern was seen. One possibility could be that a kind of floor effect was present, so that speeded sentences made the task so difficult that the beneficial effects of age were not strong enough to compensate.

Effect of vocabulary size on grammaticality judgment. As mentioned in the description of the participants, the group of children who were presented with the long fast sentence condition had a mean BPVS score that was higher than those of the other three groups. A 2 (speed) × 2 (length) × 4 (inflection type) analysis of covariance with BPVS age-standardized scores as the covariate was carried out to examine how the imbalance among the groups affected the results of the grammaticality judgment task. The main difference from the previous analysis was that the main effect of inflection type became nonsignificant, $F(3, 345) = 1.90, p > .05$. Critically, however, the interactions between inflection type and speed, $F(3, 345) = 4.87, p < .01, \eta^2 = .04$, and among inflection type, speed, and length, $F(3, 345) = 5.51, p < .01, \eta^2 = .05$, both remained significant, as before. The main effect of BPVS was also significant, $F(1, 115) = 18.93, p < .001, \eta^2 = .14$, but its interaction with inflection type was not, $F(3, 345) = 0.75, p > .05$. The difference in vocabulary level among the four groups of children obscures the overall effect of inflection but does not seem to affect the main finding of interest, namely, that the stressors of speed and length result in a differentiation of error profiles for the four inflection types that resembles the pattern of deficit seen in SLI.

As with the effects of age, there were no specific predictions about the relationship between overall performance on the grammaticality judgment task and vocabulary size, although on the whole it was expected that children with higher A' would also have larger vocabularies. Although the differences in vocabulary level across the four groups of children would inflate correlations between BPVS and grammaticality judgment across the whole sample, the correlations on these variables within the groups may still be interesting. The correlation between BPVS scores and a total A' measure of grammaticality judgment seemed to be linked to sentence speed more than to sentence length. This correlation was striking for both short fast sentences, $r_s(30) = .50, p < .01$, and long fast sentences, $r_s(30) = .58, p < .01$, but was nonsignificant for both short normal sentences, $r_s(30) = .29, p > .05$, and long normal sentences, $r_s(30) = .17, p > .05$. This was the opposite pattern to that observed for age and may suggest that a large vocabulary can act as an effective buffer under the speed stressor but is less effective for length.

Perceptual learning. A final possibility examined was whether there was an effect of perceptual learning, so that children's performance improved over the course of the task, particularly for the speeded sentences. This would have implications for a direct comparison of our simulation with actual cases of SLI, because there is evidence that children with SLI are slower to make this kind of perceptual adjustment (Helzer, Champlin, & Gillam, 1996; Robin, Tomblin, Kearney, & Hug, 1989). As stimulus presentation was randomized, we were able to compare performance on the first and last thirds of items presented to each child, for the normal-rate and speeded sentences. For the normal-rate sentences, a paired-samples t test showed no significant difference between overall A' in the first 33% ($M = .90$, $SD = .10$) and last 33% ($M = .89$, $SD = .13$) of items. For the speeded sentences, by contrast, performance improved significantly from the first items ($M = .74$, $SD = .12$) to the last set of items ($M = .79$, $SD = .13$), $t(58) = 2.75, p < .01$. When paired comparisons were carried out for each of the four inflections separately, it became clear that this difference was mostly driven by the third-person singular, in the speeded sentence condition, as this was the only inflection type to show a significant difference between the first and last 33% of items (First 33%, $M = .68$, $SD = .19$; second 33%, $M = .77$, $SD = .20$), $t(49) = 2.42, p < .05$. There was thus some evidence for perceptual learning in the speeded sentences, but it was slight and localized to one inflection type.

Discussion

The results indicate that a specific profile of linguistic errors associated with SLI can be induced in a group of children with normal linguistic representations. In particular, grammaticality judgments of sentences containing well-formed and ill-formed past tense and third-person singular verb inflections are less accurate under speeded and lengthened presentations than judgments concerning noun plural inflections. This finding is strong evidence in favor of processing deficit accounts of SLI. The results cannot be attributed to a linguistic deficit; the culprit must therefore be the heavy cognitive processing demand imposed on the children by the speeding and lengthening of the sentence stimuli.

Speed Versus Length

The relative effects of sentence speed and length on grammaticality judgment performance are interesting to consider. The initial and most obvious observation is that speeding the sentences is more detrimental to performance than lengthening. As Figure 1 illustrates, when the two factors are pitted against each other, short fast sentences elicit lower A' scores than long normal sentences. It is also clear that the effect is not additive, because long fast sentences are not that much worse off than short fast sentences. This observation is elaborated in the statistically significant three-way interaction among inflection type, speed, and length. Here it is apparent that except for the case of the plural inflection type, length only has a noticeable effect on performance for the normal-rate sentence conditions. As soon as sentences are speeded up, the effect of length becomes negligible. Thus far, the dominance of speed over length as an effective stressor seems fairly clear-cut.

Introducing the effects of age and general language level (using the BPVS as an index) complicates the picture a little. One might reasonably expect that being older and having more developed language skills would both improve performance on the grammaticality judgment task. However, neither factor correlates significantly with A' score when the entire sample of 120 children is included in the calculation.

A logical hypothesis to entertain next is that age and vocabulary might only help when the going gets tougher with increased processing demands—after all, performance in the baseline condition (short normal) is virtually at ceiling. This does appear to be the case with vocabulary level, since the correlation between BPVS and grammaticality judgment score is striking (in the region of $r = .6$) when only the groups presented with fast sentence conditions are examined. However, the situation with age is diametrically opposite: The correlation between age and grammaticality judgment score is important (again in the region of $r = .6$) only when the groups presented with normal-rate sentence conditions are examined. Perhaps the effect of age is weak, so that it is beneficial under normal circumstances but is swamped by something as overpowering as 50% compressed speech rate. However, this cannot explain why vocabulary and age are influential at different levels of the factor speed; if there were a continuum of strength for potentially beneficial factors, one would expect to see a strong correlation between BPVS and grammaticality judgment scores in the normal sentence conditions and a weaker correlation in the fast sentence conditions. This is not the case, and there are no obvious explanations for why age and vocabulary level should have a different pattern of influence on performance. However, with respect to the relative effects of speed and length, note that whether vocabulary level and age exert any influence on performance depends on the speed of the sentence and not its length. Speed maintains its position as the dominant factor.

Qualitative Versus Quantitative Accuracy of Simulation

The efficacy of sentence speeding or lengthening as a means of inducing an SLI-like pattern of errors is important in itself as demonstrating that a non-linguistically specific stress factor can result in a linguistically specific profile of performance. An additional issue, which is not directly addressed in this study, relates to how quantitatively accurate a simulation of SLI our experiment produced. This may well depend at least partly on the magnitude of the stress factor itself. The sentence compression used in the current study was 50%, which is a high level of compression and on first presentation is challenging even for adults. However, there is a successful precedent for using this rate in this type of simulation study (Dick et al., 2001), and although the children who participated in our study found it difficult, it was not beyond their capabilities. Also, although there was some evidence that children adjusted to the fast stimuli (in the speeded sentence conditions) over the course of the task, this seemed to be limited and was only significant for the third-person singular inflection.

Manipulating the magnitude of the stress factors would be an extremely interesting avenue for further exploration: that is, calibrating the compression rate to see at which point performance most closely mirrored that of children with SLI (ideally of comparable age or language level). One could speculate that there exists quite a narrow band where the stressor is mild enough to be quantitatively accurate but severe enough to produce the differentiation between linguistic types that is necessary for a qualitatively accurate simulation. It would be particularly interesting to see whether the appropriate rate would approximate the generalized cognitive slowing rate of 20% to 30% estimated by Miller et al. (2001) and Kail (1994), respectively.

With respect to the question of a qualitatively appropriate pattern of results, the comparison of speed and length effects is once again of interest. The significant Speed × Inflection Type interaction discussed in the Results section reflects the clustering of the verb-phrase inflections (past tense *-ed* and third-person singular *-s*) separately from the plural *-s* and prepositions. This grouping is precisely what one would predict based on the literature reporting omissions of these inflections in the spontaneous and elicited speech of children with SLI. The failure of sentence lengthening to produce a similar differentiation supports the notion that of the two stressors, speed is the more efficacious simulator.

Because there are only two levels for each of the factors speed and length (normal or fast, short or long) in this study, it is impossible to determine whether it is the nature of the stressor, or the magnitude of stress that it produces, that is responsible for the pattern of results. Had the sentences been quadrupled in length rather than doubled, or had they been compressed by 25% rather than 50%, would the relative effects of speed and length have been the same? If a speed-of-processing deficit is the core cause of SLI, to the exclusion of a working memory deficit, then speed should always produce a more accurate simulation and vice versa.

A more extreme version of a processing deficit account might be that there is no single core cause of SLI, but any processing deficit—which may be in speed of processing in one child and in working memory in another—will produce a similar profile of impairment because of the specific typology of the language being acquired. In this case, one might predict that the degree of stress rather than the nature of a particular stressor will be the determining factor. In the current study, these possibilities are confounded, since the degree of speeding used seems to be more stressful than the degree of lengthening used (despite a conscious attempt to control for this by doubling both speed and length). Once again, these would be interesting issues to try to untangle in further studies.

The -s Inflections

A critical part of a processing deficit approach to language impairment is the interaction between the putative processing deficit—regardless of its nature—and the specific features of the language in question. The surface hypothesis (Leonard, 1998), for example, suggests that many inflections in English have low phonetic salience and that this factor in combination with reduced speed of processing underlies the problems with inflectional morphology described in SLI. The case of plural *-s* versus third-person singular *-s* is particularly interesting when contrasting linguistic versus processing deficit accounts of SLI. These two inflections are identical in terms of their phonetic salience, yet it is clear from omission data that plural *-s* is less problematic than third-person singular *-s*. The surface feature of phonetic salience alone cannot account for the difference in difficulty, and linguistic theories of SLI have argued from this that linguistic features rather than surface features must therefore be the critical explanatory factor (e.g., Rice & Wexler, 1996). However, phonetic salience is not the only surface feature that could be involved: Frequency of the inflection in the child's linguistic input could also play a major role, and it could be argued that the inflection *-s* is heard far more often in the context of plural nouns than third-person singular verbs.

In addition, a processing deficit account does not necessarily exclude the possibility of a role for grammatical features; it just doesn't award them primary causal status. Plural *-s* and third-person singular *-s* could be treated differently because the former codes only one feature, whereas the latter codes three. An individual trying to analyze these two inflections under a heavy cognitive processing load, either extrinsic as in the current simulation study or intrinsic as (suggested) in the case of SLI, could very reasonably be expected to have greater difficulty with the grammatically complex inflection. The key difference between this perspective and a purely linguistic perspective is that here the grammatical complexity is seen as a feature of the stimulus—initially external to the language learner—and the processing deficit as a feature of the mind interacting with the stimulus. A purely linguistic position, on the other hand, would seem to make little distinction between the form of the stimulus in the environment and its mental representation, assuming a simple and direct mapping between the two.

Returning to the case of the *-s* inflections, the finding in the current study that the two were strongly differentiated as a direct consequence of increasing the processing load is a striking demonstration that a dynamic interaction between processing resources and the complexity (grammatical or surface) of the stimulus can produce the pattern of performance associated with language impairment.

Prepositions

One result of this experiment that does not fit with the predictions is the participants' performance on the prepositions condition. The choice of the prepositions *in*, *at*, and *on* as a control condition was based largely on previous work by the authors (Hayiou-Thomas, 2002), which found extremely good performance on a virtually identical set of sentences (A' M = .97, SD = .05) in a group of children with SLI. In the literature examining omissions of morphemes in the speech of children with SLI, none of these prepositions are described as problematic, and there is some evidence that *in* and *on* are acquired relatively early in SLI (Albertini, 1980). It is certainly the case that *in* and *on* are acquired at a very early stage in normal language acquisition: de Villiers and de Villiers (1973) have reported that 2-year-olds with a mean length of utterance of 2.82 were able to use *in* and *on* with over 95% accuracy in obligatory contexts. This report agrees with Brown (1973), who ranks *in* and *on* jointly in second place out of 14 morphemes for which age of acquisition was recorded. There is also recent evidence from infant preferential looking research that children understand the meaning of *on* as early as 15 months of age (Meints, Plunkett, Harris, & Dimmock, 2002). When children were shown pictures of objects or animals that were either on or under a table, they looked consistently at the appropriate image when told to (for example) *Look at the cup on/under the table!*

On the basis of all these findings, it was expected that noticing and reporting a missing preposition would not be problematic for the children taking part in this study and that performance on these sentences would be near ceiling even under the stressed sentence conditions. This was clearly not the case, as *A*' scores dropped from .98 in the baseline short normal sentence condition to between .83 and .88 on stressed sentence conditions. The young age of the children cannot account for this drop in performance, given the extremely early age of acquisition of these prepositions. Note that the results did not change when the data for *at* was excluded, to eliminate the possibility that it has a later age of acquisition, since *at* was not one of the morphemes examined by Brown (1973) and de Villiers and de Villiers (1973).

One possibility that may explain the poor performance on the preposition sentences in this study is that they required a shift in strategy: All the other sentences targeted bound morphemes and demanded a focus of attention on the end of a word. Since sentence presentation was randomized and children did not know when to expect a prepositions sentence, it seems likely that they were simply not focusing on the correct bit of the sentence, particularly under stressful task conditions. Another explanation could be that prepositions are in a prosodic "black spot" in the context of the whole sentence (relative to content words, function words tend to be unstressed and even reduced) and that the effect of the black spot is magnified when sentence difficulty is increased (S. Chiat, personal communication, December 20, 2002).

However, the stressful sentence manipulations were intended to simulate what happens every time a child with SLI encounters language. The fact that the children with SLI in Hayiou-Thomas (2002) did not have any difficulty with the prepositions sentences while the children in the current study did weakens the argument that this is a convincing simulation of SLI, even within the narrow field of functional morphology. Insofar as the purpose of including a control condition was to demonstrate that increasing task demands did not damage performance across the board, prepositions failed to demonstrate this. However, the robustness of the plural *-s* inflection served the same purpose and created the requisite differentiation in performance for different inflection types.

Finally, within the confines of the three inflectional morphemes examined—past tense *-ed*, third-person singular *-s*, and plural *-s*—the manipulation of the speed and length of sentences was effective in simulating an SLI-like profile of performance. Specifically, young children with typically developing language, who could therefore be confidently described as possessing intact linguistic representations of these three morphemes, accepted as grammatical sentences that were lacking these morphemes in an obligatory context to a significantly greater extent when the sentences were speeded or lengthened than when they were not. Furthermore, the gradient of difficulty within the three inflections (verb inflections vulnerable, noun plural inflection robust) is analogous to that seen in the speech of children with SLI. With the proviso that a control condition involving the prepositions *in*, *at*, and *on* did not produce the predicted ceiling level of performance, this could be described as a successful, if highly limited, model of SLI.

Its success strongly supports the notion that global processing deficits, such as speed of processing or verbal working memory, are the proximal cause of SLI and not faulty linguistic representations. However, a model is useful insofar as it illustrates what is possible: The finding that the mechanisms built into a model produce the desired behavior is not proof in itself that these mechanisms are actually involved in producing this behavior in people. The current study supports the plausibility of speed of processing or working memory deficits in SLI but does not demonstrate that they are actually present and causal in the disorder. Such a demonstration would be provided if alleviating processing stress were able to improve the linguistic performance of children with SLI.

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Appendix A. Examples of sentence stimuli.

Plural /z/

Yesterday, we saw three bears in the forest.

Yesterday, my sister saw three brown bears in the big, dark, scary forest.

Last week, Tom saw six pigs in a big muddy field.

Last week, Tom saw six fat, pink, happy pigs in an enormous, muddy, smelly field.

Plural /s/

Last week, we sailed two boats around the lake.

Last week, my sister and I sailed two boats all around the enormous blue lake.

Every day, both our cats eat a tasty dinner.

Every day, both of our cute, cuddly cats eat a very big and tasty dinner.

Third-person singular /z/

Every day, Sarah pours a glass of milk.

Every day, the thirsty little girl pours a big glass of cold chocolate milk.

Every week, Mary waves at the people on the train.

Every week, my little sister Mary waves at all the people on the noisy, red train.

Third-person singular /s/

Every week, Rebecca walks along the river.

Every week, my best friend Rebecca walks along the long, beautiful river.

Every day, David kicks a big football.

Every day, my little cousin David kicks a big, round, yellow plastic football.

Past tense /d/

Yesterday, the boy pulled a leaf off the tree.

Yesterday, the short, brown-haired boy pulled a shiny green leaf off the big tall tree.

Last week, the monster scared all the children.

Last week, the gigantic, wild, green monster scared all the sleepy little children.

Past tense /t/

Last week, my father fixed a dent in his car.

Last week, my very clever father fixed a nasty dent in his shiny new car.

Yesterday, Rebecca talked about the party.

Yesterday, Rebecca and Jonathan talked about the exciting birthday party.

Prepositions i*n, on,* or *at*

Yesterday, Tom saw plums in the fruit-basket.

Yesterday, Jennifer and Tom saw plums in the big, full, colorful fruit-basket.

Every day, there are socks in the laundry basket.

Every day, there are lots of dirty socks in the big, full, smelly laundry basket.

Yesterday, I slipped on the wet pavement.

Yesterday, Mary and David slipped on the slippery, shiny wet pavement.

Every day, Tom puts sugar on his cornflakes.

Every day, Tom puts lots and lots of sugar on his yummy, crunchy, yellow cornflakes.

Last week, we laughed at all the jokes.

Last week, mummy and daddy laughed at all the very funny jokes and stories.

Every week, Sue waits at the bus-stop for the bus.

Every week, Christopher and Sue wait at the cold bus-stop for the big red bus.

Note. The short version of each sentence is listed first (as used in the short normal and short fast sentence conditions) followed by the long version (used in the long normal and long fast sentence conditions).

Appendix B. Mean length of sentence stimuli in syllables, and seconds, for sentence conditions and inflection types.

	No. syllables before target word	No. syllables after target word	Total no. syllables	Length for well-formed	Length for ill-formed
Short normal					
Plural	5.7	4.6	11.3	3.28	3.10
3rd-per sing	5.4	5.2	11.6	3.06	2.95
Past	5.4	5.0	11.4	2.95	2.85
Prepositions	5.6	4.2	10.8	3.10	2.90
Short fast					
Plural	5.7	4.6	11.3	1.64	1.55
3rd-per sing	5.4	5.2	11.6	1.53	1.48
Past	5.4	5.0	11.4	1.48	1.42
Prepositions	5.6	4.2	10.8	1.55	1.45
Long normal					
Plural	9.6	9.5	20.1	5.22	5.13
3rd-per sing	9.6	9.4	20.0	5.12	4.96
Past	9.6	9.4	20.0	5.11	5.04
Prepositions	9.6	9.4	20.0	5.28	5.09
Long fast					
Plural	9.6	9.5	20.1	2.61	2.56
3rd-per sing	9.6	9.4	20.0	2.56	2.48
Past	9.6	9.4	20.0	2.56	2.52
Prepositions	9.6	9.4	20.0	2.64	2.54

Note. 3rd-per sing = third-person singular.