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Information Processing by School-Age Children With Specific Language Impairment: Evidence From a Modality Effect Paradigm

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School-age children with specific language impairment (SLI) and age-matched controls were tested for immediate recall of digits presented visually, auditorily, or audiovisually. Recall tasks compared speaking and pointing response modalities. Each participant was tested at a level that was consistent with her or his auditory short-term memory span. Traditional effects of primacy, recency, and modality (an auditory recall advantage) were obtained for both groups. The groups performed similarly when audiovisual stimuli were paired with a spoken response, but children with SLI had smaller recency effects together with an unusually poor recall when visually presented items were paired with a pointing response. Such results cannot be explained on the basis of an auditory or speech deficit per se, and suggest that children with SLI have difficulty either retaining or using phonological codes, or both, during tasks that require multiple mental operations. Capacity limitations, involving the rapid decay of phonological representations and/or performance limitations related to the use of less demanding and less effective coding and retrieval strategies, could have contributed to the working memory deficiencies in the children with SLI.

KEY WORDS: specific language impairment, memory, phonological coding, capacity limitations, retrieval strategies

Despite years of research, there is little general agreement about the most critical mechanisms underlying SLI. This state of affairs is illustrated in Table 1, which summarizes no less than eight current hypotheses about the nature of SLI. These hypotheses are not mutually exclusive, but they are discussed separately in the language disorders literature. Some hypotheses of SLI primarily concern linguistic aspects of development (Hypothesis 1), and some primarily concern conceptual aspects of development (Hypotheses 2 and 3). Recently, there has been renewed interested in information processing theories of SLI (Hypotheses 4 through 8).

One problem with the evidence that often has been used to pursue hypotheses about SLI is that it is nearly always confirmatory in nature. If an investigator sets out to obtain evidence consistent with his or her favorite hypothesis, chances are such evidence can be found. In contrast to this approach, what we hope to do in the present study is to take a disconfirmatory stance. The data from our study of modality-specific memory mechanisms will not constitute sufficient evidence for conclusively

Table 1. Current hypotheses about the nature of specific language impairment.

Adapted from the Extensive Review by Bishop (1992):

1. *Impairment of specialized linguistic mechanisms.* Innate mechanisms specific to linguistic (presumably grammatical) processing are impaired.
2. *Impaired conceptual development.* A general deficit in conceptual processing affects language as well as other types of processing.
3. *Impaired development of learning strategies.* The strategies ordinarily applied to learning, such as hypothesis-testing, are impaired.
4. *Speech output impairment.* Children with SLI have difficulty converting knowledge into a spoken response.
5. *Auditory perception impairment.* Children with SLI have a generalized (nonspecific) underlying problem perceiving speech.
6. *Impairment in the speed or capacity of information processing.* The processing of linguistic and non-linguistic information is abnormally slow, inefficient, or limited in capacity.

Adapted from Gathercole & Baddeley (1990):

7. *Impaired phonological representation.* The representation of phonological information in short-term memory is impaired.

Adapted from Tallal (1990):

8. *Impaired temporal processing.* The ability to represent the temporal order of linguistic or nonlinguistic events, especially rapid ones, is impaired.

proving one hypothesis. However, we will be able to assess the fundamental and independent contributions of some information processing hypotheses, at least as they pertain to our task situation.

Our evidence comes from an experiment that is relatively simple, involving immediate serial recall of digits presented auditorily, visually, or audiovisually. The relevance of this type of task to language impairment is that it incorporates some of the important cognitive processes that are needed for language development and use, including speech encoding, covert verbal rehearsal, response planning, and motoric execution. Gathercole and Baddeley (1989, 1990b) demonstrated that performance on at least some verbal short-term memory tasks is indicative of children's ability to learn new vocabulary and to read, suggesting that memory tasks tap important language skills. Working memory enables children to attend to verbal messages, construct mental representations of the utterances they hear, recall what they themselves usually say in the same context, detect differences between their use of language and the adult's usage, realize that the difference is important, and then store this realization in a way that enables retrieval (Gillam, 1997).

Storage, retrieval, and output are enhanced when information is coded phonologically (Baddeley, 1986; Cowan, 1995). There can be little doubt that auditory presentation, in normal individuals, leads more reliably to the creation of a vivid, mnemonically useful phonological code than does visual presentation, especially when the visual presentation involves pictures or numerals rather than printed words (Baddeley, 1986; Gathercole & Baddeley, 1990a). One type of support for this statement comes from research with an *articulatory suppression* method in which a word is repeated over and over in order to interfere with the ability to form a phonological representation and use it for covert rehearsal. Baddeley, Lewis, and Vallar (1984) found that articulatory suppression interferes with the use of a phonological code (as indicated by phonological similarity and word length effects) more pervasively with visual stimuli than with auditory stimuli.

A mental phonological code may not be formed automatically for visual stimuli, and task demands could influence the likelihood that such a code is formed. In particular, a verbal response modality, unlike some nonverbal response types, requires the formation of a phonological code for the appropriate response to be made. Speaking may force this kind of coding more often, even when formation of the code is effortful. Thus, if the difficulty of short-term memory in children with SLI is in the formation and use of a phonological code, pairing a visual stimulus with a spoken response may remove some of the disadvantage of using the visual modality. The disadvantage would be most extreme when a visual stimulus is paired with a nonverbal response, because that would not force phonological coding, allowing a visual representation to be used even though that type of representation is difficult to rehearse. Notice that this prediction, based on a phonological coding deficit (i.e., that the worst memory deficit in SLI children should occur for a visual stimulus paired with a nonverbal response), is the opposite of what one would predict if short-term memory problems result from modality-specific deficits (i.e., that the worst memory deficit in SLI children should occur for an auditory stimulus paired with a spoken response).

A prior study (Gillam, Cowan, & Day, 1995) illustrates that the distinction between auditory-speech and phonological coding deficit hypotheses remains unresolved. Gillam et al. investigated short-term memory in children with SLI using a suffix effect procedure. In that procedure, a spoken list to be recalled was followed by a final nonword (suffix) item that was not to be recalled. Even though participants were told to expect the item and to ignore it, the suffix had a detrimental effect on recency recall (i.e., recall of the last few items in a list). This outcome is typically referred to as the suffix effect (Crowder & Morton, 1969). Gillam et al. (1995) found that the suffix effect was larger for children with SLI than for normal children. Furthermore, the group difference occurred for scoring criteria that credited only items recalled in the correct serial position, but not for scoring criteria that did not require strictly correct serial position information, even though the latter still yielded large suffix effects. These results support the idea that children with SLI have a problem with serial order recall of spoken items. The fundamental problem could be in auditory memory storage, spoken response production, or in internal representation processes that intervene between memory encoding and response production, any of which would affect the ability to reproduce the correct serial order of items.

In this study, we manipulated input modality, response modality, and rate of stimulus presentation within a serial recall task. Children with SLI and their age-matched peers were tested at a level that was based on each child's working memory capacity, as determined with an auditory digit span task. The various questions that can be addressed by different aspects of the experiment are as follows.

1. *Are operations underlying speech production fundamentally responsible for working memory deficiencies in children with SLI?*

Children with SLI have difficulty repeating single nonwords (Gathercole & Baddeley, 1990a; Edwards & Lahey, in press; Kamhi, Catts, Mauer, Apel, & Gentry, 1988; Montgomery, 1995). These children also present more articulatory errors and slower times on diadochokinetic tasks (Stark & Tallal, 1988). If difficulties with speech output processes persist into preadolescence and play a fundamental and independent role in working memory performance (Table 1, Hypothesis 4), then children in the SLI group should evidence more difficulty with spoken responses than with nonverbal (pointing) responses regardless of whether information is presented auditorily, visually, or audiovisually.

A basic assumption of information processing is that individuals encode information, make decisions about appropriate responses, plan, and then execute those responses motorically. Encoding, planning, and speech output processes may be relatively independent of one another (Sanders, 1990; Sternberg, 1969, 1975). If so, effects on speech output processes should be independent of effects on input processes. On the other hand, there may be parallel or recursive interactions between encoding, planning, and speech output throughout information processing activities (Cowan, 1995). If this turns out to be the case, the factors that influence speaking processes should also influence encoding and planning processes. By manipulating two forms of output (speech and pointing), two forms of input (audition and vision), and rate of input, our procedures enable us to determine whether speech output processes are fundamental to working memory deficiencies in children with SLI and whether aspects of speech output operate separately from aspects of input processing.

2. *Are difficulties in processing and retaining the acoustic information contained in auditory signals fundamentally responsible for working memory deficiencies in children with SLI?*

With respect to Hypothesis 5 in Table 1, some evidence suggests that children with SLI have difficulties perceiving and/or discriminating speech, especially consonants (Tallal & Piercy, 1974, 1975; Stark & Tallal, 1988). Leonard (1989, 1995) notes that children with SLI often have difficulties with grammatical morphemes with surface characteristics that are difficult to process in rapid, ongoing speech (such as short word-final nonsyllabic consonants in internal positions in clauses). It is possible that some of the difficulties with grammatical morphology evidenced by young children with SLI could be attributed to limitations in auditory processing abilities.

The auditory modality is generally superior to the visual modality in short-term recall. For example, there is typically an advantage for recalling items at the end of a list when those items are presented auditorily as compared to visually (for reviews see Penney, 1975, 1989). If deficits in processing auditory information are fundamentally and independently responsible for working memory difficulties in children with SLI, these children should evidence a smaller modality effect than age-matched, nonimpaired children regardless of response mode.

3. *Are phonological coding deficits, characterized by difficulties converting nonlinguistic information into verbal forms, fundamentally responsible for working memory deficiencies in children with SLI?*

In recalling auditory information, individuals convert acoustic information into a phonological form (a process known as phonological coding) which is used for rehearsal and for subsequent storage into long-term memory. Gathercole and Baddeley (1993) and others (Edwards & Lahey, in press; Gillam et al., 1995; Montgomery, 1995) have proposed that difficulties with phonological coding processes may underlie SLI (Table 1, Hypothesis 7).

A fundamental problem in phonological representation could affect our results in several different ways. First, phonological coding comes more automatically for speech input, and would be more of a potential problem for visual input, which yields a phonological code only with additional active processing (Salamé & Baddeley, 1982). This is one reason why recall of auditorily-presented stimuli usually exceeds recall of visually-presented stimuli (Penney, 1975). It could be that by middle childhood, the phonological encoding of printed stimuli has been practiced to the point where it is performed automatically, even for children with SLI. However, a phonological coding difficulty in these children could be observed in another way. It could cause them to recall less when a pointing response is required than when a speaking response is required, just the opposite of the prediction from Question 1 above.

Considerable work shows that stimuli in short-term recall tasks must be recoded into a phonological form in order to allow verbal rehearsal (Baddeley, 1986). It is for this reason that, for example, the confusion between printed letters to be recalled is based on phonological rather than visual similarities (Conrad, 1964). Children are able to carry out this type of recoding fairly consistently by the age of 8 years, which is younger than the children in this study. For successful recall, when a speaking response is required, subjects recode the representation into a phonological form, rehearse it, and then use it to execute the spoken response. However, an extra phonological recoding step is needed when a pointing response is required. In this case, the phonological representation used in rehearsal must be transformed back into a visually-based representation in order for the pointing response to be completed.

In our study, a nonverbal pointing response to a verbal list inevitably required additional recoding of information from the stimulus list to the response format. This recoding was not required with a verbal response. Children whose short-term memory representation of speech is faulty (Table 1, Hypothesis 7) would be expected to have more difficulty performing the added recoding during the conversion of information to a nonverbal response format, or they would be expected to rely on visual information codes that cannot easily be rehearsed. This would produce poorer recall in the pointing condition than in the speaking conditions for these children. Phonological coding difficulties would be especially problematic when visual stimuli were paired with pointing responses because not one, but two difficult recodings are needed (print to speech and back to print again) if verbal rehearsal is to be used.

4. *Is a deficit in the ability to process information rapidly in time fundamentally responsible for working memory deficiencies in children with SLI?*

Evidence by Stark and Tallal (1988) suggests that children with SLI display deficits in processing visual and spoken information that is presented rapidly (Table 1, Hypothesis 8). Tallal (1990) has argued further that these children's temporal processing deficits are generalized across auditory and visual modalities. If rapid processing difficulties are persistent and pervasive in school-age children with SLI, they should present the typical modality effect for information presented slowly, but there should be specific deficiencies in performance for visual and auditory items that are presented rapidly. However, if a rapid processing deficit co-occurs with other deficits, the children in the SLI group should present an abnormal modality effect for information presented at slow and fast rates.

Another finding could also implicate temporal processing problems. Ordinarily, recall is better for the last few items in a list than for preceding items in the list, the well-known *recency effect*. This is the case even if the recall period is delayed by up to 20 seconds, provided that the items are separated by similar periods and all of the separation periods are filled with a distracting task (Bjork & Whitten, 1974). These results have led to an interpretation of the recency effect in which it is said to result from a mental representation of the temporal order of items (e.g., Lee & Estes, 1981). The account assumes that participants must discriminate between items well enough to select the one to be recalled next at each juncture in recall. Within such a temporal representation, the most recent items are the most temporally distinct because they are closer in temporal context to the time of recall.

There also is an auditory modality superiority in recall (Penney, 1975, 1989) that holds even when the items are separated by distracting tasks (Gardiner & Gregg, 1979; Glenberg, 1984). Glenberg and Swanson (1986) accounted for this pattern by assuming that the temporal representation of each item is more precise for auditory stimuli than for visual stimuli. If children with SLI have temporal representation deficits, it might be described from a similar theoretical perspective. Children with SLI should have less precise representations of the final items in a list than nonimpaired controls, a condition that would diminish the magnitude of the recency effect in children with SLI.

A relatively simple experiment was designed to address the input modality, input speed, and response modality issues inherent in the preceding questions. Children with and without SLI were asked to recall lists of digits that were presented auditorily, visually, or audiovisually at slow and fast rates. Children demonstrated their recall by saying the digits aloud or by pointing to them on a touch sensitive screen.

Method

Participants

Thirty-two children participated in this study. The experimental group contained 16 children (12 boys and 4 girls) with specific language impairment (SLI group; *M* age = 9;9, range = 8;1 to 11;11). Children in the SLI group had been diagnosed as language impaired by public school assessment teams that included, at minimum, a speech-language pathologist, a psychological examiner, and a classroom teacher. Recruitment letters were sent to parents by clinicians who worked in public-school and private-practice settings. The first 16 children whose parents responded to the recruitment letter and who met the minimum subject selection requirements (described below) were included in the SLI group. All children in this group were monolingual English speakers.

School district restrictions on the amount of time that subjects were available for testing limited the ability to perform a complete psychoeducational and language assessment in conjunction with the experimental tasks. A review of records of formal testing completed within the previous two years by psychologists and speech-language pathologists indicated that all children in the SLI group had IQ scores above 85 on the Test of Nonverbal Intelligence (Brown, Sherbenou, & Johnsen, 1982), or the performance section of the Wechsler Intelligence Scales for Children–Revised (Wechsler, 1974) together with significant deficiencies (≤1 SD below the mean) on two or more tests of language production and comprehension. None of these children had known histories of hearing loss, environmental deprivation, behavioral-emotional disorder, or gross neurological impairment. In every case, school assessment teams had concluded that the child's language impairments placed him or her at significant social and academic risk. All of the children in the SLI group were receiving language services from speech-language pathologists at the time of this investigation. Eleven of the 16 children had been identified as Learning Disabled with deficits in spoken language, listening, and reading. These children received assistance with school assignments in *content mastery* classrooms. None of the children presented academic difficulties in the area of mathematics. Independent testing at the time of this investigation indicated that all children in the SLI group scored one or more standard deviations below the mean on the verbal cluster of the Detroit Tests of Learning Aptitude–2 (DTLA-2) (Hammill, 1986). Narratives produced by children with SLI on story generation and story retelling tasks contained frequent mazes, few grammatically acceptable complex sentences, omissions of word inflections, coherence limitations, and/or a limited variety of cohesion devices.

The age-matched control (CTL) group consisted of 16 children (12 boys and 4 girls; *M* age = 9;8, range = 8;0 to 11;8). These children were recruited from after-school child care programs in schools that the children in the SLI group attended. Participants in the CTL group were monolingual English speakers, each of the same gender and age (±3 months) as a member of the SLI group, and they had no previous history of speech, language, hearing, or learning disorders. The age-matched controls were superior to children with SLI on measures of digit span, sentence imitation from the DTLA-2, and number of semantic propositions recalled from an auditorily presented story, as shown in Table 2.

Table 2. Comparisons between children in the SLI and CTL groups.

	Group				
	SLI		Control		
Measure	*M*	*SD*	*M*	*SD*	*p*
Chronological Age	9;9	1;2	9;8	1;2	n.s.
Digit Span	4.38	.5	5.56	.96	<.001
Sentence Imitation	7.93	2.77	16.38	4.94	<.001
Story Recall	17.06	6.98	28.38	5.23	<.001

Note. Chronological Age (years;months); Digit Span = highest number of auditorily presented digits recalled without an error; Sentence Imitation = raw score on the sentence imitation subtest of the Detroit Tests of Learning Aptitude–2 (Hammill, 1985); Story Recall = raw score on a story retelling task (Gillam & Patterson, 1992).

Procedures

Span-length lists of digits were constructed by sampling without replacement from the digits 1 through 9. Twenty lists (10 requiring a speaking response and 10 requiring a pointing response) were presented in each of the three modes (auditory, visual, audiovisual) for a total of 60 lists. One-half of the lists in each condition were presented in random order at a slow rate (1/s), and the other half were presented in random order at a fast rate (3/s).

To control for capacity differences between the children in the two groups, all trials were delivered at each participant's auditory digit span length. Short-term memory span was determined in a pretest with digits presented at an intermediate rate of two items per second. During the pretest, two lists were spoken at each length beginning with two digits. Span was determined to be the longest length at which the digits were repeated in correct order. Presenting all tasks at auditory digit span set the task at each participant's short-term memory capacity, and resulted in the desired level of below-ceiling-level performance across item types.

In order to present the trials in a generally increasing order of task complexity, digit recall was measured first with auditory stimuli, then with visual stimuli, and finally with audiovisual stimuli. The participants were assigned to one of two trial orders with the constraint that the two orders were evenly divided within each group. In one order, the first 10 trials within each stimulus modality required a speaking response and the second 10 trials required a pointing response. In the second order, the response modality orders were reversed. Short instructions and two sample items preceded each block. Thus, participants knew what the stimulus and response requirements for each set of 10 trials would be.

Participants were tested in a sound-attenuated laboratory at the University of Texas–Austin. They wore stereo headphones and viewed a 14-in Apple Color High Resolution RGB monitor fitted with a Microtouch touch-sensitive screen. In the auditory condition, digits spoken in a male voice were digitized, placed in a standard 500-ms window of time using an acoustic waveform editor, stored in a sound resource file, and presented binaurally through high-quality headphones. In the visual condition, digits appeared on the computer screen in a 2 × 1.5 in, white rectangle set in a light-gray background. Digits were centered in the rectangle in black, 130 point Geneva font. In the audiovisual condition, digits appeared on the computer screen in synchrony with the auditory presentation. A tone in the auditory condition and a question mark in the visual condition signaled the end of each list. The tone and question mark were paired in the audiovisual condition.

In conditions in which a speaking response was required, the examiner wrote down the responses as they were spoken. In conditions in which a pointing response was required, three rows of three rectangles containing the digits 1 through 9 appeared on the touch-sensitive screen immediately after presentation of the stimuli to be recalled. The response digits appeared in the same font, within rectangles of the same size and color as the visual stimulus digits. Participants were instructed to touch the digit boxes on the screen in the same order as they appeared in the presentation, and they successfully completed a training exercise prior to testing. The computer was programmed to store the pointing responses.

Analysis

Twelve of the 16 children in the SLI group and one of the children in the CTL group had memory spans of 4 items (whereas all others had higher spans). Responses were analyzed at the first two primacy positions (1 and 2) and the last two recency positions ($N - 1$ and N) of the serial position curve in order to avoid overlap in primacy and recency scoring for any of the participants. Primacy scoring compared the first two digits of each response to the first two digits of the stimulus. Recency scoring compared the last two digits of each response to the last two digits of the stimulus list. The scoring system rewarded recall of digits in their exact serial position.

The scoring protocols from four randomly selected students in each group (25% of each sample) were independently rescored by a graduate student in communication sciences and disorders who was blind to group membership. Point-by-point reliability calculations yielded 99% agreement between the original and rescored protocols.

Results

Correct responses (expressed as percent correct) at the primacy and recency portions of the response curve were analyzed separately with five-way, mixed analyses of variance. The between-subjects variable was Group (SLI, CTL). The within-subjects variables were Serial Position (primacy positions 1, 2 or recency positions $N - 1, N$), Input Modality (auditory, visual, audiovisual), Response Type (speaking, pointing), and Presentation Rate (fast, slow). Reported probability levels reflect Greenhouse-Geisser adjustments for potential variations from sphericity assumptions. Cohen's (1988) standardized effect size (d equals the difference between means divided by the root mean square of their respective standard deviations) is reported for all post hoc comparisons. According to Cohen, a d of .2 is considered to be small; a d of .5 is of medium size; and a d of .8 is large.

Primacy Positions

Primacy position responses yielded significant main effects for Serial Position [$F(1, 30) = 102.43$, $p < .0001$], Response Type [$F(1, 30) = 4.35$, $p < .05$], and Rate [$F(1, 30) = 15.14$, $p < .001$]. Consistent with typical primacy effects, items in the first position (M = 85.42%) were recalled more accurately than items in the second position (M = 64.84%; d = .80). Spoken responses (M = 77.5%) were generally more accurate than pointing responses (M = 72.76%; d = .17), and items that were presented at a fast rate (M = 78.59%) were recalled more accurately than those presented at a slow rate (M = 71.66%; d =.25).

A significant Input Modality × Response Type interaction [$F(2, 60) = 3.85$, $p < .05$] qualified the main effect for Response Type (Table 3). Speaking performance was significantly better than pointing performance when visual input was provided (Tukey, $p < .05$; d = .36), but not when auditory or audiovisual input was provided (d = .01 and .16 respectively). This finding supports our earlier suggestion that phonological codes, which have been shown to facilitate recall, are not required when visual stimuli are paired with a pointing response.

Table 3. Mean percent correct responding across groups for response type as a function of input modality for primacy and recency positions.

Response type	Presentation modality		
	Auditory	Visual	Audiovisual
	Primacy Positions		
Pointing	77.50 (26.79)	67.03 (32.00)	73.75 (29.88)
Speaking	77.18 (27.01)	77.03 (23.82)	78.28 (24.97)
	Recency Positions		
Pointing	72.81 (27.34)	53.12 (31.79)	70.54 (30.36)
Speaking	77.81 (27.17)	67.96 (27.98)	74.84 (26.11)

Note. SD in parentheses

The four research questions related specifically to differences between the SLI and CTL groups and differences within the SLI group. Table 4 presents within group means and standard deviations for all possible combinations of input and output modalities at the primacy positions of the response curve. A significant Input Modality × Response Type × Group interaction [$F(2, 60) = 5.78$, $p < .01$] indicated that the CTL group performed significantly better than the SLI group when pointing responses were paired with either visual or audiovisual stimuli (Tukey $p < .05$; $d = .61$ and .58 respectively). This advantage did not hold for auditory stimuli or for spoken responses (d ranged between .17 and .34; Power = .71).

Within the SLI group, the accuracy of speaking responses significantly exceeded the accuracy of pointing responses when visual or audiovisual stimuli were presented (Tukey $p < .05$; $d = .51$ and .50), but not when auditory stimuli were presented ($d = .09$). Also, their pointing responses for auditory stimuli were better than their pointing responses for visual stimuli (Tukey $p < .05$; $d = .55$). None of the differences between speaking and pointing responses reached significance for children in the CTL group within or across any of the three input modalities (d range = .08–.22). Only the SLI group presented decreases in performance under conditions in which pointing responses were paired with visual stimuli. These findings and the magnitude of their effect sizes firmly support the idea that children with SLI have particular difficulties with mentally recoding visual stimuli into a form that is most suitable for short-term recall.

Finally, there were subtle group differences that related to position, type of input, and presentation rate [Position × Input Type × Rate × Group, $F(2, 60) = 4.57$, $p < .05$]. For visually presented items, the CTL group performed significantly better (Tukey p's < .05) than the SLI group at the first (CTL M = 84.38%, SLI M = 73.75%; $d = .46$) and second serial position (CTL M = 65.63%, SLI M = 52.5%; $d = .49$) when items were presented at a slow rate, and at the first serial position (CTL M = 90.63%, SLI M = 75.63%; $d = .66$) when items were presented at a fast rate. There was only one significant group difference that obtained for auditorily presented items. At the first serial position, the SLI group performed worse on items that had been presented at a fast rate (CTL M = 95.0%, SLI M = 83.13%; Tukey $p < .05$; $d = .68$). There were no significant group differences for items presented audiovisually (Power = .65). Again, this pattern of results and their moderate effect sizes indicate that children in the SLI group primarily experienced difficulty recoding and rehearsing visual items.

Table 4. Within-group mean percent correct responding in the primacy positions for all combinations of input and output modality.

Input and output modalities	SLI group	CTL group
Auditory input		
Pointing response	75.00 (28.73)	80.00 (24.68)
Speaking response	72.18 (29.08)	82.18 (23.93)
Visual input		
Pointing response	58.75 (34.34)	75.31 (27.31)
Speaking response	73.75 (26.15)	80.31 (20.92)
Audiovisual input		
Pointing response	65.93 (31.60)	81.56 (26.01)
Speaking response	80.62 (25.19)	75.93 (24.73)

Note. SD in parentheses

Recency Positions

Analysis of percent of correct responses at the two recency positions ($N - 1$, N) yielded significant main effects for Group [$F(1, 30) = 4.30$, $p < .05$], Serial Position [$F(1, 30) = 83.05$, $p < .0001$], Input Modality [$F(2, 60) = 19.23$, $p < .001$], Response Type [$F(1, 30) = 17.52$, $p < .001$], and Rate [$F(1, 30) = 6.49$, $p < .05$].

Across input and response conditions, the CTL group (M = 75.57%) responded more accurately than the SLI group (M = 63.46%; $d = .42$). As would be expected for recency positions, participants recalled final position (N) items (M = 79.66%) with greater accuracy than $N - 1$ items (M = 59.37%; $d = .73$). This finding is traditionally referred to as the recency effect. Across groups, participants responded to auditory stimuli (M = 75.31%) and audiovisual stimuli (M = 72.69%) with greater accuracy than they responded to visual stimuli (M = 60.54%) (Tukey p's < .05; $d = .51$ and .41 respectively), the traditional modality effect. Spoken responses (M = 73.54%) were generally more accurate than pointing responses (M = 65.49%; $d = .27$), and items that were presented at a fast rate (M = 71.51%) were generally recalled better than those presented at a slow rate (M = 67.52%; $d = .13$).

Similar to the primacy results, there was a significant Input Type × Response Type interaction [$F(2, 60) = 3.19$, $p < .05$]. Tukey post hoc analyses revealed a significant pointing disadvantage when stimuli were presented visually ($d = .52$) as opposed to auditorily ($d = .17$) or audiovisually ($d = .15$) (see Table 3). Furthermore, the effect size of speaking versus pointing for visual items was larger for the recency positions (.52) than the analogous difference at the primacy positions ($d = .36$).

In addition to the significant group main effect favoring the CTL group, there were two significant interactions involving group differences. A significant Position ×

Group interaction [$F(2, 60) = 6.44$, $p < .05$] indicated that children in the CTL group recalled a significantly higher percentage of final position items ($M = 88.54\%$) than children in the SLI group ($M = 70.78$; Tukey $p < .05$; $d = .75$). This finding indicates that there was a reduced recency effect for the children with SLI in comparison to their age-matched controls. Comparison of within group recency effect sizes adds more support to this conclusion. The children in the SLI group recalled 56.1% of the $N - 1$ (next to the last position) items and 70.78% of the N (last position) items correctly, resulting in a recency effect size of .47. The comparable within-group recency effect size for the CTL group was 1.18 ($N = 88.54$; $N - 1 = 62.60$) which is a recency effect size that is 2.5 times greater than the recency effect size for the SLI group.

The second significant group interaction in the recency analysis concerned group differences for type of response. Across input modalities, the SLI and CTL groups differed on the accuracy of their pointing versus speaking responses (Response Type × Group, $F(1, 30) = 4.78$, $p < .05$). Table 5 presents group means and standard deviations for all combinations of input and output modalities at the recency positions of the response curve. Students in the CTL group performed significantly better (Tukey p's $< .05$) than students in the SLI group on pointing (CTL $M = 73.64\%$, SLI $M = 57.34\%$, $d = .55$) and speaking responses (CTL $M = 77.5\%$, SLI $M = 69.58\%$, $d = .29$). Looking at within-group differences, only the students in the SLI group evidenced significantly better recency recall when speaking responses were required than when pointing responses were required (Tukey $p < .05$, $d = .39$). Performance in speaking and pointing conditions did not differ for children in the CTL group ($d = .15$).

The overall data trends indicated traditional primacy effects and recency effects for both groups in each of the conditions. However, recency effects for the SLI group were much less pronounced than those for the CTL group. The most pronounced differences between the groups occurred when pointing responses were paired with visual input. Table 6 presents the absolute differences between the groups and standardized effect sizes for each combination of input and output modality. Note that the absolute differences favored the CTL group in every case but one. Children in the SLI group had unusual difficulty with pointing responses. The average effect size of group differences on items requiring pointing responses was .50. In comparison, the average effect size of group differences on speaking items was .29. Clearly, children with SLI had the most difficulty recalling digits in the last two positions of the list when pointing responses were paired with visual input ($d = .73$).

Table 5. Within-group mean percent correct responding in the recency positions for all combinations of input and output modality.

Input and output modalities	SLI group	CTL group
Auditory input		
Pointing response	65.93 (30.59)	79.68 (21.82)
Speaking response	73.12 (28.55)	82.50 (25.07)
Visual input		
Pointing response	42.50 (32.95)	63.75 (26.87)
Speaking response	63.12 (31.31)	72.81 (23.46)
Audiovisual input		
Pointing response	63.59 (31.28)	77.50 (27.94)
Speaking response	72.50 (26.30)	77.18 (25.91)

Note. SD in parentheses

Discussion

The modality effect (Crowder & Morton, 1969; Penney, 1975, 1989) refers to the phenomenon that serial verbal recall accuracy for items at the end of a list is greater for auditorily presented items than for visually presented items. We used a variant of the modality effect paradigm to investigate modality specific memory mechanisms in school-age children with SLI. We hypothesized that patterns of within- and between-group differences in recall accuracy that occur as a function of input modality, rate of input, and response modality would act as a partial test of hypotheses about fundamental information processing deficiencies in children with SLI.

We found an auditory modality superiority in both groups. Despite the fact that we controlled for capacity differences between groups by presenting the task at

Table 6. Absolute group differences (CTL – SLI) and standardized d's for percent correct at all combinations of input and output modalities.

Input and output modalities	Primacy positions: Absolute difference	Primacy positions: Standardized *d*	Recency positions: Absolute difference	Recency positions: Standardized *d*
Auditory input				
Pointing response	5.0[C]	.19	13.75[C]	.52
Speaking response	10.0[C]	.37	9.38[C]	.35
Visual input				
Pointing response	16.56[C]	.54	21.25[C]	.73
Speaking response	6.56[C]	.28	9.69[C]	.35
Audiovisual input				
Pointing response	15.63[C]	.54	13.91[C]	.47
Speaking response	4.69[S]	.19	4.68[C]	.18

Note. [C] = Difference favors the CTL group; [S] = Difference favors the SLI group.

each child's short-term memory span, there were group differences as a function of interactions between input and output modalities. In the primacy positions of the response curve, the children in the SLI group showed especially poor performance when a visual stimulus was combined with a pointing response. Similar findings were obtained for the recency positions of the response curve. By far, the worst performance on our tasks occurred for children in the SLI group with respect to recency recall under conditions that paired a visual stimulus with a pointing response. We also found a much smaller recency effect in the SLI group, and a general superiority of speaking responses in comparison to pointing responses in these children. This superiority was not evidenced by the CTL group.

The literature on children with SLI (reviewed above) suggests that they present a variety of processing deficits. However, given the central role of working memory in language (e.g., Cowan & Saults, 1995; Gathercole & Baddeley, 1993), the primary goal of this study was to identify specific deficits that do or do not underlie working memory difficulties in these children. The present evidence will be evaluated with that aim in mind. Each of the four specific questions enumerated in the introduction will be considered in turn.

Speech Production and SLI

Our first research question was whether speech output constraints are fundamentally responsible for limitations in the immediate memory abilities of children with language impairment. As noted in the introduction, speech production processes have been shown to play an important role in working memory, and children with SLI have been known to exhibit difficulties with speech production. If deficiencies associated with output processes played a fundamental, causal role in the short-term memory deficits in children with SLI, then there should have been within-group differences between spoken and pointing responses that favored the pointing response modality, regardless of the input modality or the rate of presentation. Even though our research design provided plenty of power for this result to occur (87% chance to detect moderately-sized differences) such was not the case in this study. In fact, the results for children in the SLI group were the opposite of what was predicted if speech production processes played an important role in working memory deficiencies. Children with SLI presented significantly better recall when a speaking response was required than when a pointing response was required (d = .39). Therefore, problems with overt pronunciation processes (e.g., turning phonological codes into articulatory codes) are not fundamentally or independently responsible for working memory deficiencies in school-age children. Children with SLI had worse recency recall than children in the CTL group for spoken output conditions at the recency positions of the response curve. However, the SLI group also had worse recency recall for pointing conditions, and the effect size of group differences for pointing (d = .55) was greater than the effect size of group differences for speaking (d = .29). Our results suggest that speech output factors are not fundamental to the working memory deficiencies that children with SLI displayed on our tasks.

Auditory Retention and SLI

Our second research question was whether working memory difficulties experienced by children with SLI were specific to the auditory modality or generalized across auditory and visual modalities. Numerous previous investigations (e.g., Gathercole & Baddeley, 1990a; Gillam et al., 1995; Kamhi & Catts, 1986) have shown that children with SLI have deficiencies in recalling auditorily presented information. For example, preliminary testing revealed that the auditory digit span of the children in our SLI group was significantly lower than that of the children in the CTL group (SLI M = 4.38; CTL M = 5.56). To control for these differences, results of span testing were used to set the difficulty level of the experimental task to each participant's auditory memory capacity.

We reasoned in the introduction that if auditory processing deficiencies were fundamental to the working memory deficiencies in children with SLI, and if their memory deficiencies were limited to the auditory modality, then we should have found a smaller modality effect for the children in the SLI group regardless of response mode. However, we did not find a significant input type × group interaction for either the primacy or recency portions of the response curve, even though there was ample power for either of these two-way interactions (97% chance to detect moderately-sized group differences). There were no residual group differences after the separate main effects of group and input type were allowed for. Looking specifically at the within-group modality effect sizes for the recency data, there was a 12.81% auditory advantage (d = .40) for the CTL group and a 16.72% auditory advantage (d = .52) for the SLI group. Both groups presented moderately-sized modality effects that favored auditory stimuli, and the means for the CTL group were generally higher than the means for the SLI group. This is easily confirmed by referring to Tables 4 and 5.

If there were specific auditory deficiencies in children with SLI that played a fundamental role in working memory, we also should have found a strong visual advantage for the children in the SLI group. In contrast to this suggestion, however, recall for the SLI group was poorest when visual stimuli were paired with pointing responses. Our findings are consistent with evidence that children with SLI experience difficulty with certain visual representation processes (Johnston & Ellis Weismer, 1983; Johnston & Ramstad, 1983; Kamhi, Catts, Koenig, & Lewis, 1984; Montgomery, 1993). The findings of similar-sized modality effects in both groups, together with a decrease in memory performance in children with SLI when visual stimuli were paired with pointing responses, are inconsistent with the hypothesis that specific difficulties in processing and retaining the acoustic information contained in auditory signals is fundamentally responsible for working memory deficiencies in children with SLI.

Phonological Coding and SLI

In our third question, we asked whether children with SLI evidenced difficulties with phonological representation processes. In recalling auditory information, individuals convert acoustic information into a phonological form that is used for rehearsal and for subsequent storage into long-term memory. Gathercole and Baddeley (1990a, 1993), Gillam et al. (1995), and Montgomery (1995, 1996) have proposed that children with SLI have unusual difficulties with phonological coding.

A problem in phonological coding could have affected our results in two ways. First, phonological coding occurs more automatically for speech input than for visual input, which yields a phonological code only with additional active mental processing (Baddeley, Lewis, & Vallar, 1984; Salamé & Baddeley, 1982). As mentioned in the introduction, this is one reason why recall of auditorily-presented stimuli usually exceeds recall of visually-presented stimuli (Penney, 1989), even when the items are separated by distracting tasks (Gardiner & Gregg, 1979; Glenberg, 1984). Consistent with the phonological coding hypothesis, we found that children with SLI recalled significantly less when a visual stimulus was presented. Secondly, serial-position effects at the end of recalled lists yield information about serial order representation (Baddeley & Hitch, 1993; Lee & Estes, 1981). If children with SLI have difficulty representing information about serial order within a phonological code, they should show reduced recency effects in comparison to their age-matched controls. Our results were generally consistent with this hypothesis. Children with SLI recalled fewer items in the recency positions than children in the CTL group. This primarily occurred because of better recency recall for the children in the CTL group on items requiring a pointing response.

These results suggest to us that children with SLI have difficulty with phonological representation. A skeptic might point out that, by middle childhood, the phonological encoding of printed digits has been practiced to the point where it should not be a problem, even for children with SLI. However, a phonological coding difficulty still could cause these children to recall less when they know that a pointing response is required than when a speaking response is required (just the opposite of what one would expect if difficulties related to speech production were the basis of the short-term memory deficit). To see why this is the case, consider the following task analysis. For successful recall when a speaking response is required, participants must code the acoustic form of the stimulus into a phonological form, rehearse it, and then execute a spoken response. However, an extra phonological recoding step is needed when a pointing response is required. In this case, the phonological representation used in rehearsal must be transformed back into a visually-based representation in order to complete the pointing response. Thus, the findings of reduced recency recall and unusually poor recall when a visual stimulus was paired with a pointing response are consistent with the hypothesis that poor phonological representation is an important contributor to working memory deficiencies in children with SLI.

Real-Time Processing and SLI

Our fourth research question concerned the influence that rate of presentation had on immediate recall in children with SLI. Results of a number of investigations have suggested slowed information processing in children with SLI. Using the Sternberg paradigm, Sininger, Klatzky, and Kirchner (1989) found evidence of slowed short-term memory search processes in children with SLI. Stark and Tallal (1988) summarize the results of numerous investigations indicating that children with specific SLI perform variants of their repetition test better under slow conditions than fast conditions. Additionally, Ellis Weismer and Hesketh (1996) have shown that children with SLI learn novel vocabulary better when information is presented at a slow rate than when it is presented at a fast rate.

If deficiencies in working memory resulted primarily from difficulties with rapid-speech processing, then children in the SLI group should have displayed poorer recall when items were presented quickly. However, that was not the case. Across the two groups of children in this study, immediate recall was significantly better when lists of digits were presented at a fast rate than when they were presented at a slow rate. This finding occurred for both primacy and recency positions of the response curve. In general, children in the SLI group responded more accurately when items were presented quickly than when they were presented slowly. This result was reinforced by a significant interaction. In the primacy positions of the response curve, children in the SLI group had poorer recall accuracy than children in the

CTL group when slow items were presented auditorily.

These results appear to be at odds with those of other investigations (e.g., Stark & Tallal, 1988) showing a deficit in rapid processing in children with SLI. Unfortunately, our fast items may not have been fast enough to provide a reliable test of the rapid auditory processing abilities of the children in this investigation. Our fast stimuli were presented at a rate of 3/s, and our slow stimuli at a rate of 1/s. When we asked a group of graduate students to listen to our stimuli, they all judged the speaking of our fast items to be "comfortable" and our slow items to be "very slow." If the participants in this investigation perceived the fast and slow items similarly to this sample of adult listeners, our fast stimuli may have been too slow to examine this hypothesis fairly.

The slow items, however, may be interesting for another reason. It appears that children with SLI have difficulty retaining items that are presented too slowly. There are at least two explanations for this finding. One possibility relates to attention, the other relates to memory decay. First, children with SLI may not have been able to hold items in a buffer long enough for them to maintain their availability until the time of recall. Secondly, it could be that the rate of passive memory decay is greater in children with SLI, and the slow presentation rate allowed more decay.

Age differences in decay rates have been observed in other studies. For example, Saults and Cowan (1996) found that younger children forgot ignored speech faster than older children. If rate of memory decay slows as a function of development, the children in the SLI group may have evidenced unusually poor recall when stimuli were presented slowly, simply because they had generally less mature memory systems. Unfortunately, our procedure does not enable us to choose between the attention and decay rate explanations. In future research on forgetting in children with SLI, we intend to build slowed rates of presentation into our research protocols.

Conclusions

We noted at the beginning of this paper that results from our study would not constitute sufficient evidence for conclusively proving the validity of any one information processing hypotheses about the nature of SLI. For example, little can be said about the potential role of abstract linguistic or conceptual factors (Table 1, Hypotheses 1–3) from this experiment because these factors were not varied, though it would be possible to do so usefully within a short-term memory procedure (Hulme, Maughan, & Brown, 1991; Roodenrys, Hulme, & Brown, 1993). We hoped to provide reasonably compelling evidence about some information processing hypotheses (Table 1, Hypotheses 4–8) to the extent that they pertain to our modality effect task. Our results suggest that working memory deficiencies in school-age children with SLI do not result primarily from deficits in translating phonological representations into articulation (Table 1, Hypothesis 4), or from specific auditory processing deficits (Table 1, Hypothesis 5). This does not mean that auditory processing or speech production deficits never contribute to language impairment. At earlier points in development or in communication contexts that are much more demanding than the experimental protocol used in this study, these factors may play important roles in language impairment. Nevertheless, we can be reasonably certain that perceptual and output processes, in and of themselves, are not sufficient to explain the kinds of difficulties that children with SLI present on basic working memory tasks. Given that children with SLI had poorer recall of lists presented at slow rates, our results do not support the hypothesis that difficulties with rapid temporal processing (Table 1, Hypothesis 7) contribute fundamentally to working memory deficits. As noted earlier, a somewhat faster presentation procedure would serve as a better test of this hypothesis.

The hypothesis that appears to be the most consistent with the pattern of our results is that children with SLI have difficulties transforming and retaining well-specified mental phonological representations. We have explained how internal mental codes comprise an essential link in the causal chain leading from auditory stimulus presentation to overt spoken response (see also, Cowan & Saults, 1995; Massaro & Cowan, 1993; Sanders, 1990). Even with visual stimuli, mental codes usually take a phonetically-based form that is similar to the codes that are created for spoken stimuli (Conrad, 1964). Baddeley, Lewis, and Vallar (1984) have shown that phonological coding is more easily interrupted or prevented when visual stimuli are presented. Additionally, developmental evidence suggests that children use phonological coding and covert rehearsal for short-term retention of auditory information before they use phonological coding and covert rehearsal for retention of visual information (Hitch, Halliday, Dodd, & Littler, 1989; Hitch, Halliday, Schaafstal, & Heffernan, 1991). If verbal codes are poorly created, retained, or used, one would expect reasonably good primacy and recency recall when auditorily presented stimuli are paired with spoken responses, difficulties with recency recall, and difficulties with the rapid conversion of visual input into phonological forms for rehearsal and then back into nonspeech (pointing) responses. This is precisely the pattern of results that were demonstrated by the school-age children with SLI who participated in our investigation.

If children with SLI do, in fact, have difficulties with phonological coding (Table 1, Hypothesis 7), what might be the nature of such a deficit? First, as suggested by

Gathercole and Baddeley (1990a), children with SLI may be limited in their capacity to form adequate phonological codes. That is, they may create incomplete or "fuzzy" phonological representations of spoken or written words. It does not appear that the children with SLI in this investigation experienced difficulty generating relatively complete phonological representations. Otherwise, they would not have been able to respond reasonably well when auditory stimuli were paired with spoken responses. Children with SLI may, in fact, form inadequate phonological representations of phonologically complex and/or semantically unfamiliar words, but it does not appear that they did so with the stimuli in this experiment.

A second explanation might be that phonological coding deficiencies may involve limitations in the capacity to retain adequate representations across multiple processing conversions. Such phonological coding problems could be a consequence of phonologically-specific processes or of general difficulties with mental processing and retention of any type of information, including phonological representations (a version of Hypothesis 6 in Table 1). We explained earlier how two phonological conversion steps are necessary under recall conditions in which visual input is paired with spoken responses. It is likely that children in the CTL group were able to automatically code visually presented digits into a phonological form that facilitated rehearsal and recall, and then recode the phonological form back into a visual form during the pointing response. For children with SLI, the increased mental processing required for recoding the phonological representation back into a visual form or simply the time required to perform a recoding operation, may have interfered with retention of the initial phonological codes. As a result of extra mental processing and increased time, phonological representations, or any other type of representation for that matter, might have decayed such that they were not available for recall processes. It is also likely that children with SLI did not have the substantive long-term phonological representations and/or the mental capacities that would be needed to quickly rebuild decayed representations. Thus, they were more likely to "forget" the visually presented digits when a pointing response was required than when a speaking response was required.

A third explanation might be that children with SLI opted not to carry out the double phonological conversion in favor of another, logically possible route. They knew from the training that preceded the items in the visual input-pointing response block that visual information was going to be available in both the input and the response modes. Given that prior knowledge, children with SLI may have attempted to directly associate visual input forms to visual representations and visual recall forms. Such a strategy involves fewer processing steps, but is less likely to facilitate recall because phonological codes are preferable to visual codes for retaining serial order information. If the children in the CTL group were able to automatically recode visually presented digits into a phonological form that facilitated rehearsal and recall, they would have a distinct advantage.

We could test the explanatory adequacy of the second and third explanations by altering one aspect of this study. The performance limitation explanation depends on subjects knowing what the response modality is going to be before it occurs; the capacity limitation explanation does not. If participants did not know whether they would have to produce a spoken response or a pointing response, their representation strategy would be likely to be similar for both response modalities. Similar preparation should result in no difference in the visual input-spoken response and the visual input-pointing response conditions. If the capacity limitation explanation is correct, the disadvantage in the visual input and speaking response condition should occur whether children with SLI have prior knowledge of the response condition or not. Therefore, we plan to conduct an additional study in which one group of children with SLI and one group of controls will receive training for all input and response conditions prior to testing, followed by randomized response conditions presented within blocks of visual or auditory stimuli. A second group of children with SLI and a second group of controls will receive training prior to each block of similar items, as was the case in the present investigation. This procedure will enable direct comparisons of capacity and performance limitation explanations of phonological coding deficiencies related to the modality effect.

In summary, research suggests that verbal information is mentally coded and remains accessible through activation and reactivation processes. Acoustic and temporal aspects of sounds are saved in a sensory trace that is recoded into a phonological form (Cowan, 1995; Cowan & Saults, 1995). This same process occurs when pictures are represented phonologically (Gathercole & Baddeley, 1990b, 1993). We have suggested in this paper that such recoding requires extra mental processes. We believe that children with SLI may have difficulty retaining previously formed phonological codes during multiple mental operations or that they avoid creating phonological representations unless such codes are necessitated by task requirements. Either explanation could contribute to deficiencies in retaining and using phonological codes and to previous observations of unusually large dissociations between speaking, reading, and writing in this group of children (Gillam & Johnston, 1992; Gillam & Carlile, 1997). Fortunately, there are clinical procedures that are relevant to this problem. As noted by Gillam and van Kleeck (1996), for example, training in phonological awareness abilities appears to influence the creation and retention of phonological codes.

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