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# A Functional Magnetic Resonance Imaging Investigation of Verbal Working Memory in Adolescents With Specific Language Impairment

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This study used neuroimaging and behavioral techniques to examine the claim that processing capacity limitations underlie specific language impairment (SLI). Functional magnetic resonance imaging (fMRI) was used to investigate verbal working memory in adolescents with SLI and normal language (NL) controls. The experimental task involved a modified listening span measure that included sentence encoding and recognition of final words in prior sets of sentences. The SLI group performed significantly poorer than the NL group for both encoding and recognition and displayed slower reaction times for correct responses on high complexity encoding items. fMRI results revealed that the SLI group exhibited significant hypoactivation during encoding in regions that have been implicated in attentional and memory processes, as well as hypoactivation during recognition in regions associated with language processing. Correlational analyses indicated that adolescents with SLI exhibited different patterns of coordinating activation among brain regions relative to controls for both encoding and recognition, suggesting reliance on a less functional network. These findings are interpreted as supporting the notion that constraints in nonlinguistic systems play a role in SLI.

**KEY WORDS:** neuroimaging, specific language impairment (SLI), language processing, memory, attention

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Various models of language processing have been proposed that incorporate the notion of a limited capacity system (e.g., Baddeley, 1986, 1998, 2003; Gathercole & Baddeley, 1993; Just & Carpenter, 1992; Just, Carpenter, & Keller, 1996). The major premise of these models is that there is a limited pool of operational resources available to perform computations and when demands exceed available resources, the processing and storage of linguistic information are degraded. According to this view, success in comprehending and producing language is dependent on the ability to actively maintain and integrate linguistic material in working memory. Behavioral research has indicated direct associations between working memory capacity and language abilities (including spoken language and reading) for both adults and children with normal language functioning (e.g., Baddeley, 2003; Baddeley, Gathercole, & Papagno, 1998; Caplan & Waters, 2002; Carpenter, Miyake, & Just, 1994; Gathercole, Service, Hitch, Adams, & Martin,

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1999; Gathercole, Willis, Emslie, & Baddeley, 1992; King & Just, 1991; Swanson, 1996).

Based on findings from behavioral tasks, a number of investigators have proposed that children with specific language impairment (SLI) have processing capacity limitations that involve restrictions in working memory (Ellis Weismer & Thordardottir, 2002; Ellis Weismer et al., 2000; Gathercole & Baddeley, 1990; Gillam, 1998; Montgomery, 1995, 2000, 2003). Various behavioral tasks have been used to assess verbal working memory skills in SLI, including adaptations of measures that were originally developed to examine working memory in adults, such as nonword repetition (Baddeley, 1986, 1998) and listening span measures (Daneman & Carpenter, 1980). Ellis Weismer and colleagues have found that elementary school-age children with SLI perform significantly more poorly than normal language (NL) controls on these measures (Ellis Weismer & Thordardottir, 2002; Ellis Weismer, Evans, & Hesketh, 1999). Based on results from a hierarchical multiple regression analysis, Ellis Weismer and Thordardottir (2002) reported that performance on three verbal working memory measures (nonword repetition, listening span, and dual processing sentence comprehension) combined with nonverbal cognitive scores predicted children's performance on a standardized measure of language comprehension and production ( $r^2 = .41$ ,  $p < .05$ ). After the contribution of nonverbal cognition was accounted for (21% of the variance), each of the verbal working memory measures added significant unique variance in language scores, but the listening span measure accounted for substantially more variance than the other tasks.

If the pattern of deficits exhibited by children with SLI is due to capacity limitations in a broad sense, as opposed to linguistic deficits in a narrow sense, then we need to consider how linguistic and nonlinguistic systems contribute to language processing and the extent to which capacity limitations in this population are a product of nonlinguistic constraints or some combination of linguistic and nonlinguistic constraints. Functional magnetic resonance imaging (fMRI) offers an advantage over behavioral methods for examining these issues. When behavioral methods are used to assess language processing, we can accurately measure decrements in processing without being clear about what components of processing contribute to processing problems. This is because factors such as attention or memory are often intimately tied to linguistic difficulty. The technique of fMRI offers an alternate approach. By identifying areas of activation known to be part of language, memory, and attention networks, fMRI can provide a brain-based framework for examining the relative contribution to these regions to language processing and establish whether they are functionally different in

children with SLI. In addition, physiologic patterns of activation can reveal differences even in cases when behavioral performance is highly accurate in both controls and individuals with language impairment (Plante, Van Petten, & Senkfor, 2000). Therefore, fMRI offers the possibility of examining residual inefficiencies or compensatory mechanisms in a way that is not possible with behavioral methods.

In this study, we present findings from functional imaging of adolescents with SLI during a verbal working memory task in order to examine the relative contribution of cortical regions associated with linguistic processing as well as regions that reflect more general processing capacities that support working memory. Verbal working memory tasks provide the advantage of permitting an explicit examination of factors beyond language in verbal processing. One difficulty with this approach is the lack of agreement on the definition of working memory. In its basic form, Baddeley's multiple-component model of working memory (Baddeley, 1986, 2003; Baddeley & Hitch, 1974) comprises a central executive and modality-specific slave systems for rehearsal of visual or phonological information. This model differentiates between working memory, which is the process by which information is held in conscious awareness, and long-term memory, which stores information on a long-term basis. The amount of operational resources available within the rehearsal subsystems and from the central executive dictates the capacity limitations for working memory. This view of working memory contrasts with other definitions. Cowan's (1999) embedded-processes model suggests that working memory is not distinct from long-term memory, but instead reflects information within the long-term memory store that is actively the focus of attention. In this model, attention is specified as a key "operational resource" in working memory and maintenance of attentional focus, rather than rehearsal, is key to maintaining items in working memory. In contrast, attentional control of working memory is a function of the central executive in Baddeley's model, and long-term memory is distinct from working memory (though the more recent addition of the episodic buffer to the model blurs this distinction to some extent; Baddeley, 2003). Similar to Cowan's model, the capacity theory of comprehension proposed by Just, Carpenter, and colleagues (Just & Carpenter, 1992; Just, Carpenter, & Keller, 1996) considers active processing of information as central to their notion of working memory. Within this view, capacity—which is presumed to vary across individuals—is defined as the maximum amount of activation available in working memory to support information maintenance and computation. Attentional control processes, attributed to the central executive within Baddeley's model, are incorporated within working memory in Just and Carpenter's model. Resource allocation

schemes are thought to take effect when demand exceeds available resources such that trade-offs occur between storage and processing of information.

Each of these models is supported by empirical data, and as of yet, none of these models is considered definitive. It has been suggested that neuroimaging data may serve to validate constructs represented in different models that are difficult to distinguish by behavioral methods alone (Chein, Ravizza, & Fiez, 2003). For example, all working memory tasks have encoding and recall or recognition phases. However, factors that affect encoding (e.g., word frequency and length, sentence complexity) are only inferred based on recall performance. Our strategy was to use a working memory task that is generally consistent with the definition of working memory across models (although it is most closely aligned with the models espoused by Just and Carpenter and by Cowan). This involved use of a task that entailed both memory for verbal stimuli and processing of information during the time that verbal stimuli are to be encoded and remembered. We can then use fMRI to illuminate the processes during both encoding and recognition phases that may contribute to verbal working memory deficits for individuals with SLI by examining activation within brain systems that support verbal working memory.

## **Brain Systems Supporting Verbal Working Memory**

In all theoretical models, verbal working memory presupposes some level of processing of verbal information, whether that is phonological, semantic, or syntactic. Numerous neuroimaging studies of language functioning have examined each of these components of language processing (e.g., Buschbaum, Hickok, & Humphries, 2001; Caplan, 2001; Friederici, Meyer, & von Cramon, 2000; Giraud & Price, 2001). Two areas critical to language processing are the superior temporal gyrus (STG) and the inferior frontal gyrus (IFG); (see summary by Gernsbacher & Kaschak, 2003). Both of these regions have also been implicated in maintenance of verbal information based on lesion data (Frisk & Milner, 1990). Furthermore, increased processing load during language tasks tends to increase activation within classic language areas (Just, Carpenter, Keller, Eddy, & Thurborn, 1996), as well as additional cortical areas such as middle frontal and inferior parietal sites (Keller, Carpenter & Just, 2001). This is consistent with the notion that more capacities, including memory, may contribute to linguistic performance.

fMRI studies of working memory abilities in adults have provided insights into brain regions mediating components of memory and have also demonstrated

differential patterns/levels of activation for differing processing loads (e.g., Braver et al., 1997; Crosson et al., 1999; Rypma, Berger, & D'Esposito, 2002; Rypma, Prabhakaran, Desmond, Glover, & Gabrieli, 1999). Various investigations have shown that the dorsal lateral prefrontal cortex is predictably involved in working memory (Braver et al., 1997; Crosson et al., 1999; Wagner et al., 1998), though findings reported by D'Esposito and colleagues indicate that prefrontal cortex supports processes in addition to working memory (D'Esposito, Ballard, Aguirre, & Zarahn, 1998). Recent results from memory studies suggest that frontal activations contribute to many types of memory tasks rather than to working memory specifically (Cabeza et al., 2003; Nyberg et al., 2003; Ranganath, Johnson, & D'Esposito, 2003). Likewise, Cabeza et al. (2003) have shown that activation patterns typically attributed to memory processes (episodic memory retrieval) also occur during attention tasks, suggesting that both attention and mnemonic processes are involved in these tasks. This overlap might be accounted for as reflecting the central role of attention in working memory (Cowan, 1999) or the contribution of central executive processes to working memory under Baddeley's multiple-component model of working memory.

In any case, it is difficult to conceive of verbal memory performance in the absence of attention to the information to be remembered. Indeed, attention is a basic resource that is drawn upon for most processing tasks (see Shaywitz et al., 2001). Although attention has been viewed in terms of a single, limited cognitive resource (Kahneman, 1973), most current theoretical frameworks conceptualize attention as being comprised of multiple systems that are associated with different aspects of controlled processing (e.g., Posner & Dehaene, 1994). Within this type of functionalist account, Shaywitz and colleagues (2001) used fMRI to examine the neural architecture of components of attention in the context of verbal processing (word recognition) tasks in neurologically normal adults. Findings from this study indicated that attentional control mechanisms associated with perceptual selectivity (selective attention and divided attention) primarily involved parietal and inferior frontal sites, whereas executive function (involving complex decision making) engaged prefrontal regions. Thus, Shaywitz et al. (2001) concluded that particular functional aspects of attentional control in language processing involve cortical systems that are widely distributed but yet distinctive from classic language cortex.

There has been considerable investigation of working memory in SLI (see overview by Ellis Weismer, 2004), with this group generally performing poorly compared with their typically developing peers. However, there is relatively little research in the area of attention in SLI. Research that has referred to attention in the SLI

population has dealt primarily with the comorbidity of attention deficit disorder (ADD) rather than attentional control mechanisms per se. However, some investigators have pointed to attention as a possible explanation for behavioral findings in SLI (Helzer, Champlin, & Gillam, 1996). At the present time, there is a lack of data to address whether attentional constraints that may be inherent to SLI, and existing independent of ADD, contribute to verbal processing deficits.

## Neuroimaging in SLI

Neuroimaging investigations of children with SLI are relatively few and largely limited to reports of anatomical differences (Gauger, Lombardino, & Leonard, 1997; Jackson & Plante, 1997; Jernigan, Hesselink, Sowell, & Tallal, 1991; C. Leonard et al., 2002; Plante, 1991; Plante, Swisher, Vance, & Rapcsak, 1991). Although anatomical differences suggest brain function may also be altered, only one recent study has used fMRI techniques to examine language processing in SLI. Hugdahl and colleagues (Hugdahl et al., 2004) investigated differences in brain activation in 5 members of a Finnish family who expressed SLI (ages 11–70) compared with a control group of 6 individuals with intact language development (ages 15–61). The family with SLI showed reduced activation compared with controls during a task that involved passive listening to vowels, pseudowords, and real words. Differences were greatest in the anterior-ventral areas around the middle temporal gyrus (MTG) and superior temporal sulcus (STS). Hugdahl et al. concluded that SLI is characterized by reduced activation in brain regions (MTG/STS) that are critical for speech perception and phonological awareness according to a model proposed by Binder and Price (2001). Of further interest to the present study, the control participants, in contrast to those with SLI, also activated an area in the right inferior frontal lobe thought to reflect working memory and attention effects (Demonet, Price, Wise, & Frackowiak, 1994).

The purpose of the present study was to examine the claim that the language deficits of children with SLI are a reflection of more general processing capacity limitations (Ellis Weismer, 1996; Ellis Weismer, Evans, & Hesketh, 1999; Montgomery, 2000; Lahey & Edwards, 1996). Specifically, we used a verbal working memory task to test the claim that limitations in processing capacity play a role in SLI. This type of task maximizes our ability to consider the contribution of systems that support language as well as systems that support more general capacities including memory and attention. In keeping with this view, specific regions of interest that have been associated with semantic and syntactic language processing, working memory, and attention were examined.

Although there is not a one-to-one association between activation patterns and task difficulty, there is evidence that increased levels of activation, spread of activation, or recruitment of homologous areas in the right hemisphere is linked to increased task complexity in typical participants (Braver et al., 1997; Just, Carpenter, Keller, et al., 1996; Keller et al., 2001; Rypma et al., 2002). However, previous studies of individuals with language disorder in combination with ADD or apraxia have reported hypoperfusion during resting states (Denays et al., 1989; Lou, Henriksen, & Bruhn, 1984), which suggests that the SLI group may be characterized by less activation than their NL peers. Based on these studies, we predicted that the SLI group would demonstrate hypoactivation and/or less clear lateralization than NL controls on this verbal working memory task, particularly under more complex task conditions. We further predicted that individuals with SLI may exhibit a reliance on ineffective neural networks involving both classic language areas and areas associated with more general processing capacities.

## Method

### Participants

The participants in this study were 16 adolescents drawn from a large, well-defined sample of children who have been participating in a longitudinal, epidemiological investigation of developmental language impairment (Collaboration on Specific Language Impairment, J. Bruce Tomblin, Director). This included 8 adolescents who had typical language development and 8 adolescents with SLI. The adolescents who composed the sample for the current study were among randomly selected individuals whose families were recruited and agreed to travel from Iowa to the University of Wisconsin—Madison, where the neuroimaging was conducted. Written informed consent to participate was obtained from parents, along with written assent from the adolescents (institutional review board approvals were obtained from all three universities represented in this collaborative research project). Data were collected from a total of 19 adolescents. In 2 cases the data were not usable due to excessive head motion. The data from a 3rd participant with a history of language impairment were not included because subsequent behavioral testing conducted shortly after the neuroimaging was completed (as part of the larger longitudinal investigation) did not reveal persistent language delay.

The participants were originally identified as having either NL development or SLI at kindergarten based on the EpiSLI diagnostic criteria established by Tomblin, Records, and Zhang (1996). That is, they scored 1.25 *SDs* or more below the mean on at least two of five composite

**Table 1.** Group means and standard deviations on the second grade cognitive and language diagnostic testing for the adolescents with normal language (NL) and with specific language impairment (SLI).

Measure	NL (N = 8)		SLI (N = 8)	
	M	SD	M	SD
Nonverbal cognition <sup>a*</sup>	105.50	6.40	95.38	8.50
Receptive Language: Concepts and Directions <sup>a</sup>	9.13	2.95	6.50	2.07
Expressive Language: Recalling Sentences <sup>b*</sup>	10.00	2.83	5.50	2.00
Receptive Language: Sentence Structure <sup>b</sup>	11.13	3.27	8.25	3.11
Expressive Language: Word Structure <sup>b*</sup>	12.13	2.95	7.63	1.92
CELF-3 composite <sup>c*</sup>	0.25	0.99	-1.28	0.58
Receptive/expressive vocabulary <sup>d</sup>	104.75	19.96	87.50	12.87
Receptive vocabulary <sup>e*</sup>	114.25	15.05	88.75	13.16
Nonword repetition <sup>f*</sup>	88.63	6.99	74.50	16.77
Listening span <sup>g*</sup>	63.00	11.60	44.60	14.70

<sup>a</sup>Wechsler Intelligence Scale for Children—Third Edition: Performance scale. <sup>b</sup>Clinical Evaluation of Language Fundamentals–3: subtest. <sup>c</sup>Clinical Evaluation of Language Fundamentals–3: composite z score. <sup>d</sup>Comprehensive Receptive and Expressive Vocabulary Test. <sup>e</sup>Peabody Picture Vocabulary Test—Revised. <sup>f</sup>Nonword Repetition Task: percentage phonemes correct. <sup>g</sup>Competing Language Processing Test: Word Recall.

\*Significant difference between groups at  $p < .05$ .

scores representing comprehension, expression, vocabulary, grammar, and narrative skills. Additional language and cognitive testing was conducted during the grade school period and during middle school (see Tables 1 and 2 for a summary of these results for second and eighth grade, respectively). At the time of this study (eighth grade assessments), the group with SLI was comparable

to the NL group in terms of nonverbal cognition based on the Performance scale score from the Wechsler Intelligence Scale for Children—Third Edition (Wechsler, 1991) but scored significantly worse on each of the measures of receptive and expressive language abilities. The eighth grade language measures included the Clinical Evaluation of Language Fundamentals—Third Edition

**Table 2.** Group means and standard deviations on the eighth grade cognitive and language diagnostic testing for the adolescents with normal language (NL) and with specific language impairment (SLI).

Measure	NL (N = 8)		SLI (N = 8)	
	M	SD	M	SD
Nonverbal cognition <sup>a</sup>	101.75	14.02	99.37	12.82
Receptive Language: Concepts and Directions <sup>b*</sup>	10.00	2.73	6.00	2.72
Expressive Language: Recalling Sentences <sup>b*</sup>	9.63	2.67	5.00	2.07
CELF-3 composite <sup>c*</sup>	-0.07	0.96	-1.73	0.70
Receptive/expressive vocabulary <sup>d*</sup>	104.25	15.44	80.75	10.22
Receptive vocabulary <sup>e*</sup>	111.25	15.75	94.88	13.03
Nonword repetition <sup>f*</sup>	93.63	2.92	83.00	9.12
Listening span <sup>g*</sup>	81.38	9.81	60.88	15.07

<sup>a</sup>Wechsler Intelligence Scale for Children—Third Edition: Performance Scale. <sup>b</sup>Clinical Evaluation of Language Fundamentals–3: subtest. <sup>c</sup>Clinical Evaluation of Language Fundamentals–3: composite z-score. <sup>d</sup>Comprehensive Receptive and Expressive Vocabulary Test. <sup>e</sup>Peabody Picture Vocabulary Test—Revised. <sup>f</sup>Nonword Repetition Task: percentage phonemes correct. <sup>g</sup>Competing Language Processing Test: Word Recall.

\*Significant difference between groups at  $p < .05$ .

(Semel, Wiig, & Secord, 1995), the Peabody Picture Vocabulary Test—Revised (Dunn & Dunn, 1981), and the Comprehensive Receptive and Expressive Vocabulary Test (Wallace & Hammill, 1997). Furthermore, the group with SLI scored significantly more poorly than the NL group on two measures of verbal working memory, the Nonword Repetition Task (Dollaghan & Campbell, 1998) and the Competing Language Processing Task (Gaulin & Campbell, 1994). In addition to having persistent spoken language deficits, 2 of the adolescents with SLI demonstrated reading disabilities in eighth grade.

Clinical assessments documented that all children included in the present study exhibited nonverbal cognitive abilities in the normal range, normal hearing acuity, no emotional/social disturbance, or sensory/motor deficits. Parent ratings of attention problems on the Child Behavior Checklist (CBCL; Achenbach, 1991) obtained at eighth grade indicated that the groups did not differ significantly, though the average attention deficit percentile score for the group with SLI was somewhat higher than that for the normal language (NL) group (SLI:  $M = 74.4$ ,  $SD = 22.2$ ; NL:  $M = 64.13$ ,  $SD = 16.51$ ),  $t(14) = -1.048$ ,  $p = .312$ . There was a wide range of performance in both groups and participants were not excluded on the basis of attention problems. Two participants (1 NL, 1 SLI) scored more than 2  $SDs$  above the mean and 2 others (2 SLI) scored more than 1.5  $SDs$  above the mean on the Attention Problems scale of the CBCL; 2 of the SLI adolescents had a clinical diagnosis of ADD/ADHD. With respect to ethnic, socioeconomic, and linguistic background, the 16 participants were Caucasian and were native speakers of Standard American English who came from middle-class families. At the time of this study, the NL group had a mean chronological age of 14 years, 1 month ( $SD = 6$  months). The mean age of the group with SLI was 13 years, 10 months ( $SD = 7$  months). There were 6 males and 2 females in the NL group and 5 males and 3 females in the SLI group. All participants were right-handed, except for 1 control and 1 adolescent with SLI.

## General Procedure

Data were collected during a 1½-hr session conducted at the Waisman Center Keck Imaging Laboratory on the University of Wisconsin—Madison campus. Each session consisted of metal screening, training on the experimental task outside the scanner, and practice in a simulator (mock scanner) to acclimate the participant to the testing environment. The total time required to collect the structural and functional scans in the magnet was approximately 30 min.

## Design and Experimental Task Overview

The activation task consisted of a verbal working memory task adapted from Daneman and Carpenter's (1980) listening span measure. This task entailed sentence encoding (Encoding), as well as recalling the final word of each sentence within the sets of sentence stimuli (Recognition). Eight cycles that made up the experiment were equally divided into four cycles of low complexity sentences and four cycles of high complexity sentences (described below); the reason for including both simple and complex sentences was to attempt to vary the cognitive load of the task. The activation task was interspersed with a brief (21 s) control task involving recognition of a target tone that the child had been trained to identify. During these intervals, the participants were engaged in appropriate control activities (involving auditory processing, decision making, and button pressing), as described below. The experimental task was created and delivered using E-Prime (Psychology Software Tools, Inc.), a Windows-based software program designed for generating and running psychological experiments. E-Prime randomizes stimulus delivery within blocks and records responses for both accuracy and reaction time (in milliseconds).

Drawing on the capacity theory of comprehension and the assumptions underlying the listening span task on which the experimental task in this study was based (Daneman & Carpenter, 1980; Just & Carpenter, 1992), the processing component of working memory is tapped by sentence encoding, and the storage component is tapped by word recognition performance. This is the classic view of listening span measures, as typically interpreted on the basis of behavioral responses (see discussion by Montgomery, 2003). However, it is important to note that moment-to-moment processing cannot be so clearly delineated. The combined demands of the task mean that the encoding portion entails cognitive processes in addition to those devoted to sentence processing. That is, there is a competing requirement to attend to final words in sentences and maintain these words while completing the comprehension task. Thus, activation patterns during the encoding phase of this task are presumably different than what would be observed for a sentence processing task in which there were no concurrent memory demands. In addition to the memory demands, this task also draws on attention. Using a functionalist framework of attention in language processing adopted by Shaywitz et al. (2001), our task can be viewed as involving attentional control mechanisms associated with perceptual selectivity, namely, selective attention and divided attention. It was not the intent of this study, however, to address the role

of specific attentional mechanisms within verbal working memory. In order to accommodate an fMRI block design in this study, a brief control (tone) task was inserted between the encoding and recognition phases of the verbal working memory task. Although an intervening task might be assumed to disrupt the contents of items temporarily stored in a rehearsal buffer according to Baddeley's multiple-component model of working memory, this would not be the case according to other models of working memory as long as the material was being actively refreshed to maintain it for retrieval (e.g., Cowan, 1999).

## Experimental Structure of Stimuli

fMRI is used to identify brain regions that show changes in blood oxygen level dependent (BOLD) signal that correspond to changes in the experimental and control tasks. This signal is an indirect index of neural activity (Thompson, Peterson, & Freeman, 2003). In order to quantify these changes in BOLD signal, we used a block design common to fMRI studies. This design alternates cycles or "blocks" of stimuli corresponding to experimental or control conditions, which allows for a statistical evaluation of the amount of change in BOLD signal that can be accounted for by the periods of time during which participants are asked to perform experimental and control conditions.

In this experiment, eight cycles of stimuli were presented following a 12-s period that began the scan. This period was primarily used to allow the magnet to reach equilibrium before stimuli were presented and data collected. The cycle of blocks began with an encoding task followed by a control task (a tone detection task). This was followed by a recognition task and a repetition of the control task. These cycles were repeated eight times during the course of the scan. For half the participants, the first four cycles included low complexity encoding and recognition conditions, and the second four cycles included high complexity conditions. The other half received low and high complexity conditions in reverse order. These conditions were completed during a single scan.

Because the block design requires participants to switch between experimental and control tasks, we also introduced a 3-s cue period before each block. This period allowed us to present prompts concerning the upcoming task to facilitate participant performance. The prompts were as follows: encoding prompt—"Answer these questions"; tone prompt—"Listen for your sound"; recognition prompt—"Did you hear the word...?" The specific structure of each cycle consisted of the following four-block sequence each preceded by their cue period: encoding block (6 sentences), tone block (6 tone sequences), recognition block (9 target/foil words), and tone block (3 tone sequences). For the four cycles in-

volving low complexity sentences, each block was 21 s long, with the exception of the last tone block, which was 12 s. In the cycles with high complexity sentences, the encoding block was 27 s long (in order to accommodate the same number of longer, more grammatically complex sentences). A set response window of 1.0 s was used for the activation and control intervals. Half of the participants heard low complexity encoding stimuli during the first four cycles followed by high complexity stimuli in the last four cycles; the other half heard the high complexity stimuli first, followed by low complexity.

## Verbal Stimuli

Two types of encoding stimuli were created (both involved yes-no questions); one set consisted of low complexity sentences and the other was comprised of high complexity sentences. The low complexity sentences were 7–8 syllables and 2.5 s long. Examples include *Do people ride on horses?* and *Can a farmer grow dollars?* High complexity stimuli were 10–11 syllables and 3.5 s long. These sentences were similar to those in the other condition, but included a relative clause that modified the subject of the sentence. Examples include *Do cats that are furry live in the ocean?* and *Can a person who is hungry eat an apple?* It should be noted that the length and grammatical complexity of the experimental sentences (in both the low and high complexity conditions) were designed to be more challenging than the simple three-word sentences (e.g., *Water is dry*) comprising the Competing Language Processing Task (CLPT; Gaulin & Campbell, 1994) administered before the fMRI protocol. Experimental stimuli were specifically designed with adolescent participants in mind, whereas the CLPT was intended for children ages 6–12 years. The final words in each of the experimental sentences were carefully selected and balanced across the lists in terms of their frequency of occurrence based on the *American Heritage Word Frequency Book* (Carroll, Davies, & Richman, 1971). These sentence-final words were all two-syllable singular or plural nouns, with stress on the first syllable (e.g., *apple*, *dollars*). There were an equal number of questions requiring yes-no responses within each trial block. Recognition stimuli consisted of a list of words that included sentence-final words from the encoding sentences (targets), as well as foils that were semantically and phonetically dissimilar from the target words for a given set of sentences. The foil items were matched to the target items with respect to word frequency, syllable length, and stress pattern. Each recognition stimulus word was approximately 1 s in duration. The number of yes-no responses for recognition items was evenly divided across the trial blocks of the experimental task.

Verbal stimuli were recorded using a Sony Minidisk recorder and lapel microphone in a sound-treated booth.

The recordings were then digitized and edited using Cool Edit 2000 such that the signal energy was adjusted to fill the range of the D/A converter without clipping the signal. Pilot testing with an adult listener during the collection of a scan indicated near perfect levels of performance in response to the auditory stimuli used in this study. Experimental stimuli were presented to listeners under nonferromagnetic headphones designed to attenuate ambient noise in the scanner.

## Tone Stimuli

A tone detection task was selected as a control task. Participants were asked to listen to a series of tones and indicate whether each was their target tone (introduced to them during prescan practice). A control task that required participants to attend to auditory stimuli and make responses was preferred over a passive “resting” interval for several reasons. First, we wanted to prevent explicit rehearsal of the verbal stimuli between the encoding and recognition period by providing an alternate task for participants to complete. Requiring additional processing while items must be held in memory also increased the computational demand, which was desirable under the assumption that capacity limitations influence verbal memory performance. In addition, a control task that required a response from participants provided evidence that they were complying with task demands during the control blocks as well as for the encoding and recognition blocks. Note that the task demands of the tone tasks (i.e., listening to auditory stimuli, making decisions, motor movements for responses) mirrored aspects of the experimental tasks that were not directly related to the constructs of primary interest (i.e., verbal memory). However, we elected not to parallel the experimental tasks with a verbal or phonological control task because we did not wish to obscure any activation related to language processing during the encoding and recognition blocks. Because these task demands were common to both the encoding and recognition blocks, we were able to use a single control task as a contrast for both aspects of the verbal memory task. This also facilitated performance of the participants because it minimized the number of tasks they had to perform during the course of a scan.

Tone stimuli were 2.5 s long, followed by a 1-s response interval. The first 2 s of each stimulus consisted of a sequence of pure tone segments, with each segment 0.25–0.5 s long. Half of the sequences ended with the target tone, a 1000 Hz warble tone that was 0.5 s long. The other sequences ended with pure tones of various frequencies (ranging from 100 to 5000 Hz) that were also 0.5 s long. The amplitudes of the tones were manipulated as necessary to create stimuli that were perceptually equivalent in loudness across the sequences. As noted previously, participants were trained prior to the actual

experiment to listen for the target tone and to press the “yes” button if they heard the target or the “no” button if they did not. The number of items for which the correct response was yes or no was evenly divided across the experimental blocks.

## Imaging Protocol and Analysis Procedures

Structural and functional scans were obtained on a 3 Tesla GE magnet. The protocol included two T1-weighted structural scans. The first was obtained with the slice placement and thickness used in the functional images (FSE sequence, repetition time [TR] = 500, echo time [TE] = minimum full, number of excitations [NEX] = 1, field of view [FOV] = 24 × 24 cm, matrix = 256 × 128, twenty-six 5 mm contiguous slices in the axial plane over the full brain volume, scan time: 2 min 24 s) and was used to identify neuroanatomical regions on the lower resolution functional image. The second structural scan was a high-resolution three-dimensional image (SPGR sequence, TR = min full, TE = 1, NEX = 1, FOV = 24 × 24 cm, matrix = 256 × 192, one hundred twenty-four 1.5 mm slices in the sagittal plane, scan time: 8 min 40 s) and was used for display purposes. A single functional echo-planar scan (Epibold sequence, TR = 3,000, TE = 30, FOV = 24 × 24 cm, matrix = 64 × 64, time points: 212, twenty-six 5 mm contiguous slices in the axial plane over the full brain volume, scan time: 10 min 36 s) was obtained while participants performed the encoding and recognition portions of the verbal memory task.

Functional images were analyzed using AFNI (Cox, 2002). Individual images from each scan were reconstructed into three-dimensional (length × width × height) data sets for structural scans and four-dimensional (length × width × height × time) data sets for the functional scan. Scans from individual participants were registered to a base image to minimize the effects of minor amounts of movement, such as that associated with breathing and heartbeats. During these two processes, AFNI provides graphic and numerical data that can be used to evaluate the integrity of the data. The functional image data from 2 children were found to have unacceptable movement artifacts and these participants were excluded from the data set. Following these analyses, slow-changing linear trends in the data were removed through a regression procedure. Finally, the signal variations in the functional images were correlated with a set of numerical models of the hemodynamic response that had been convolved with the periods of time during which participants were engaged in the behavioral or control tasks. Because the onset of the hemodynamic response can vary from individual to individual, and from brain region to brain region, multiple models that lagged the onset of the

response from 0 to 3 s after stimulus onset were provided. The analysis program iteratively correlated each of the models to the functional image data and retained the results from the model that best fit the data. The percentage change in the hemodynamic response, the baseline level on which the percentage change was based, and the time lag of the hemodynamic model that best fit the functional data were calculated and retained for statistical analysis.

Given the nature of the tasks used in this study, a priori predictions could be made about brain systems that were of interest for specific analysis. This prevented the problem of alpha slippage that would occur if a voxel-by-voxel search for activation were conducted across the full volume of the brain. Regions of interest (ROIs) were identified in a two-step procedure. First, anatomical areas were identified from the literature that corresponded to components of the tasks used in this study (frontal-memory regions, parietal-attention regions, frontal and temporal language regions). Then, clusters of voxels within these anatomical areas that showed reliable activation both within and across subjects were identified. For voxels to be included within an ROI, they had to show reliable covariation with the hemodynamic response ( $r^2 > .10$ ). This criterion reflects a minimum acceptable effect size for the BOLD signal that is based on signal fidelity corresponding to the blocks of the experiment. We used this metric of signal fidelity to judge activation rather than signal amplitude because the latter can be high even when signal fidelity is low.

To increase the likelihood that voxels thus identified represented true activation rather than chance varia-

tion, voxels that did not occur in a cluster of at least three suprathreshold voxels (173.4 mm) were disregarded. Furthermore, it can be expected that some clusters of activation that meet the correlational threshold will be idiosyncratic to specific individuals. Therefore, clusters of voxels were retained for analysis that exceeded this threshold in at least half ( $n = 4$ ) the NL participants or half the SLI participants. This maximized the likelihood of identifying regions of functional neuroanatomy for further analysis that best reflected the patterns common to both groups.

## Results

### Behavioral Analyses

A summary of the behavioral data for the verbal working memory task is provided in Table 3, including means and standard deviations for the accuracy and reaction time (RT) responses broken down by group, condition, and complexity. Accuracy and RT data were analyzed separately using a mixed model, repeated measures analysis of variance (ANOVA) in which group (SLI and NL) was the between-subjects variable and condition (encoding and recognition) and complexity (low and high syntactic complexity) were the within-subjects variables. Only correct responses were analyzed for RT. An a priori alpha level of  $p < .05$  was set for the detection of significant effects. Partial eta squared ( $\eta_p^2$ ) was used as a measure of effect size; this measure reflects the proportion of the effect plus error variance that is attributable to that effect.

**Table 3.** Behavioral data for the verbal memory task reported in terms of percentage accuracy (means and standard deviations) and reaction times (RTs) in milliseconds for correct responses.

Task	Group			
	NL		SLI	
	M	SD	M	SD
Low complexity encoding				
Accuracy	89.06	8.31	71.88	19.51
RT	309.66	88.10	360.90	108.18
High complexity encoding				
Accuracy	77.60	18.22	68.23	12.97
RT	295.40	126.42	405.29	128.49
Low complexity recognition				
Accuracy	87.85	6.11	71.88	13.40
RT	296.10	68.23	334.43	135.84
High complexity recognition				
Accuracy	88.19	8.62	75.69	9.00
RT	310.02	76.86	320.20	121.09

Results of the 2 (group)  $\times$  2 (condition)  $\times$  2 (complexity) ANOVA for accuracy indicated a significant main effect for group,  $F(1, 14) = 10.12, p < .05, \eta_p^2 = .42$ . As expected, the overall performance of the NL group was better than that of the SLI group on this verbal working memory measure (86% accuracy compared to 72% accuracy). The relatively large effect size indicates the robust nature of this effect. No other main or interaction effects were significant for the accuracy data. Because the RT data were not normally distributed, an ANOVA was conducted using the log transformation of these data. The results of this analysis were statistically equivalent to that of an ANOVA using untransformed RT scores. Analysis of the log transformed RT data for correct responses (using the same analysis as for the accuracy data), revealed a significant Group  $\times$  Condition  $\times$  Complexity interaction effect,  $F(1, 14) = 5.71, p < .05, \eta_p^2 = .29$ . Pairwise comparisons indicated that the group with SLI exhibited longer RTs for high encoding items compared to the other group or conditions. There were no other significant main or interaction effects for RT.

A one-way ANOVA revealed that accuracy performance of the groups on the tone (control) task was not significantly different,  $F(1, 14) = 2.31, p = .15$ , though the group with SLI exhibited a somewhat lower mean percentage correct and more variability than the NL group (SLI:  $M = 81, SD = 17$ ; NL:  $M = 90, SD = 6$ ). When data from 1 participant (from the SLI group) who performed at chance level on this task was removed from the analysis, differences in the groups' performance remained nonsignificant,  $F(1, 13) = 1.14, p = .305$  (SLI:  $M = 85, SD = 14$ ; NL:  $M = 90, SD = 6$ ). There was also no significant difference between the two groups with respect to RT on correct items for the tone task,  $F(1, 14) = 0.21, p = .651$  (SLI:  $M = 346.16, SD = 83.85$ ; NL:  $M = 323.99, SD = 106.73$ ).

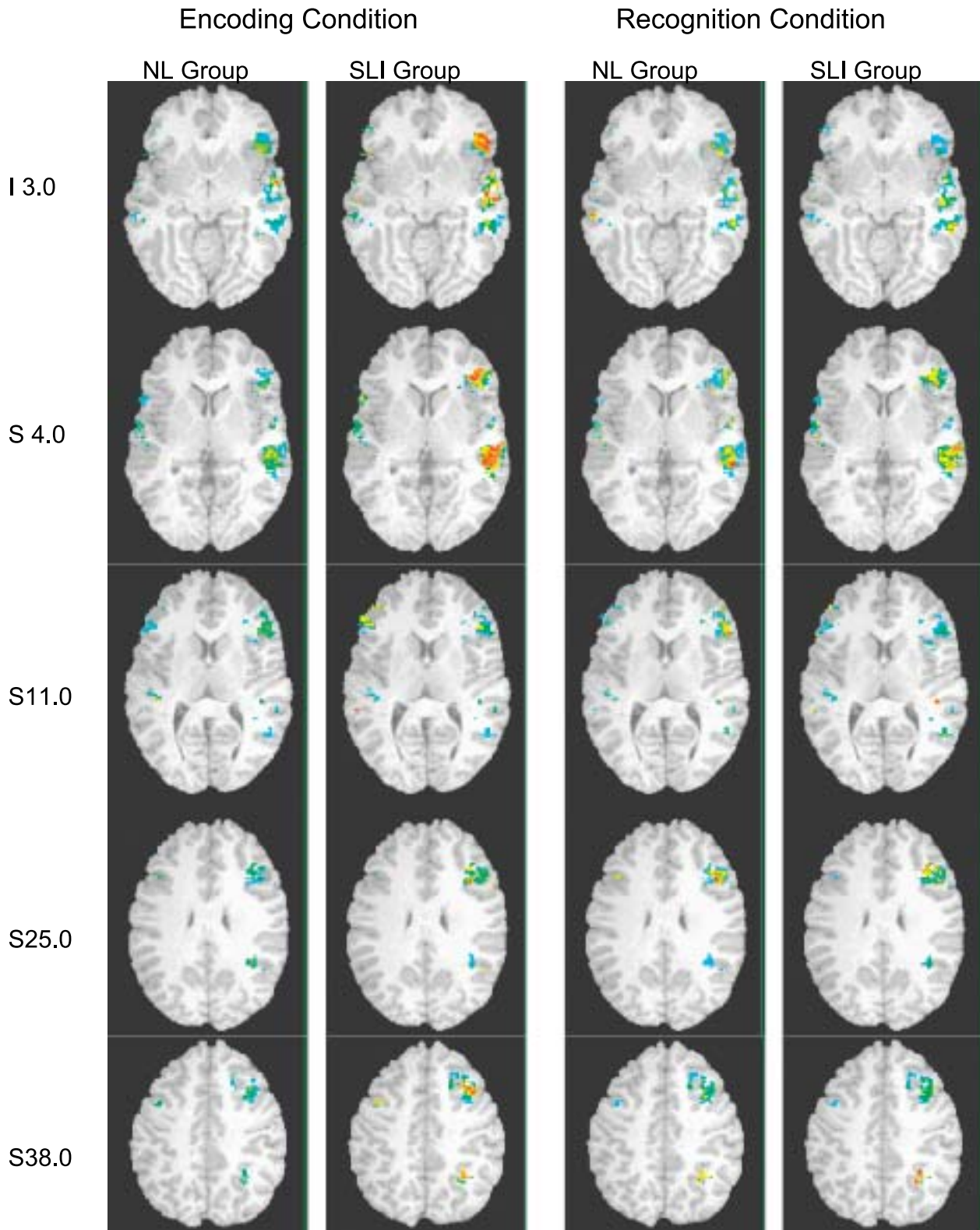
## Preliminary Imaging Analyses

The procedure for identifying ROIs for analysis in this study (described above) assumed that there is no major difference in the location of regions activated by the NL and SLI groups. If it were the case that NL and SLI participants used fundamentally different regions to perform the same tasks, this would have to be accounted for in the statistical analysis. We identified clusters of active voxels as described above for the individual participants within both groups. We then superimposed these participants' activation maps to determine whether there were any regions unique to each group. There were no anatomical regions (defined by gyral boundaries) for which 4 or more members of one group showed activation and at least 2 members of the other group did not. Indeed, the degree of difference between these two groups is consistent with the amount of

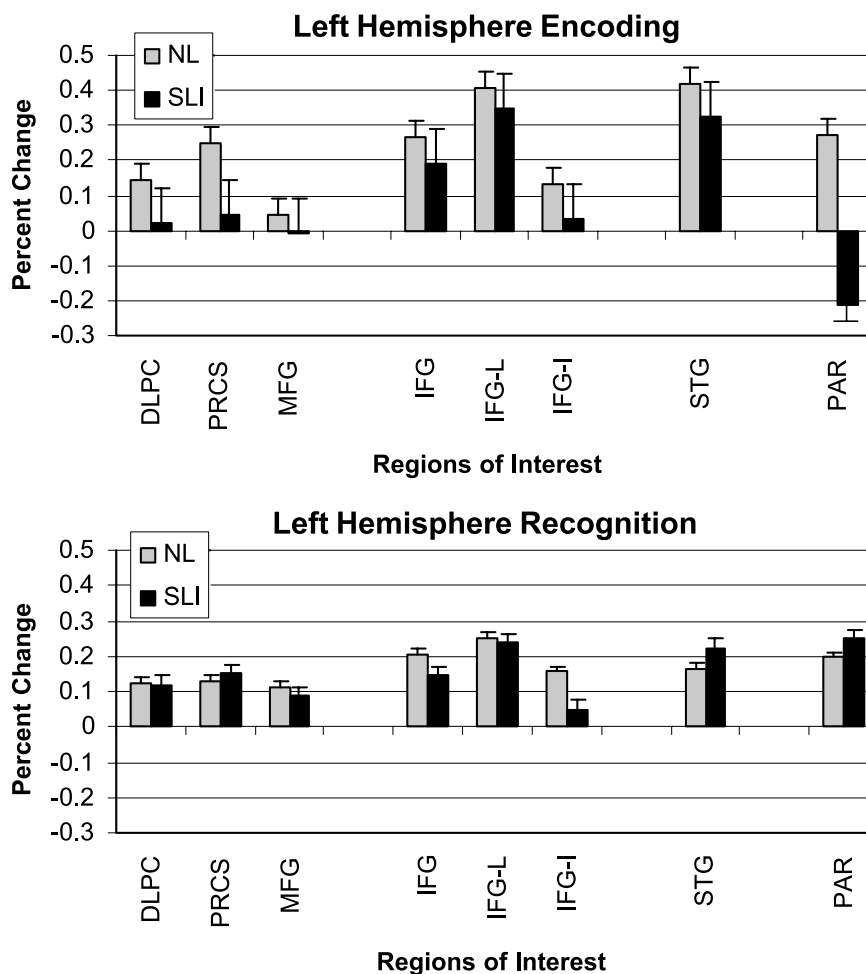
variation that is associated with multiple fMRI scans within individuals (Cohen & DuBois, 1999; Rutten, Ramsey, van Rijen, & van Veelen, 2002). Figure 1 displays the regions that were identified as active for each group. In this figure, the color gradient represents the number of participants within each group for whom activation occurred at a particular site. Therefore, the consistency of regional activation within and between groups can be seen.

The regions of overlap among participants seen in Figure 1 also correspond to the regions of interest selected a priori for analysis. These regions included the IFG (BA 44/45), STG (BA 22), dorsolateral prefrontal cortex including regions centered on the middle frontal gyrus and precentral sulcus (BA 6/8/9/45), and parietal lobe (BA 7/40). As described above, clusters of voxels that reached threshold ( $r > .31$ ) in at least half of all participants defined the functional regions of interests within each of these areas. When clusters of active voxels were close to the margins of anatomical regions that comprised separate systems (e.g., inferior frontal and middle frontal gyri), the boundaries of the underlying anatomy from the individual participants' structural scans guided classification of the activation. Although these broad ROIs reflected the functional systems related to our task demands, inspection of the data suggested functionally independent subregions existed within two of the four broader regions. Previous imaging studies have indicated that the lateral portions of the IFG and a region at the junction of the pars opercularis of the IFG and the anterior insula (hereafter referred to as the insular portion of the IFG) can activate differentially in language tasks (e.g., Buckner, Raichle, & Petersen, 1995; Friederici, Opitz, & von Cramon, 2000; Morro et al., 2001; Roskies, Fiez, Balota, Raichle, & Petersen, 2001). Data from our participants likewise indicated that there were two spatially distinct areas of activation within the IFG. One is on the lateral surface of the gyrus (BA 44/45) and one is within the insular portion of this gyrus (BA44). Similarly, activation within the dorsolateral prefrontal cortex could be subdivided into an area along the precentral sulcus (BA 6) and activation falling within the margins of the middle frontal gyrus (BA8/9/46). Inspection of the patterns of activation across these subregions in the NL group suggested differential contribution to different task conditions (i.e., encoding vs. recognition). This can be seen in Figure 2, which shows the mean percentage change for each of the four ROIs along with the subregions for the dorsolateral prefrontal cortex and the IFG. Given this pattern of differential activation within subregions of the larger ROIs, we targeted both the combined regions (IFG, dorsolateral prefrontal cortex) and their subregions for analysis. In contrast, the anterior and posterior aspects of the STG might activate differentially given that the anterior regions contain primary auditory cortex and the

**Figure 1.** Activation within study regions of interest for the normal language (NL) and specific language impairment (SLI) groups during encoding and recognition conditions. Colors from blue ( $n = 2$ ) to red ( $n = 8$ ) indicate increasing numbers of participants with activation ( $r > .32$ ) at that location. The values represent the specific locations on the inferior (I) to superior (S) axis of Talairach space.



**Figure 2.** Percentage change activation in the left hemisphere for the specified regions of interest for the normal language (NL) and specific language impairment (SLI) groups during encoding (top panel) and recognition (bottom panel). DLPC = dorsolateral prefrontal cortex; PRCS = precentral sulcus; MFG = middle frontal gyrus; IFG = inferior frontal gyrus; IFG-L = lateral portion of the IFG; IFG-I = insular portion of the IFG; STG = superior temporal gyrus; PAR = parietal region.



posterior aspects of this gyrus include Wernicke's area, which is classically associated with speech processing. However, functional imaging data indicate that both anterior and posterior temporal cortex show activation for auditory sentence comprehension (Humphries, Willard, Buchsbaum, & Hickok, 2001). Because the anterior and posterior regions of the STG showed similar patterns of activation in our participants, these regions were combined. In addition to the a priori regions of interest, additional activation was noted for both groups in the regions of posterior cingulate gyrus and precuneus gyrus medially (BA23/31) and dorsomedial (BA9) and ventromedial (BA10) portions of the superior frontal gyrus. All of these regions have been noted in memory studies, but we lacked a particular reason to predict their activation a priori given the specific demands of the task we used.

Because we used percentage change from the participant's baseline intensity as the dependent variable for analysis, we wanted to ensure that this metric was not affected significantly by group differences in the average baseline intensity from which the percentage change was calculated. In this case, the baseline intensity reflects the signal obtained during the control task. We conducted a series of *t* tests on each system, including those of subregions that composed the systems analyzed above. The probability levels associated with these *t* tests were not alpha-corrected for multiple comparisons (in order to err on the side of detecting any possible differences that might exist). There were no significant group differences for any of the systems or subregions in either hemisphere under either encoding or recognition conditions.

## Intensity of Activation

The verbal memory and tone detection components of the task can be expected to produce some differential patterns of activation across the left and right hemispheres (see Zatorre, Evans, & Meyer, 1994). Our data indicated that the left hemisphere ROIs all showed activation to the verbal memory task, whereas right hemisphere ROIs often were associated with activation to the tone task. Therefore, our first analysis of the group differences in BOLD response involved only left hemisphere regions. In a preliminary analysis, a mixed ANOVA with group as the between-subjects variable and condition, complexity, and ROI as within-subjects variables confirmed the lack of a complexity main effect or interaction effects on the percentage change in the BOLD response. In this case, the absence of a physiological effect for complexity in the fMRI data was consistent with the limited effect associated with sentence complexity manipulations in the behavioral data. Consequently, all subsequent analyses were performed by calculating the BOLD response collapsed across high and low complexity stimuli. In the primary analysis, the percentage change in the BOLD signal was analyzed with a mixed ANOVA, with group as the between-subjects variable and condition (encoding vs. recognition) and ROI (dorsolateral prefrontal cortex, IFG, STG, and parietal region) as within-subjects variables. This analysis revealed a significant three-way interaction of Group  $\times$  Condition  $\times$  ROI,  $F(3, 42) = 3.03, p = .040, \eta_p^2 = .18$ . The means and standard errors associated with this effect are displayed in Figure 2. Post hoc testing of group effects within each of the major ROIs (dorsolateral prefrontal cortex, IFG, STG, parietal region) revealed a significant group difference for the parietal region in the encoding condition (Tukey's honestly significant difference,  $p < .05$ ). Additional  $t$ -test analysis of the subregions within the dorsolateral prefrontal cortex and IFG revealed a significant group difference for the precentral sulcus region during encoding,  $t(14) = -1.83, p < .05, \delta = 0.89$ , and the insular portion of the IFG during recognition,  $t(14) = -2.06, p < .05, \delta = 0.89$ . For descriptive purposes, and to guide future research, effect sizes for between-group comparisons for each of the ROIs are reported in Table 4.

Additional significant effects from the ANOVA included the Condition  $\times$  Group interaction,  $F(1, 14) = 5.02, p < .05, \eta_p^2 = .27$ ; the main effect for ROI,  $F(3, 42) = 8.11, p < .05, \eta_p^2 = .37$ ; and the ROI  $\times$  Condition interaction,  $F(3, 42) = 5.80, p < .05, \eta_p^2 = .29$ . The main effects for group,  $F(1, 14) = 0.88, p = 0.36$ , and condition,  $F(1, 14) = 0.00, p = .98$ , and the interaction effects for ROI  $\times$  Group,  $F(3, 42) = 2.24, p = .097$ , were all statistically nonsignificant.

It is possible that the SLI group offset underactivation seen in left hemisphere structures by recruit-

**Table 4.** Effect sizes ( $\delta$ ) for group differences (between adolescents with normal language and adolescents with specific language impairment) in intensity of activation for each region of interest, on the encoding and recognition portions of the task.

Region of interest	Encoding	Recognition
Dorsolateral prefrontal cortex	0.502	0.015
Precentral sulcus	0.894	0.150
Middle frontal gyrus	0.162	0.093
Inferior frontal gyrus (total)	0.256	0.377
Lateral portion	0.115	0.042
Insular portion	0.640	0.889
Superior temporal gyrus	0.220	0.315
Parietal region	1.034	0.166

Note.  $\delta$  indicates differences in units of standard deviation.

ing right hemisphere structures. To examine this possibility, we conducted a follow-up analysis of right hemisphere activation for the ROIs examined above, using a mixed ANOVA with group as the between-subjects variable and condition and ROI as within-subject variables. This analysis revealed a significant Condition  $\times$  ROI effect,  $F(1, 14) = 4.97, p < .05, \eta_p^2 = .26$ , with no other significant effects. The Condition  $\times$  ROI effect was due to significant differences during encoding versus recognition for the right frontal and parietal region ROIs. Both of these ROIs activated to the tone task in the encoding condition but showed a weak activation to the language task during recognition. Note that difference in activation during the recognition task could either reflect minimal right hemisphere engagement for the language task or relatively equal engagement of the right hemisphere for both the language and tone tasks. The design and present results do not allow us to disambiguate these two possibilities.

Given that the regions within the frontal lobe can contribute differentially to task performance, we further analyzed the subregions that made up the dorsolateral prefrontal and inferior frontal ROIs. There was a significant group difference for the area of the lateral portion of the right IFG,  $t(14) = 2.09, p = .028$ . As predicted, the direction of this effect suggested greater recruitment of the right hemisphere for the SLI group than for the NL group. However, this result did not remain significant after alpha correction ( $p = .0125$ ) to account for the multiple comparisons made within the frontal ROIs.

## Timing of Activation

It is possible that brain systems will work less effectively not due to underactivation but due to the fact that areas do not activate in a timely manner, preventing

coordination among systems. We tested this possibility by running *t* tests on each system, including those of subregions that composed the systems analyzed above. The probability levels associated with these *t* tests were not alpha-corrected for multiple comparisons because Type II error was a larger concern than Type I error in this analysis. In the left hemisphere, no significant timing difference was found for any system or subregion within a system. During the encoding task, the BOLD response for the right parietal region had a later onset in the SLI group than in the NL group,  $t(14) = -2.57, p < .05, \delta = 1.25$  (two-tailed test). All other comparisons in the right hemisphere were nonsignificant.

### Exploratory Correlational Analyses

Since the systems we targeted do not work in isolation, we examined the correlations among them (see Figure 3). There are no existing data for individuals with SLI to motivate specific hypotheses related to these comparisons; therefore, this analysis is considered to be exploratory. However, such correlations can provide insight into how these ROIs interacted for the participants of this study. Pearson product-moment correlations were calculated for left hemisphere activation in the designated regions. Correlations in bold above solid arrows in Figure 3 indicate significance at  $p < .05$ . The exploratory nature of this analysis was intended to identify interesting phenomena for later follow-up; therefore, we used a more lenient alpha level (not adjusting for multiple correlations) in order to detect possible differences between the groups. Given the small effects (small differences in amount of activation) and the limited number of partic-

ipants per group, the power to detect existing group differences was small even with an alpha of .05.

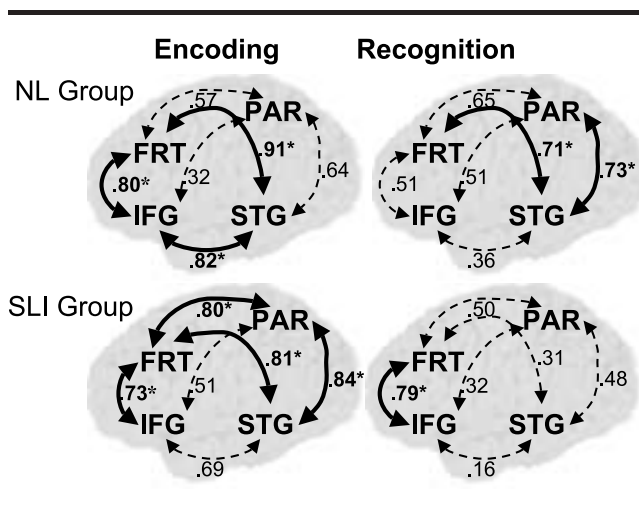
These exploratory findings revealed differential correlational patterns for the SLI and NL groups during both the encoding and recognition phases of the task. During encoding, the group with SLI demonstrated relatively less coactivation between the IFG and the STG than the NL group ( $r = .69$  and  $r = .82$ , respectively). On the other hand, the SLI group showed significant correlations between activation in the parietal (PAR) and frontal (FRT) memory regions and the PAR and STG, which were less strongly associated during encoding for the NL group (PAR:FRT  $r = .80$  compared to  $r = .57$ ; PAR:STG  $r = .84$  compared to  $r = .64$ ). For recognition, the only significant correlation for the SLI group occurred between the IFG and the FRT memory regions ( $r = .79$ ). Compared to the NL group's activation patterns during recognition, the SLI group demonstrated a weak association between the STG and FRT region ( $r = .31$  compared to  $.71$ ) and the STG and PAR region ( $r = .48$  compared to  $.73$ ).

## Discussion

### Behavioral Results

For the behavioral data, the main finding was that the group with SLI was significantly less accurate for both the encoding and recognition phases of this verbal working memory task. Additionally, the adolescents with SLI exhibited slower RTs for correct responses on the high complexity encoding items compared to the controls. Although there was a general tendency for the SLI group to exhibit somewhat longer RTs than the controls, this difference was not statistically significant for three out of the four conditions. Thus, the RT data from this study do not provide overall support for the generalized slowing account of SLI (Kail, 1994; L. Leonard, 1998; Miller, Kail, Leonard, & Tomblin, 2001). It is important to note, however, that the RT results (which only included analysis of correct responses) were likely impacted by the large group differences in accuracy in this study. Prior research has typically focused on RT differences on tasks for which both the SLI and NL groups demonstrated high levels of accuracy (e.g., Miller et al., 2001). The age level of participants in the published studies examining the generalized slowing account of SLI has also been considerably younger than the age of participants in the current study. This factor does not appear to explain these discrepant findings, however, since recent findings by the same investigators suggest that adolescents with SLI continue to exhibit slower RTs than controls on the measures used in that study (personal communication, C. Miller and L. Leonard, presentation at the annual meeting of the Collaboration on

**Figure 3.** Correlation patterns for the normal language (NL) and specific language impairment (SLI) groups during encoding and recognition. FRT = frontal region; IFG = inferior frontal gyrus; STG = superior temporal gyrus; PAR = parietal region. \*Significant at the  $p < .05$  level.



Specific Language Impairment project, October 2003). It is further noteworthy that the experimental design of this fMRI task constrained the range of possible RTs by setting a specific time interval for all responses. When a participant did not respond within the specified response window, that item was recorded as incorrect. Therefore, it was impossible to discern from the behavioral data the extent to which inaccurate responses reflected inefficient or slower rates of responding. However, evidence from the physiologic data (discussed below), also did not suggest substantial timing differences between the groups.

The adolescents with SLI in this study were exhibiting the type of difficulty on this verbal working memory measure that has been reported in other behavioral research; children with SLI have been found to demonstrate poorer word recall than NL controls on listening span measures, even when sentence comprehension was equivalent or statistically controlled (Ellis Weismer et al., 1999; Ellis Weismer & Thordardottir, 2002). For the present study, an analysis of covariance revealed that the SLI group demonstrated significantly poorer word recognition than the NL group when level of sentence comprehension was controlled,  $F(1, 13) = 6.46$ ,  $p < .05$ ,  $\eta_p^2 = .332$ . Thus, the poorer recognition performance of the SLI group was not simply a reflection of their generally lower linguistic abilities. It should be noted that the behavioral findings from the experimental task were consistent with the results from the eighth grade clinical assessments that documented poor verbal working memory abilities for these same participants on two different tasks. That is, the group with SLI scored significantly worse than the controls on a measure of phonological working memory (Nonword Repetition Task; Dollaghan & Campbell, 1998) and on word recall from a listening span measure (Competing Language Processing Task; Gaulin & Campbell, 1994).

The two types of sentences (low and high complexity) were designed to vary cognitive load of the experimental task. However, sentence complexity manipulations resulted in minimal differences in performance on this task, contrary to expectations based on pilot data with these particular stimuli. Both groups performed well above chance level during encoding of low complexity (72%–89% accuracy) and high complexity (68%–77% accuracy) sentences. Accuracy differences in the predicted direction were observed across sentence types, but these did not reach statistical significance. The only significant effect for complexity was the three-way interaction, which revealed that the group with SLI demonstrated slower RTs than the NL group on high complexity encoding. Neuroimaging studies of adult language processing have demonstrated effects of manipulating sentence complexity using stimuli such as conjoined active sentences versus object-relative construc-

tions (Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Keller et al., 2001). Our ongoing research (Ellis Weismer and colleagues) with the larger sample from which these participants were drawn indicates that at eighth grade, the type of complex sentence that most clearly differentiates adolescents with SLI from those without language disorder is the object-cleft construction (based on a complex sentence processing task developed by Naucler, Wulfeck, & Bates, 1998). In designing the task used in the present study, we did not want to make the linguistic demands so difficult for the encoding portion for complex sentences that adolescents with SLI were unable to complete the word recognition (storage) portion. We apparently underestimated the impact of this particular linguistic manipulation involving the addition of a relative clause. Despite the fact that the processing complexity/cognitive load factor did not work as expected, the task allowed us to examine the interplay of brain systems during the verbal working memory task.

## **fMRI Data**

Preliminary analyses of the imaging data revealed that the group with SLI was similar to the control group in several fundamental ways. Adolescents with SLI were comparable to NL adolescents with respect to the areas of activation for this task. It was not the case that the SLI group was activating regions that were not being activated by the NL group or failing to activate areas seen in the NL group. Both groups exhibited patterns that would be expected based on the adult language processing and working memory literature with respect to ROIs activated and left hemisphere bias for verbal stimuli (Gernsbacher & Kaschak, 2003; Jonides, 2000). With regard to timing of activation, there was no indication that the SLI group showed a slower physiologic response relative to the NL group. In fact, the hemodynamic models that best fit the two groups' data were quite comparable. If the adolescents with SLI had been exhibiting substantially slower physiologic response patterns than the controls, different hemodynamic models would have been required to account for the two groups' data.

The percentage change activation analysis revealed no overall laterality differences between the SLI and NL groups. In other words, the SLI group did not disproportionately draw on right hemisphere structures for language processing compared to the NL group, even though one might have predicted this to be the case for several reasons. One might expect to find functional evidence that individuals with SLI are not as well lateralized as individuals with typical language development, given the structural imaging findings of a rightward asymmetry in SLI (Plante et al., 1991). However, Hugdahl et al. (2004) reported findings that are similar

to those of the present study in that individuals with SLI, like controls, exhibited a leftward activation bias (even though bilateral activation was observed) for the language processing tasks in that investigation. Just, Carpenter, Keller, et al. (1996) have reported increases in adults' activation of right hemisphere homologues in regions activated for sentence processing under conditions of increased task difficulty; they attributed this effect to the resource-intensive nature of processing complex sentences. One might assume that the adolescents with SLI in the present study would show increased recruitment of resources in order to complete the task. Although analysis of subregions within the frontal lobe indicated that the SLI group demonstrated more activation in the lateral portion of the right IFG during encoding than controls, this effect did not survive alpha correction.

The group differences in the imaging data that did emerge shed light on the nature of processing in SLI that is not those readily accessible by behavioral methods alone. In behavioral studies, inferences about processing are linked to group differences in participant responses; this necessarily confounds both encoding and response phases of the task. In contrast, imaging studies make visible the contributions of various processes that are not otherwise readily apparent. The results of this study suggest that processing differences during both the encoding and recognition phases of the task lead to group differences in behavioral performance.

During the encoding phase, significant activation differences occurred for both an area centered on the precentral sulcus and in the parietal region. These areas are routinely activated in tasks that target memory. The frontal region in particular modulates with memory load manipulations (e.g., Barch et al., 1997; Braver et al., 1997; Goldberg et al., 1998). Furthermore, activation in the frontal region is not specific to verbal material or to working memory versus long-term memory tasks (Cabeza, Dolcos, Graham, & Nyberg, 2002; Ranganath et al., 2003). Parietal regions typically also show activation during tasks that require memory but appear to modulate with the attentional demands inherent to the tasks (Shaywitz et al., 2001; Sylvester et al., 2003). The group differences in frontal and parietal regions in this study suggest that performance differences on this type of task might be mediated more by these nonlinguistic factors (i.e., memory and attention) that influence overall processing capacity than by strictly linguistic ones.

Differences in the insular portion of the IFG were noted during the recognition phase of the task. This region activates with a variety of language tasks. However, when elements of language are isolated or emphasized by task demands, activation tends to occur in tasks that target semantic processing (Binder et al., 1997),

recognition of semantically encoded words (Buckner, Koutstaal, Schacter, Wagner, & Rosen, 1998), and detection of semantic rather than syntactic anomalies (Kang, Constable, Gore, & Avrutin, 1999). However, it appears that this area is not specific to semantic processing in that activation has also occurred with syntactic judgement of sentences (Ni et al., 2000) even when those sentences were composed of pseudowords (Morro et al., 2001). Thus, it appears that this region may be active with several aspects of language processing but is more likely to appear when semantic processing is emphasized. The fact that the words in the recognition phase of our task had been embedded in a sentence context during encoding is likely to have promoted semantic encoding along with encoding of their lexical forms. During recognition of semantically encoded words, neurologically normal adults increase activation of this region with retrieval effort (Buckner et al., 1998). However, in the SLI group studied here, this region showed a pattern of hypoactivation. This occurred despite the fact that the performance data indicated this task was more difficult for the SLI group than for the NL group. Thus, the SLI group did not appear to "step up" activation when task demands proved difficult.

In addition to regional differences between groups, there was evidence that the SLI group was not coordinating activation between regions during both encoding and recognition phases. Encoding in the NL group was characterized by correlations between the STG, dorsolateral prefrontal regions, and the IFG. This suggests that receptive language processing (the STG) was coordinated with processes involving the IFG that are associated with later successful recall of encoded information (Buckner, Wheeler, & Sheridan, 2001; Casasanto et al., 2002; Clark & Wagner, 2003; Wagner et al., 1998). Activation in each of these areas correlated with that in the dorsolateral prefrontal gyrus, which has been associated with memory processes. However, in the SLI group, the pattern of processing during encoding was characterized by a weaker association between the superior temporal and inferior frontal regions. Thus, part of the encoding network most closely associated with later success in memory recall appears to be less efficient both in terms of strength of activation and coordination among relevant regions. In addition, the SLI group showed stronger than expected correlations for frontal and temporal regions with the parietal region. This is unlikely to reflect compensation given that the parietal region showed less activation in the SLI group than in the NL group during encoding. One might hypothesize that contributions by this hypoactivated area were unlikely to have improved later performance. The pattern of hypoactivation in the parietal region, combined with anomalous correlations with frontal and temporal regions, suggests an overreliance on a less

functional network by the SLI group during the encoding phase of this task. A similar phenomenon has been described for poor readers (compared with good readers) who have an overreliance on the dorsal reading circuit rather than the ventral reading circuit (Pugh et al., 2000).

Differences in the coordination of activation during the recognition phase were also noted. In the NL group, activation in the STG, frontal, and parietal ROIs showed a pattern of intercorrelation. This suggests coordination between regions important for language processing with regions that modulate attention to the word stimuli and memory performance. However, the SLI group showed less correlation among these structures and greater correlation among dorsolateral prefrontal and inferior frontal regions. Again, this pattern included a region that showed significantly less activation by the SLI group. This pattern indicates an overdependence on a relatively underactive region, instead of on regions that were more similar in their level of activation to that seen in the NL group. Given that these patterns of activation were also associated with poorer performance by the SLI group, it can be concluded that these patterns did not reflect successful compensation. If this were the case, one might expect similar behavioral performance despite different patterns of activation (see Plante et al., 2000).

The findings from the present investigation can be compared to the results from the Hugdahl et al. (2004) study of language processing in SLI; however, conclusions must be tempered in the light of the differences between the studies with respect to task, design, and age range of participants. Similar to the present results, Hugdahl and colleagues reported that both the SLI and control group demonstrated a leftward bias in activation during language processing. The experimental and control groups in both studies generally activated ROIs similar to each other; however, Hugdahl et al. reported that the controls in their study produced a small area of activation in the right inferior frontal lobe, thought to reflect working memory and attention effects, that was not observed for the group with SLI. In both studies, participants with SLI displayed hypoactivation compared with controls, despite differences in task difficulty/performance levels. In the Hugdahl et al. study, all participants performed at ceiling during a separate condition (conducted after the passive listening task) in which behavioral responses were collected to determine if they could correctly detect the auditory stimuli, but these investigators noted that the underactivation exhibited by the SLI group would be expected to correspond with poorer response patterns on a more cognitively demanding task.

Differences in the particular ROIs in which hypoactivation was found for the individuals with SLI are

likely due to the differing nature of the tasks within the present study and the study by Hugdahl et al. (2004). Hugdahl and colleagues concluded that individuals with SLI primarily demonstrated reduced activation in brain areas critical for speech processing and phonological awareness (MTG/STS) based on their examination of activation patterns in the temporal and frontal lobes during passive listening to vowels, pseudowords, and real words. Although the SLI group in the present study tended to exhibit reduced activation in the temporal lobe region during encoding, significant group differences were found only in the parietal and frontal lobes for this verbal working memory task in which participants were asked to process sentences and retain target words within those sentences.

In summary, the poor performance on this verbal working memory measure by adolescents with SLI was associated with both similarities and differences in neural functioning compared to typically developing adolescents. The fMRI data revealed that the two groups activated similar brain regions in response to the experimental task within the ROIs that were examined, showed comparable timing of activation (as indexed by the latency of the optimal hemodynamic models), and did not display significant differences in laterality. However, the group with SLI displayed hypoactivation of the left PAR and the precentral sulcus (PCS) during encoding, as well as hypoactivation of the insular portion of the IFG during recognition. Findings from the correlational analyses suggest that adolescents with SLI exhibit atypical coordination of activation across brain regions during encoding and recognition. Thus, differences were observed in regions associated with attentional control mechanisms (PAR) and memory processes (PCS), as well as language processing and retention of verbal information (IFG).

## **Limitations and Future Directions**

This study provides an initial neuroimaging investigation of processing capacity limitations in SLI. One obvious limitation of the current study is the relatively small sample size, which may have resulted in a lack of significant group differences where they actually existed. Studies with larger samples are needed to confirm the present findings and further characterize language processing and recall in SLI. Also, a wider developmental range should be examined, starting with younger children with language impairment, in order to gain a broader understanding of the neural circuitry underlying language functioning in this population. This study included participants who exhibited a wide range of attentional skills. Further studies are needed to tease apart the role of attention deficits in verbal

working memory for children with and without language impairment. In the current study, we used an adapted listening span task that could be compared to prior behavioral results for children with SLI; performance on this task was compared to that for a tone task using a block design. Future fMRI investigations might use tasks (such as the n-back task) that have been well established with adults and utilize event related designs to more precisely detail the nature of verbal working memory processes associated with both successful and unsuccessful item performance. In the light of the present results, additional research utilizing measures like those used by Shaywitz et al. (2001) is also warranted to specifically examine attentional mechanisms during language processing by individuals with SLI.

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