Speed of Processing, Working Memory, and Language Impairment in Children

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Purpose: Children with language impairment (LI) often perform below the level of typically developing peers on measures of both processing speed and working memory. This study examined the relationship between these 2 types of measures and attempted to determine whether such measures can account for the LI itself.
Method: Fourteen-year-old children with LI and their typically developing peers participated in a wide range of processing speed and working memory tasks and were administered a comprehensive language test battery. Confirmatory factor analyses were used to compare 3 nested models designed to examine the dimensionality of the speed and working memory measures. A model that included a general speed factor was also evaluated.
Results: The models meeting our evaluation criteria treated speed and working memory as separable factors. Furthermore, nonverbal as well as verbal processing factors emerged from these analyses. Latent variable regression analyses showed that each of the appropriate models accounted for 62% of the variance in the children's concurrent composite language test scores, with verbal working memory making the largest contribution.
Conclusions: These findings shed light on the relationship among different types of processing and suggest that processing factors can contribute to the understanding of language disorders.

KEY WORDS: memory, cognition, language disorders

The term *language impairment* (LI) is often applied to children exhibiting a significant deficit in language development without accompanying problems such as hearing impairment, neurological damage, or mental retardation. Because these children's medical or developmental profiles reveal no obvious obstacles to their learning of language, it is often assumed that language itself is the problem. These children may simply have difficulty learning the meaning of words and the rules for using these words in sentences and larger units.

However, there are other possibilities. It is plausible that these children have difficulty processing the information that is needed to acquire language adequately. That is, language itself may not be the problem; instead, processing limitations may significantly affect the child's ability to access language from the input and, once (finally) acquired, use it with facility. For example, some children may have no difficulty recognizing that a new word refers to a particular object. However, if the children are unable to retain the phonological sequence that makes up the word, they will probably require multiple encounters with that word before it can be adequately learned. Other children may be capable of hypothesizing that a grammatical inflection such as *–ed* refers to past tense but do not process the continuous speech stream quickly enough to identify this morpheme,

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hypothesize its grammatical function, and store the morpheme before attention must be directed to the portion of the speech stream that follows.

In the past 25 years, there has been considerable evidence that factors apart from language content and form are at least contributing to the problems experienced by children with LI. This evidence has prompted many authors to propose that these children have limited processing abilities (e.g., Ellis Weismer & Hesketh, 1996; Evans, 1996; Gillam, Cowan, & Marler, 1998; Johnston, 1994; Kail, 1994; Montgomery, 2000). The studies supporting this view have used different models of processing. However, they share the common finding that the determining factors proved to be the amount of material to be integrated and stored, and the time available for completing these operations, not the particular type of material (e.g., digits, words, novel figures, locations in space) that is used (see Bishop, 1992).

The purpose of the present study was to determine the extent to which processing factors predict the concurrent language test scores of 14-year-old children with LI and their typically developing (TD) peers. As shown in subsequent sections, we considered processing limitations from different vantage points, as each might make a unique contribution to a greater understanding of this disorder.

Processing Speed and Working Memory

Kail and Salthouse (1994) noted that processing limitations can be considered from different perspectives. Viewed from the perspective of a spatial metaphor, processing limitations can be interpreted to mean that the computational region of memory is restricted; there is too little work space. Processing limitations can also be considered from the perspective of energy. In this instance, the energy or fuel necessary for a task is expended before the task has been completed. Finally, viewed from the perspective of time, if the information is not processed quickly enough, it will be vulnerable to decay or interference from additional incoming information. The first two of these perspectives—space and energy—are often discussed in terms of processing capacity. Whether described as limitations in amount of space or amount of energy, limitations in processing capacity are typically revealed through tasks of working memory—the system used to store small amounts of information briefly while keeping it accessible for mental manipulation/transformation. For this reason, we use the term *working memory* when referring to this line of work. The third perspective—time—is often discussed in terms of processing speed. In this study, we focused on processing from the perspectives of speed and working memory.

The notions of limitations in processing speed and limitations in working memory are not unrelated. For example, faster speed can mean faster rehearsal, which should permit a greater amount of information to be held in working memory. The links between speed and working memory may be fundamental. Processes assumed to be vital for performing timed tasks, such as attention, have been found to be critical components of working memory as well. For example, maintaining attentional focus may be as important as rehearsal in retaining information in working memory (Cowan, 1999). Jonides, Lacey, and Nee (2005) have proposed that brain mechanisms responsible for attention are the same as those used to refresh internal representations in working memory. In a recent study that used functional magnetic resonance imaging (fMRI), Ellis Weismer, Plante, Jones, and Tomblin (2005) found that a group of adolescents with LI differed from TD peers in regions associated with both attentional control mechanisms (the parietal region) and memory processes (the precentral sulcus).

However, it is unlikely that speed and working memory are identical. First, event-related potential studies of teenagers exhibiting LI have shown delayed N100s elicited by brief, rapidly presented tones, suggesting that even at lower levels of processing and with working memory demands kept to a minimum, the speed of processing information may be slower than expected (Weber-Fox et al., 2005). Second, slower response times (RTs) can also reflect degree of knowledge even when working memory demands are relatively constant. For example, it is well known that individuals name pictures more rapidly when the names of the depicted objects have a high frequency of occurrence than when they have a lower frequency of occurrence. A typical explanation for this finding is that words with high frequency have both a greater number of associations and stronger associations in semantic memory than words with lower frequency. Thus, accessing the less frequent names requires slightly more time. In such tasks, the picture that evokes the lexical search remains on the screen, allowing the image to be continuously "refreshed," which should significantly reduce the demands on working memory. Children with LI show the same pattern of responding more slowly to pictures with names of lower frequency. In addition, these children show slower RTs than same-age peers for words across the frequency range (Leonard, Nippold, Kail, & Hale, 1983).

Findings from Gillam and Ellis Weismer (1997) suggest that effects attributable to speed and those attributable to working memory may be separable. These investigators matched a group of school-age children with LI with a group of younger TD children on a working memory task. The children were given a task in which they had to memorize 12 target sentences and then verify whether a sentence was one they had actually studied. The children with LI were comparable to the younger TD children in their verification accuracy but were significantly slower than the younger TD children in responding to all sentence types.

Considering that speed and working memory can be distinguished both logically and methodologically, it is surprising that so little research has been done on whether these two processes are functionally different. Indeed, frequent descriptions of children with LI having a *processing limitation* seem to tacitly acknowledge that alternative terms such as *speed deficit* or *working memory deficit* may be defining the problem too narrowly. One goal of the present work was to determine whether speed and working memory function similarly enough to be regarded as a single factor in the study of LI or, alternatively, whether they should be treated as separate factors. Here, *function* refers to how strongly the processes of speed and working memory covary with other measures. If these processes show a high degree of covariance, they are viewed as functioning similarly.

Verbal and Nonverbal Processing Limitations

In the literature on both speed and working memory, there is debate as to whether the limitations are confined to select domains (such as language) or are more widespread. Within the realm of speed, Kail (1994) originally proposed that the RTs of school-age children with LI were uniformly slower than those of TD children regardless of task and domain. He analyzed data across several studies and found that the children with LI showed general, proportional slowing (33% slower) across a range of language and nonlanguage tasks. Windsor and Hwang (1999) also examined data from different studies and reported a general slowing (of 18%) across diverse tasks. More recently, Miller, Kail, Leonard, and Tomblin (2001) presented an even wider array of tasks to the same group of second-grade children. The tasks included simple motor tasks (e.g., pressing a button once a cue appeared on a computer screen), nonlinguistic cognitive tasks (e.g., judging whether two figures were identical, when one figure differed from the other in orientation), and linguistic tasks (e.g., judging whether a sentence accurately described the events in a picture). Miller et al. found that across domains, tasks, and conditions, the children with LI were approximately 14% slower than TD peers.

The evidence interpreted as reflecting a general slowing in children with LI comes from regression procedures that show the RTs of children with LI increasing linearly as a function of the RTs of TD children across the same domains, tasks, and conditions. Other researchers, citing the need to use alternative regression procedures, have reported slower RTs on the part of children with LI that is best described as domain- or process-specific. Windsor, Milbrath, Carney, and Rakowski (2001) conducted analyses using data from separate studies and found that slowing seemed limited to particular investigations. However, because some of the processes examined were not the same across studies, the between-study differences in degree of slowing may have been reflecting slowing differences between particular processes. Such a view finds support in studies of cognitive aging, which show that some domains and processes (e.g., motor tasks, lexical tasks) do not show the same pattern of slowing as others (e.g., Cerella & Hale, 1994; Lima, Hale, & Myerson, 1991).

Studies of the working memory abilities of children with LI have also varied in the breadth of difficulties observed. Several studies have used the working memory model of Baddeley (1986; see also Gathercole & Baddeley, 1993), which includes a central executive along with two modality-specific storage systems. One storage system, the phonological loop, retains language material briefly unless it is refreshed through rehearsal. The other storage system, the visuospatial sketchpad, functions much like the phonological loop but with information of a visual nature. The central executive coordinates the flow of information by encoding and retrieving information from both the phonological loop and the visuospatial sketchpad. In a series of experiments, Gathercole and Baddeley (1990) found evidence suggesting that the problems of children with LI centered on phonological memory. They found that children with specific language impairment (SLI) had great difficulty repeating nonwords, but did not differ from control children in discrimination of word pairs or in articulation rate. Other studies have also uncovered problems in nonword repetition by children with LI (e.g., Dollaghan & Campbell, 1998; Ellis Weismer et al., 2000; Kamhi, Catts, Mauer, Apel, & Gentry, 1988; Montgomery, 1995), adding credence to the view that working memory for phonological material is quite weak in these children.

However, there is also evidence to suggest that working memory limitations may not be confined to phonology or even to language more generally (Bavin, Wilson, Maruff, & Sleeman, 2005; Hoffman & Gillam, 2004). For example, Hoffman and Gillam administered tasks to children with LI that required involvement not only of the phonological loop (recalling digits) but also the visuospatial sketchpad (recalling locations of Xs that appear on a grid), and the central executive (e.g., saying the color names of the Xs during their presentation, then recalling their locations by pointing to the appropriate cells on the grid). The children with LI performed below the level of same-age peers on both digit recall and visuospatial recall. In addition, unlike their TD counterparts, these children did not benefit from the opportunity to disperse processing efforts across the verbal and spatial response modalities, an operation that ordinarily serves to reduce the capacity demands on any single storage system.

Evidence supporting the interpretation of relative broad-based processing limitations in children with LI would have major implications. From a theoretical perspective, such evidence would suggest that LI is not strictly a disorder of language. That is, this disorder may include a limitation in children's ability to retain or quickly process information that they might otherwise be capable of understanding. Intervention practices might also be modified. For example, along with devoting significant attention to new semantic and morphosyntactic details of language, clinicians might also provide children with activities that promote the mental manipulation of language and nonlanguage material that the children have previously acquired.

One of the goals of the present study was to determine whether processing speed operates in a sufficiently similar manner across tasks to be regarded as a single speed factor in the study of LI or whether functional differences across tasks (limited covariance) warrant treatment of nonlinguistic and linguistic speed as separate factors. Likewise, we sought to determine whether working memory functions as a single factor or should instead be divided into nonverbal and verbal working memory.

Working Memory and Language Knowledge

Even if speed and working memory limitations are found in children with LI, it is not clear that these limitations contribute to the poor language ability of these children. Logically, of course, it is reasonable to assume that if children cannot retain phonological information long enough to form a phonological representation of a word, or if their slower speed does not allow them to keep up with the processing of a full sentence, their language development should be hampered. However, it is also possible that limited processing abilities and poor language ability are comorbid conditions, that is, conditions that frequently co-occur without a direct cause and effect.

Another possibility is that limited processing abilities have the potential to create difficulties but their causal effect is diminished under certain language learning conditions. For example, it is plausible that the multiple occurrences of words and sentences in the input are sufficient to override subtle problems in working memory that lead some tokens in the input to be lost. Children who acquire language normally do so in spite of wide variability in the quality and quantity of input. If children with LI have the good fortune of an optimum linguistic input, their speed and/or working memory limitations may constitute less of a burden. Consistent with this possibility is the finding from language intervention studies that by increasing the frequency of target forms, clinicians enable children with LI to begin acquiring the target forms at a rate commensurate with typical development (see Leonard, 1998, for a review).

Obviously, if speed or working memory limitations are not the direct cause of some children's language problems, these problems must have another source, which might be specific to language. For example, some children may have difficulty forming or refining phonological representations even when these have been stored adequately. Other children may be capable of learning grammatical details such as tense and agreement marking but fail to grasp that such marking is obligatory in main clauses (e.g., Rice, Wexler, & Cleave, 1995).

Current models of working memory differ in their assumptions about the effects of working memory on language knowledge. In Baddeley's model (see Baddeley, Gathercole, & Papagno, 1998), phonological memory plays an important role in the learning of new words, whose unique phoneme sequences must be retained long enough to be assigned a semantic interpretation. In his most recent work, Baddeley (2000, 2003) has proposed a new component, the *episodic buffer,* which entails a temporary storage system that is capable of combining phonological or visual information with information from long-term memory to form integrated chunks.

According to the working memory model of Just and Carpenter (1992), individual differences seen in language comprehension might be explained by differences in working memory capacity. For example, a larger working memory capacity could assist individuals in resolving syntactically ambiguous sentences by allowing them to maintain multiple interpretations. Just and Carpenter also noted that there may be cases of "syntactic encapsulation"—apparent modularity of syntax—that are instead due to working memory capacities that are too limited to consider both nonsyntactic and syntactic information simultaneously during mental computation. The work of Just and Carpenter focused on adults, and these investigators examined language comprehension in the moment, rather than the underlying language knowledge of the participants. However, one can easily adapt their assumptions to the development of language knowledge in children. Language knowledge requires the building up of lexical and grammatical representations based on information in the input. For children with limited working memory capacities, comprehension of the language in the input would be only partial and lexical, and grammatical representations would be built up only slowly.

In the Just and Carpenter (1992) model, working memory and language comprehension are functionally separate. In contrast, in the model proposed by MacDonald and Christiansen (2002), working memory and language comprehension—indeed, working memory and language knowledge—are not distinct entities. Rather, they emerge together from an interaction between language experience and biological factors. In this model, representations and processing occur in the same system and constitute alternate states of a neural network in which processing consists of activation of a distributed network of connections that comprises the representation. Enhancement or strengthening of the network of connections will jointly improve representation and likewise enhance the network's capacity for activation. Applying this model to the case of language development, if biological factors were identical in two individuals but the individuals differed in language experience, the individual having greater experience with language would exhibit greater working memory for language.

In the embedded processes model of Cowan (1999), working memory and language knowledge are also related. In this model, working memory is not distinct from information in long-term memory but, rather, reflects information in long-term memory that is the focus of attention. Because verbal information in long-term memory is, essentially, language knowledge, the chief difference between verbal working memory and language knowledge lies in the degree to which the activity requires attentional control. Of course, there are tasks in which working memory must function with relatively little information in long-term memory. Contrast a nonword repetition task using English phonemes and syllable sequences that obey the phonotactic constraints of English with a task in which the phonemes and syllable sequences are alien to English. Nonword repetition performance by a monolingual speaker of English would be considerably better on the first task than on the second. The speaker did not have different working memory abilities on the two tasks; rather, significantly less information from long-term memory was available in the second task. It can be seen, then, that several models of working memory offer a rationale for expecting a demonstrable relationship between working memory and language knowledge.

The Present Study

From the above review, it is clear that at least three issues must be addressed before we can have an adequate understanding of the role of processing factors in LI. Specifically, we must determine (a) whether the conceptually and methodologically distinct processes of speed and working memory function in a manner (showing strong covariance) that allows them to be regarded as a single processing factor, (b) whether processing limitations extend to nonverbal areas, and (c) whether processing measures can predict children's performance on measures that presumably reflect language knowledge. Although current models of processing speed or working memory allow for predictions concerning some of these questions, they were not designed to address the full complement of issues raised here. Accordingly, in the present study, we took a different tack. We examined the degree to which verbal and nonverbal processing speed and working memory can predict the language test scores of teenagers with LI and their TD peers. The study proceeded in two steps. First, we applied confirmatory factor analysis to compare alternative, theoretically motivated models that differ in the dimensionality of the speed and working memory measures used. Model 1 treats speed and working memory as a single (general) processing factor. Model 2 treats speed and working memory as separate factors, and Model 3 further subdivides both speed and working memory into linguistic/verbal and nonlinguistic/nonverbal factors. Model 4 is a different type of model that introduces a general speed factor along with more specific factors of linguistic and nonlinguistic speed. The models emerging from these analyses as appropriate for the data were then used to predict the concurrent language test scores of the children. The findings should provide an important indication of the potential role of processing factors in children's language ability.

Method

Participants

Two hundred four 14-year-olds participated in this study. The participants were a subset of those involved in a large-scale investigation of the prevalence of SLI reported by Tomblin et al. (1997). They were first seen at age 5 years as part of a large sample of children drawn from urban, suburban, and rural communities in the state of Iowa. At that time, all of the children received a brief language screening test and all children who failed the screening, and approximately 33% of those who passed, were invited to participate in a diagnostic testing phase. Children were excluded from participating in this phase if they did not have English as their primary language; had a history of mental retardation, autism, or neurological impairment; or were blind or used hearing aids. Details of the sampling and procedure can be found in Tomblin et al. (1997).

During the diagnostic session, the children were administered tests of hearing, language, speech, and nonverbal intelligence. Children scoring more than 1.25 *SD*s below the mean for their age group on two or more composite scores on the language battery were considered below age level in language ability. All children who met the criterion for below-age-level language ability were invited to participate in a longitudinal study, and 231 (82% of those invited) agreed to join. In addition, 442 children who scored at age level in language ability were randomly sampled and invited to participate, and 373 agreed. Details regarding the participant recruitment and selection process can be found in Tomblin, Zhang, Buckwalter, and Catts (2000).

These children were administered a similar battery of tests when they were 8 years old and at 14 years of age. The language test battery used at age 14 years consisted of the Peabody Picture Vocabulary Test—Revised (PPVT–R; Dunn & Dunn, 1981), the Expressive scale of the Comprehensive Receptive and Expressive Vocabulary Test (CREVT; Wallace & Hammill, 1994), the Concepts and Directions and Recalling Sentences subtests of the Clinical Evaluation of Language Fundamentals—Third Edition (CELF–3; Semel, Wiig, & Secord, 1994), and narrative comprehension and production measures based on passages from the Qualitative Reading Inventory—3 (QRI–3; Leslie & Caldwell, 2001). A composite z score was computed based on the participant's performance across the entire language test battery. In the computation of the composite, each measure in the battery carried the same weight. The z scores were based on norms from the larger Iowa sample, with differential weightings to adjust for the oversampling of children with LI relative to their prevalence in the general population. Nonverbal intelligence was measured using the Block Design and Picture Completion subtests of the Performance scale of the Wechsler Intelligence Scale for Children—Third Edition (WISC–III; Wechsler, 1991).

At age 14 years, 204 children (out of 527 in the study) were administered the processing speed and working memory measures. The resulting sample of participants included 116 who showed age-appropriate language test scores (mean composite z score = –0.21) and nonverbal intelligence test scores (M = 101.6). An additional 51 children had two or more language test scores that were more than 1.25 *SD*s below the mean for their age (mean composite z score = –1.53) but nonverbal intelligence scores at age level (M = 97.9). Twenty-seven children were below age level on both the language test scores (mean composite z score = –1.77) and the nonverbal intelligence score (M = 75.8). Finally, 10 children scored at age level on the language tests (mean composite z score = –0.78) but were below age level in nonverbal intelligence (M = 80.0). Descriptive information about the children is summarized in Appendix A. The divisions shown in Appendix A correspond to traditional distinctions according to level of language and nonverbal intelligence. However, as will be seen in the Results section, such categories were not used in the data analysis, as we were interested in examining the dimensionality of speed and working memory measures and their relationship to language test scores in the sample as a whole.

Processing Speed Tasks

The processing speed tasks were those used by Miller et al. (2001); however, picture naming was not used in the present study, as this task differed from all others in requiring a vocal response rather than a manual key press. All of the speed tasks used were presented on a laptop computer, and children responded by striking a key on the keyboard. Auditory stimuli were presented monaurally by computer over headphones. Each task included several conditions. For most tasks, items across different conditions were presented in random or quasirandom order. For the remaining tasks, items were blocked. All children did the tasks in the same order. Children were instructed to always respond as quickly as possible without sacrificing accuracy. A set of practice items preceded each task. A summary of the tasks appears in Appendix B.

Motor tasks. Tasks described as motor tasks had minimal cognitive or language elements associated with them. In the tapping task, children tapped a key as many times as possible in 5 s. Responding began when the word *Start* appeared on the screen, accompanied by a tone. Responding ceased when another tone occurred and *Stop* appeared on the screen. Three conditions were used, with three trials in each. The trials were blocked by condition. In the first condition, children tapped one key with the index finger of the preferred hand. In the second, two keys (located on the same row but with one key between them) were tapped in alternation, using the index finger of the preferred hand. In the third condition, children tapped the same two keys in alternation but used the first two fingers of the preferred hand. Colored dots were placed on the two keys to be used.

The second motor task used was the strike-to-signal task. Children struck a key (marked by a colored dot) as quickly as possible in response to a visual signal. Preceding each item, the word *Ready* appeared on the screen followed by the response signal of three asterisks. Three conditions were created by delaying the presentation of the asterisks for 1, 2, or 5 s after the appearance of *Ready*. There were eight items at each delay. The conditions were randomly ordered.

Nonlinguistic cognitive tasks. Tasks that were regarded as nonlinguistic cognitive tasks involved more cognitive operations than the motor tasks but did not require linguistic information for an appropriate response. In the visual search task, simple nonsense figures used by Kail, Pellegrino, and Carter (1980) were used. Children were shown a target figure and then were required to scan a five-figure array for the target, which remained visible. Children were told to scan the array from left to right, pressing one key (marked with a green dot) when the target was present and a different key (marked with a red dot) when it was absent. Six conditions were used in this task; these corresponded to the five positions from left to right, and the case when a match was not present. Six items were used per condition.

The second nonlinguistic cognitive task was the mental rotation task. This task used the same figures that were used in the visual search task. The children were shown a target figure on the left, simultaneously with the same figure on the right, and had to press one key (marked with a green dot) when the second figure was exactly the same as the target, or a different key (marked with a red dot) when it was a mirror image. The second figure was rotated 0°, 60°, or 120° clockwise relative to the position of the target figure. There were six items in each of the six conditions.

The picture matching task, adapted from Experiment 3 of Kail and Leonard (1986), required children to judge whether two pictures, presented simultaneously, matched on a given criterion. Items were blocked by condition, with 12 items per condition. In the first block of items, children judged whether the two pictures were identical physically. In the second block, they judged whether the pictures had the same name (e.g., two nonidentical cats). In the third block of items, children judged whether the pictures belonged to the same category (e.g., animals).[1] Children pressed one computer key (marked with a green dot) for "yes" or a positive response and a different key (marked with a red dot) for a "no" or negative response.

Linguistic tasks. Four different tasks requiring language were used. In these tasks, one key was pressed to indicate a positive response, and another was pressed to indicate a negative response. In the truth-value judgment task, children were shown a picture and after 2 s, a sentence was presented auditorily while the picture remained visible. The children then judged whether the meaning of the sentence matched the picture. Three types of sentences were used: simple active, simple passive, and active with a compound subject noun phrase. For each sentence type, six matches and six mismatches were presented. In the grammaticality judgment task, children judged whether an auditorily presented sentence was "good" or "bad." Half of the sentences were grammatical; the other half were ungrammatical in one of three ways: incorrect subject–verb agreement, incorrect word order, or omission of a preposition from an oblique argument. Six correct and six incorrect sentences were used for each sentence type.

The two remaining tasks shared a common structure. In each, a picture appeared at the top of the screen, and then after 4 s the children either heard a word, saw a printed word at the bottom of the screen, or saw a picture at the bottom of the screen. Each of these conditions included 12 items, for a total of 36 items in each task. In the judging rhymes task, children judged whether the second stimulus (auditorily presented word, printed word, or name of picture) rhymed with the first. In the judging initial consonants task, children judged whether the second stimulus began with the same sound as the first.

Scoring. Prior to performing analyses, we eliminated two types of RTs: (a) those from trials in which the response was incorrect and (b) those less than 10 ms. The latter were considered too short to be legitimate responses to the stimuli. We refer to RTs in these two categories as unusable items. Outliers were then removed, as is customary for RT studies (e.g., Bowers, Vigliocco, Stadthagen-Gonzalez, & Vinson, 1999; Kail, 1991). Low outliers were first identified and eliminated from the data. These were defined as any RT less than 350 ms, except for the two motor tasks, since shorter RTs are common in such tasks. Mean RTs in each condition for each participant were then calculated. If any single RT was greater than twice the participant's mean RT for that condition, the data point was removed and the mean RT was again calculated. This procedure was repeated until there were no outliers.

Working Memory Tasks

The working memory measures comprised four tasks that entailed verbal working memory and one task focused on nonverbal spatial working memory. These measures included one standardized test and four experimental tasks. A description of each of the working memory tasks is provided below, with a summary appearing in Appendix B.

Verbal working memory tasks. The Auditory Working Memory subtest (Test 9) of the Woodcock-Johnson III (Woodcock, McGrew, & Mather, 2001) is a standardized measure in which a series of digits and words (e.g., "dog, 1, shoe, 8, 2, apple") is presented via audio recorded stimuli. The task is to repeat the object labels in sequential order and then repeat the digits in the order in which they were presented. This task requires that participants manipulate the stimuli to form categories while retaining the appropriate sequence of the items.

The Nonword Repetition Task (NRT; Dollaghan & Campbell, 1998) was used to assess phonological working memory. This task consists of a set of 16 nonsense words ranging from one to four syllables in length (e.g., /naɪb/–/tævɑtʃinaɪg/) that participants are asked to repeat immediately following the presentation of each item. The nonsense words comprise acoustically salient sounds, they do not follow English metrical stress patterns, and none of the syllables that constitute the nonsense words correspond to actual English words. The stimulus tape used by

[1]As can be seen, the first condition (physical identity) can easily be regarded as a nonlinguistic task. The remaining two conditions use linguistic criteria (e.g., name) but also involve categorization based on visual information, an ability available to children from a young age (e.g., infants' ability to use correlated visual attributes to form categories; see Younger & Cohen, 1983, 1986). To determine whether these two conditions should be classified with the first condition (as nonlinguistic cognitive speed measures) or should be classified differently (as linguistic speed measures), it was necessary to examine the factor loadings (see the Results section). These loadings indicated that all conditions of the picture matching task could be regarded as nonlinguistic cognitive measures. It is important to note that these steps taken to classify the picture matching task were based strictly on the a priori ambiguity that this task presented in terms of its linguistic versus nonlinguistic nature. For the central questions of this study, it was less important that picture matching was nonlinguistic (or linguistic) than it was to classify the task appropriately.

Dollaghan and Campbell was used to ensure standardized administration. This measure has been shown to be useful in distinguishing between children with and without LI (Dollaghan & Campbell, 1998; Ellis Weismer et al., 2000).

Two listening span measures based on the Daneman and Carpenter (1980) listening span task were also used to assess limitations in verbal working memory. These tasks require sentence processing and concurrent word recall. One of the measures was the Competing Language Processing Task (CLPT; Gaulin & Campbell, 1994), which consists of sets of one to six short sentences. True/false responses are elicited following each sentence to ensure comprehension processing. These sentences tap vocabulary and basic world knowledge (e.g., "Sugar is sweet"). Concurrently, participants are asked to recall the last word in each sentence after all sentences in the set have been presented. Stimuli are presented via audiotape. Children with LI have been shown to display significantly poorer word recall on the CLPT than those with normal language skills (Ellis Weismer, Evans, & Hesketh, 1999; Ellis Weismer & Thordardottir, 2002), controlling for sentence comprehension differences when applicable.

We also administered a second listening span task developed by Ellis Weismer (2006), the Grammatical Judgment Listening Span Task, in which the concurrent tasks consist of grammatical judgments of sentences and final word recall for each set of sentences. Prior studies have successfully used acceptability judgments of sentences and final word recall in reading span measures with adults (Waters & Caplan, 1996). This task provides an index of verbal working memory that involves more demanding linguistic processing than the comprehension items of the CLPT. The Grammatical Judgment Listening Span Task consists of five levels of sentences, with each level increasing in length from two to six sentences. Two sets of sentences are presented at each list length. Sentences in one set entail judgments of third person singular, regular past tense, or their bare-stem (noninflected) counterparts (e.g., "Last summer my brother play baseball"), whereas the other set involves judgments of possessive morphemes, plural morphemes, or their noninflected equivalents (e.g., "Six big bird flew by the snowman"). Stimuli are active sentences that are five to seven words in length; half of the sentences are grammatical and half are ungrammatical. Target words to be recalled are two-syllable words (nouns or modifiers) that have a strong–weak stress pattern (e.g., *baseball* and *snowman* in the prior examples). Target words are different across sets, and within a set they are not phonetically similar or semantically related. The range of lexical frequency of the final target words was similar for the two sentence types; frequency was determined based on *The Educator's Word Frequency Guide* (Zeno, Ivens, Millard, & Duvvuri, 1995). In constructing the stimulus sentences, care was taken to avoid co-articulatory effects that might affect grammatical judgments (e.g., words beginning with *s* were not used following omission of plural or possessive markers). The task involves responding "yes" or "no" regarding the grammatical acceptability of each sentence in a set and then recalling the final word in each sentence. Like the CLPT, the stimuli for the grammatical judgment listening span task are presented via audiotape.

Nonverbal working memory task. To evaluate nonverbal working memory, a spatial working memory task involving a complex odd-one-out procedure was administered. This task was adapted from a measure developed by Russell, Jarrold, and Henry (1996) to investigate working memory abilities of children with autism. A similar task was also used by Nation and colleagues (Nation, Adams, Bowyer-Crane, & Snowling, 1999) to assess memory skills in normal readers and poor comprehenders. In this task, participants are required to point to one of three complex shapes that is different from the other two shapes. The shapes are presented within a divided rectangle, with the rectangles being aligned in a row across the computer screen. Each rectangle contains three squares in which each of the target shapes appears. The rectangles containing the sets of complex shapes are presented from left to right, with each rectangle fading from view as the subsequent one is presented. The number of rectangles corresponds to the list length. Four trials are presented at each list length; the list lengths range from two to six sets of three complex shapes. After all of the sets of shapes have been presented at a particular length, participants are asked to point to the location of the odd-one-out shapes on a blank grid on the screen. The spatial working memory task was presented on a laptop computer using E-Prime software (Psychology Software Tools, Inc., n.d; Schneider, Eschmann, & Zuccolutto, 2002).

Scoring and interjudge agreement. The working memory tasks were scored with respect to accuracy of responses. The scoring conventions adopted for the Nonword Repetition Task were those specified by Dollaghan and Campbell (1998). For the purposes of the current study, the total percentage of phonemes correct score was entered into the analyses. Standard scores were used for the Woodcock Johnson III Auditory Working Memory subtest. The raw word recall score was used for the two listening span tasks. In the case of the grammatical judgment listening span measure, the total word recall score was used because there was not a significant difference for the two sentence types (those involving verb inflections and those involving noun inflections). The raw storage score was used for the spatial working memory task. Ten percent of the tape recorded responses per task were randomly selected for re-scoring by an independent rater. Scoring agreement was 100% for the CLPT, grammatical judgment listening span task, and Woodcock Johnson III Auditory Working Memory subtest; agreement was 97% for the NRT.

Results

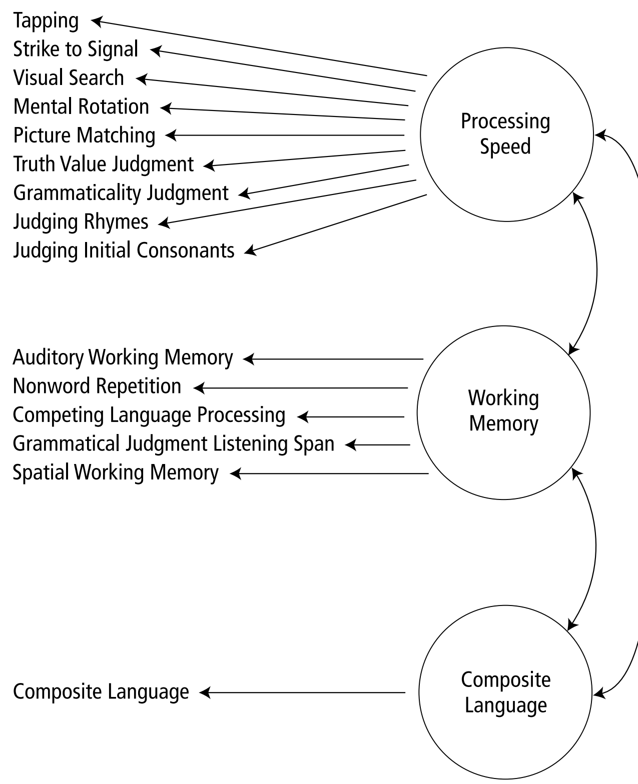
Confirmatory Factor Analysis: Nested Models

Data analysis was conducted in two steps. The first step involved using confirmatory factor analysis to compare three theoretically motivated nested models that differed in the dimensionality of the speed and working memory measures used. The most appropriate of these three models was then used to predict the children's concurrent composite language test scores. The first model examined (Model 1) was a model in which all speed and working memory measures were treated as a single (general) factor. Model 2 treated speed and working memory as separate factors. Model 3 involved separate motor speed, nonlinguistic cognitive speed, and linguistic speed factors as well as separate nonverbal working memory and verbal working memory factors rather than the broader, overarching speed and working memory factors used in Model 2. All analyses included composite language test score as a separate factor to ensure that any model emerging from the confirmatory factor analyses did not reflect a dimensionality of the speed and working memory measures that was strictly insular. That is, by including the language test score, we increased discriminant power of the analysis by taking into account that the measures might be related differently to language. It is important to note that in this first step of confirmatory factor analysis, the relationships that emerge between each factor and the comprehensive language test score are strictly correlational; only the regression procedures applied in the second step of data analysis permit us to determine whether a particular factor in the model is successful in uniquely predicting the children's composite language test scores.

Path diagrams of Models 2 and 3 are shown in Figures 1 and 2, respectively. The circles in each figure represent factors. The unidirectional arrows reflect the presumed factor loadings, and the bidirectional arrows that connect the factors reflect the assumption that the factors are correlated with one another. (From this description, it is clear that a comparable figure for Model 1 would depict a single Processing factor with 14 unidirectional arrows radiating from it.)

Earlier it was noted that the picture matching task was not unambiguously nonlinguistic or linguistic in nature. Because Model 3 used the separate factors of nonlinguistic cognitive speed and linguistic speed, it was important to classify this task appropriately. The physical

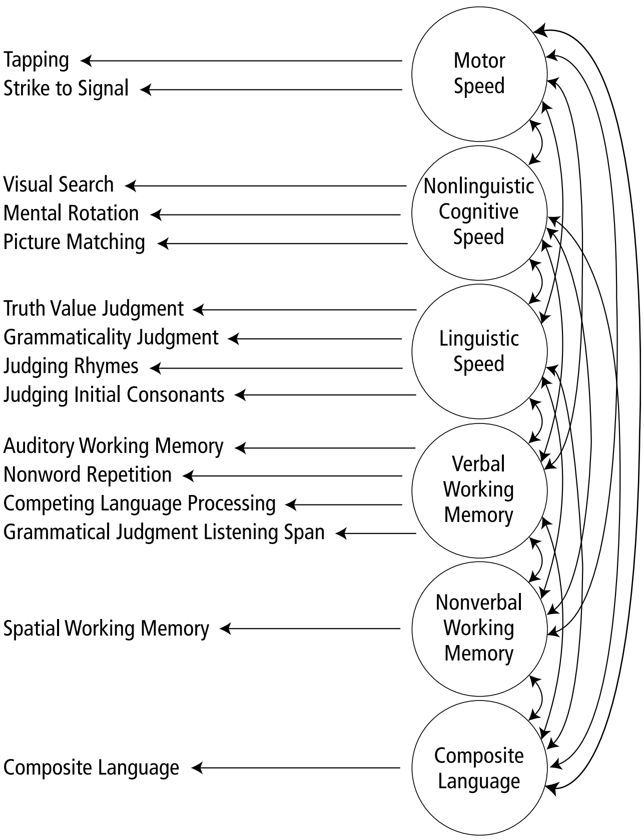
Figure 1. Path diagram of Model 2, in which processing speed and working memory are separate factors, along with composite language.



identity condition of this task was clearly nonlinguistic. We found that the scores for the remaining two conditions also loaded significantly on the nonlinguistic speed factor. For this reason, in Model 3, the scores from all three conditions of the picture matching task were allowed to load on the nonlinguistic speed factor.

In this first step of confirmatory factor analysis, the results for each model were compared according to several criteria. First, the values of the fit indices—the normed fit index and the nonnormed fit index—were inspected to see if the values approached a value of 1.00. Second, the root-mean-square error of approximation (RMSEA) and the root-mean-square residual (RMSR) were examined to determine if these values approached .05. We also compared the three models in terms of their degrees of freedom and chi-square values. It can be seen that the three competing models are nested; that is, the models are successively more elaborate versions of a common model. This nesting made it possible to statistically compare the competing models for the data through the chi-square difference test. For nested models, the difference in chi squares for any two models is also chi-square distributed with degrees of freedom equal to the difference in degrees of freedom between the two models. Because we tested Models 1, 2, and 3 in that order, each successive model could be compared

Figure 2. Path diagram of Model 3, in which motor speed, nonlinguistic cognitive speed, linguistic speed, verbal working memory, and nonverbal working memory are separate factors, along with composite language.



with the preceding model to assess the improvement in model fit due to increased specificity in the model. If the subsequently tested model produced a significant reduction in chi square relative to the reduction in degrees of freedom, higher values for the fit indices, and lower values for the root-mean-square (RMS) calculations than those of the preceding model, it was regarded as superior.

Table 1 provides each model's values for the measures serving as the criteria for evaluation. It can be seen that Model 3 was superior to each of the other models according to all of the criteria. The conventionally adopted 90% confidence interval (CI) for the RMSEA revealed a narrow range (.10–.12) whose lower bound of .10 is often taken as the upper cut-off point for an acceptable fit (MacCallum, Browne, & Sugawara, 1996). Comparison of this CI with the CIs of the other models revealed a significant difference favoring Model 3.

The intercorrelations among the factors in Model 3 are shown in Table 2. It can be seen that each factor was only moderately correlated with other factors with which it could have been plausibly related. For example, the relationship between linguistic speed and verbal working memory was not especially strong. The relationship between verbal and nonverbal working memory was somewhat stronger, though still moderate.

Table 1. Summary statistics for Models 1–3.

	Model		
Criterion	1[a]	2[b]	3[c]
χ^2	1087	742	465
df	152	150	139
NFI	.80	.87	.92
NNFI	.80	.87	.93
RMSEA	.20	.15	.11
90% CI	.19–.21	.14–.16	.10–.12
RMSR	.13	.10	.09

Note. χ^2 values are rounded to the nearest whole number. NFI = normed fit index; NNFI = nonnormed fit index; RMSEA = root-mean-square error of approximation; CI = confidence interval; RMSR = root-mean-square residual.

[a]Factor = all speed and working memory. [b]Factors = speed, working memory. [c]Factors = motor speed, nonlinguistic cognitive speed, linguistic speed, nonverbal working memory, verbal working memory.

Confirmatory Factor Analysis: General Speed Models

Although Model 3 was a more appropriate model than Models 1 and 2, it seemed important to evaluate another type of model for the dimensionality of the speed of processing tasks and conditions. It can be recalled that in Model 2 (see Figure 1), all speed tasks and conditions were treated as a single factor. This model was less satisfactory than Model 3, which split the more general speed factors into distinct, but correlated, factors. An alternative to decomposing the general speed factor into correlated specific dimensions is to introduce a general speed factor on which all of the speed tasks and conditions

Table 2. Correlation matrix for the factors of Model 3.

	1	2	3	4	5	6
1. Motor speed	1.00					
2. Nonlinguistic speed	.73	1.00				
3. Linguistic speed	.44	.62	1.00			
4. Nonverbal WM	.62	.39	.21	1.00		
5. Verbal WM	.60	.40	.35	.63	1.00	
6. Composite language	.52	.46	.34	.48	.77	1.00

Note. WM = working memory.

loaded, along with the specific nonlinguistic and linguistic speed dimensions that are both uncorrelated to each other and to the general speed factor. The path diagram for this model is shown in Figure 3. Hereafter, we refer to this general model as Model 4.

Model 4 allowed us to capture the relationship among tasks and conditions that held because of the speed component that they shared without this relationship being obscured by the relationships that held due to other types of shared characteristics. For example, the nonlinguistic speed task of mental rotation and the linguistic speed task involving truth-value judgments were probably related not only because both involved a speeded response but also because both required binary "yes"/"no" judgments and comparisons of a stimulus to a standard. For a clearer picture of the contribution of speed itself, we assumed a general speed factor that was uncorrelated with the specific factors of nonlinguistic speed and linguistic speed, shown in Figure 3 as a factor with unidirectional arrows directed toward each speed task but no bidirectional arrows connecting it to the nonlinguistic or linguistic speed factors. This restriction of the correlation between specific and general factors is necessary for identification in the model (i.e., unique estimates for the factor loadings and correlations for the working memory and composite language test scores). Nonverbal working memory, verbal working memory, and the factor comprising the single language composite served as the remaining factors.

Figure 3. Path diagram of Model 4, in which a general speed factor is assumed along with specific nonlinguistic and linguistic speed factors, verbal and nonverbal working memory factors, and composite language.

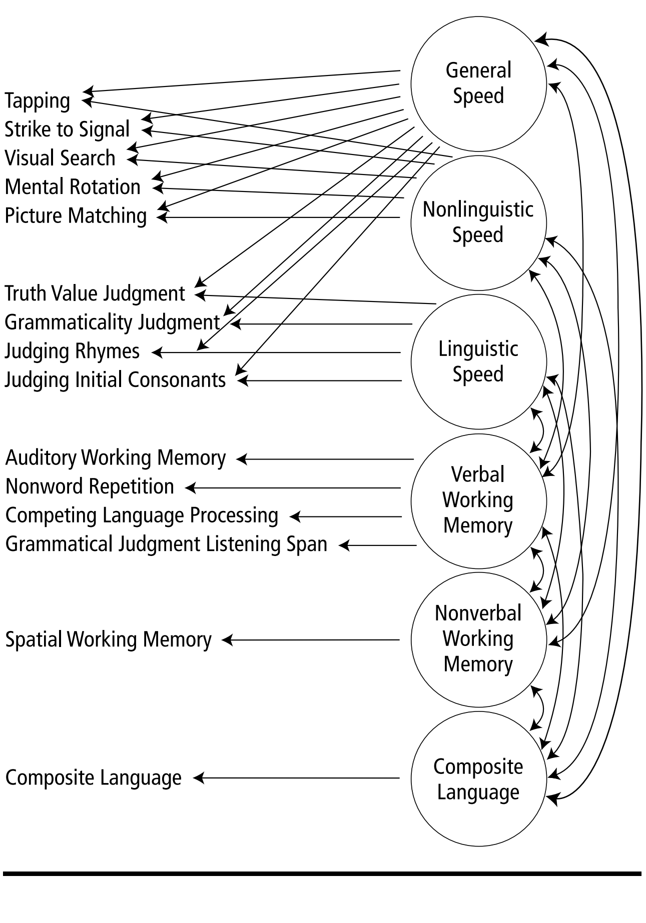


Table 3. Summary statistics for Model 4.

Criterion	4[a]
χ^2	216
df	125
NFI	.96
NNFI	.98
RMSEA	.060
90% CI	.044–.071
RMSR	.054

Note. The χ^2 value was rounded to nearest whole number.

[a]Factors = general speed, nonlinguistic speed, linguistic speed, nonverbal working memory, verbal working memory.

The summary statistics for the analysis of Model 4 appear in Table 3. Whereas Model 3 had a chi-square value of 465 with 139 degrees of freedom, Model 4 had a chi-square of 216 with 125 degrees of freedom. The normed fit index (.96) and nonnormed fit index (.98) for Model 4 were likewise favorable. Furthermore, the RMSEA of .06 with a narrow confidence interval of .044–.071, and an RMSR of .054, suggest a successful fit.

The intercorrelations among the working memory and speed factors in Model 4 are shown in Table 4. Recall that general speed, nonlinguistic speed, and linguistic speed dimensions are constrained to be uncorrelated with one another. As is to be expected, the correlations between the two working memory factors and the correlations between these factors and the composite language test scores were the same as in Model 3, as the definition of these factors is identical in the two models. The correlations between the general speed factor and the working

Table 4. Correlation matrix for the factors of Model 4.

	1	2	3	4	5	6
1. General speed	1.00					
2. Nonlinguistic speed	—	1.00				
3. Linguistic speed	—	—	1.00			
4. Nonverbal WM	.45	.51	−.02	1.00		
5. Verbal WM	.49	.44	.00	.63	1.00	
6. Composite language	.52	.23	−.01	.48	.77	1.00

Table 5. Summary statistics for prediction of Composite Language Test scores by Model 3.

Statistic	Factor in model				
	Motor speed	Nonling speed	Ling speed	Nonverbal WM	Verbal WM
Standardized Beta	−0.08	0.27	−0.04	−0.04	0.75
Unstandardized Beta	−0.13	0.42	−0.04	−0.04	0.99
(standard error)	(0.26)	(0.21)	(0.06)	(0.08)	(0.14)
t	−0.49	2.03*	−0.74	−0.43	7.10*

*$p < .05$.

memory factors and those between the general speed factor and the composite language test scores were in line with the intercorrelations seen for Model 3.

Latent Variable Regression Analysis

In this step of analysis, we attempted to determine how well each model of the children's speed and working memory performance could predict the children's concurrent composite language test scores. A latent variable regression analysis was first performed using Model 3. The results indicated that this model accounted for 62% of the variance in the children's composite language test scores. The resulting standardized Beta weights are shown in Table 5, along with the nonstandardized Beta weights (with standard errors) and t values. From this table, it can be seen that the nonverbal cognitive speed factor and verbal working memory factor emerged as relevant factors. The t value for each was statistically significant ($p < .05$). From the standardized Beta weights, it is clear that the verbal working memory factor (Beta = 0.75) played an especially important role, with a smaller, though nontrivial, role played by nonverbal cognitive speed (Beta = 0.27).

We then performed a latent variable regression analysis using the model with a general speed of processing factor, Model 4. This model, like Model 3, accounted for 62% of the variance. Table 6 provides the standardized Beta weights, nonstandardized Beta weights (with standard errors), and t values. From Table 6, one can see that only the general speed factor and the verbal working memory factor were statistically significant ($p < .05$), with the larger role played by verbal working memory (Beta = 0.73) than general speed (Beta = 0.17).

Discussion

We begin this section by considering several caveats that limit conclusions that can be drawn from this work. Then we discuss the findings in terms of the issues raised at the outset of this paper: (a) whether processing speed and working memory function in a manner that allows them to be regarded as a single processing factor, (b) whether nonverbal as well as verbal processing factors prove important, and (c) whether processing factors can predict language test scores that might be taken to reflect language knowledge.

Some Caveats

The present findings must be considered in light of several caveats. First, the confirmatory factor analyses yielded two models that proved satisfactory for examining the data. However, we do not claim that these are the only suitable models that could be devised. Nevertheless, as shown in Tables 1 and 3, these two models met important criteria and can be regarded as quite appropriate.

Second, the latent variable regression analyses involved predictions of concurrent language test scores. It is possible that the results could have been different if, for

Table 6. Summary statistics for prediction of Composite Language Test scores by Model 4.

Statistic	Factor in model				
	General speed	Nonling speed	Ling speed	Nonverbal WM	Verbal WM
Standardized Beta	0.17	−0.08	−0.01	−0.02	0.73
Unstandardized Beta	0.17	−0.27	−0.01	−0.02	0.97
(standard error)	(0.08)	(0.39)	(0.01)	(0.09)	(0.14)
t	1.99*	−0.70	−0.73	−0.19	6.93*

*$p < .05$.

example, processing measures obtained at 9 years of age were used to predict language test scores at 14 years of age. Even the results of the concurrent predictions may have been age specific. For example, it is plausible that concurrent predictions at 9 years of age would yield results that differed from the ones obtained at 14 years as in the present study.

Third, although we selected a wide variety of processing speed and working memory tasks, across nonverbal as well as verbal areas, the tasks probably do not reflect the full range of speed and working memory operations that can be involved. For this reason, it is possible that a different set of tasks could produce slightly different results. For example, because all of the linguistic speed of processing tasks involved a manual response, whereas all of the verbal memory tasks involved an oral response, one might ask whether response modality played a role in addition to the distinction between speed and working memory in these tasks. However, the correlation matrix in Table 2 does not provide evidence of a strong modality effect. For example, the correlation (.39) between nonlinguistic speed and nonverbal working memory (the latter requiring a pointing response) was no higher than the correlation (.40) between nonlinguistic speed and verbal working memory (the latter requiring an oral response). Neither of these correlations was reliably higher than the correlation (.35) between linguistic speed (manual response) and verbal working memory (oral response). Although our tasks might have been improved upon, given the number and variety of tasks used in the present study, we believe that our tasks were in the very least representative of the speed and working memory operations that are involved during verbal and nonverbal processing.

Finally, the processing speed and working memory measures were used to predict language ability as reflected in a single composite score. This score was a z score based on the participant's performance across a variety of language tests. Certainly there was some variability among the children that was not captured by a single composite score, and this variability could have influenced the results. However, Tomblin and Zhang (1999) conducted cluster analyses on data from these same children upon entry into the Iowa study and found that the children's performance on vocabulary, grammar, and narratives clustered together and did not permit identification of subgroups on these measures. The same areas of language were used in computing composite scores for the present investigation. Therefore, although there was variability in the sample, we do not believe that our use of composite scores masked the presence of subgroups with clearly distinct language profiles.

Composite scores can also be justified on the basis of psychometric criteria and ecological validity. Specifically, composite scores were z scores based on norms from the larger Iowa sample and thus provide an accurate picture of the children's performance relative to peers. Furthermore, composite scores are often used as appropriate measures of children's language ability in the diagnosis of LI (see Leonard, 1998). Because it was important to predict scores that are likely to matter in clinical settings, composite scores appeared to be especially useful. (It can also be noted that even when composite scores are not used, a proxy for such scores is often seen in the form of requiring low scores on at least two language tests before a child qualifies for clinical services.)

Processing Speed and Working Memory

One of the important findings from the present study is that speed and working memory are not interchangeable measures of processing. Although the two types of measures are clearly related, both Model 3 and Model 4 provided evidence that speed and working memory processes are functionally separable. Obviously, processing speed uses RT as a dependent measure whereas working memory uses accuracy, or more precisely, number of items correctly recalled. However, in other respects there are similarities between these two types of processes. On logical grounds, faster execution of mental operations should mean faster rehearsal, which should allow a greater amount of material to be held in working memory. In addition, both the speed tasks and the working memory tasks emphasized material that was well within the children's comprehension level. The challenge was to respond to this material quickly (processing speed measures) or to remember combinations or whole lists of this material (working memory measures). Despite these similarities, in both Model 3 and Model 4, there was evidence for functional distinctions between these two types of processes. For example, in both models, nonverbal working memory was more closely related to verbal working memory than to nonlinguistic speed.

We can imagine an alternative outcome, where the dimensions emerging from the analyses were organized differently. For example, Cowan et al. (1998) found that children's rate of rehearsing words and their rate of retrieving words were not correlated with each other but that both were correlated with memory span. At least within the relatively narrow confines of word recall tasks, then, some speed measures may not cluster together and/or they may form a single dimension with a measure of working memory. Because our processing speed measures were aimed at covering a wide range of tasks rather than decomposing single tasks into separate operations (e.g., rehearsing as opposed to retrieving words), a model with this type of dimensionality was not evaluated.

In the working memory model of Cowan (1999), attentional focus plays an essential role. Because active attention was also critical in responding to the processing speed tasks, the separability of speed and working memory suggests that the working memory tasks involved important processes that extended beyond those pertaining to attention itself. The fMRI investigation of Ellis Weismer et al. (2005) provides data consistent with this interpretation. These investigators found that adolescents with LI displayed hypoactivation in regions associated not only with attentional control mechanisms but also those associated with memory processes.

The fact that processing speed and working memory were distinguishable also seems to suggest that working memory is not determined solely by speed-related factors such as rehearsal rate. Bayliss, Jarrold, Baddeley, Gunn, and Leigh (2005) recently reported a similar finding in a study of age-related variation in typically developing children's working memory. For some time, investigators have left room for the possibility that differences in the sophistication of children's retrieval strategies may contribute to differences in working memory performance even when processing speed is taken into account (e.g., Kail & Park, 1994). The same could have been true in the present study.

Verbal and Nonverbal Processing Limitations

According to the nested Model 3, both speed and working memory can be subdivided. The model provided evidence that motor speed, nonlinguistic cognitive speed, and linguistic speed could be differentiated. Likewise, working memory could be further divided into nonverbal and verbal working memory. Model 4 produced a general speed factor, with nonverbal and verbal working memory again functioning as separate dimensions.

Probably the most important detail emerging from these subdivisions is the finding that nonlinguistic/nonverbal tasks functioned as separable dimensions in the two models. In one sense, this may not be surprising, as children with below-average nonverbal intelligence scores were included in the LI group. These children's performance on nonlinguistic/nonverbal processing tasks, then, might also be expected to deviate from that of the other children. However, in typically developing children and young adults, individual differences in raw scores on nonverbal intelligence tests are predicted rather well by processing speed and working memory (Fry & Hale, 1996). Given that nonverbal intelligence measures involve reasoning processes (e.g., determining which of several stimulus patterns is missing from an array) in addition to the perception, storage, and rehearsal of information, it seems that speed and working memory are more likely to be primitives than is nonverbal intelligence. The fact that some children had relatively low nonverbal intelligence scores, then, may well have been the result rather than the cause of these children's poorer nonlinguistic/nonverbal processing.

Another reason to view lower nonverbal intelligence scores as only minor factors in the separability of linguistic/verbal and nonlinguistic/nonverbal processing is our inclusion of children with age-appropriate language abilities but below age level nonverbal intelligence. Because our models were used to predict composite language test scores, the participation of these children worked to the detriment of the hypothesis that nonverbal processing would emerge as an important dimension.

Our inclusion of a sizable number of children with LI with age-appropriate nonverbal intelligence scores could have worked against finding that nonlinguistic/nonverbal processing contributed to our models. However, based on prior research, this seemed unlikely. Nonverbal factors have long been implicated in children of this type, and investigations of both processing speed (e.g., mental rotation speed; Johnston & Ellis Weismer, 1983) and working memory (e.g., visual-spatial working memory; Hoffman & Gillam, 2004) have revealed limitations on nonverbal cognitive tasks in these children. In addition, several investigations have reported slower RTs on (nonlinguistic) motor tasks by children with LI than by typically developing peers (e.g., Bishop, 1990; Hughes & Sussman, 1983), a finding that has prompted researchers to use RTs on such tasks as a covariate in studies dealing with other types of processing speed tasks (e.g., Montgomery & Leonard, 1998). Because children with LI with age-appropriate nonverbal intelligence scores represented a substantial percentage of the children participating in the present study, it is likely that these children's limitations in nonlinguistic/nonverbal processing contributed to the type of models found to be most appropriate.

The contributing role of nonlinguistic/nonverbal factors found in both Model 3 and Model 4 suggests that any comprehensive account of LI should consider the role of motor and cognitive factors that fall outside of language proper. As discussed below, the role that such factors play in the language disorder itself must be clarified through additional research. However, it seems that the list of symptoms commonly seen in LI should include weaknesses in nonlinguistic/nonverbal areas. Inclusion of such symptoms in empirical reports of LI should promote replicability across studies. If important differences in language skills are found to pattern with particular nonlinguistic/nonverbal processing abilities, it may be possible to refine current phenotypes of language disorders that could, in turn, promote the discovery of the genetic bases of these disorders.

The nonlinguistic/nonverbal processing factors that emerged from this study may also have implications for clinical assessment and treatment. For example, whether or not these factors are found to cause or exacerbate the children's language disorder, the fact that nonlinguistic/nonverbal abilities may be poor suggests that intervention should be broad-based. Whereas language treatment may be very beneficial, the children's overall developmental functioning might be better aided with a more general approach to intervention.

Processing Factors and Language Knowledge

One of the major findings of this study emerged from the latent variable regression analyses: Both nested Model 3 and Model 4 accounted for 62% of the variance in the children's composite language test scores. In both models, verbal working memory proved to be the most important dimension, though Nonlinguistic Cognitive Speed (Model 3) or General Speed, which incorporated aspects of nonlinguistic speed (Model 4), also played a significant, if less central, role. There are alternative ways to view the relationship between processing measures and composite language test scores, and these hinge on assumptions made about the degree to which language test scores can be taken to reflect language knowledge.

Responding to language tests requires attention to detail, storage and rehearsal of information, and other online processes in addition to knowledge of language. This is true for language production as well as language comprehension, because in the former the children must, for example, listen to the lexical items and syntactic frame provided by the examiner in order to complete the sentence, or listen and recall an entire sentence in order to accurately repeat it, and so on. In the extreme, processing limitations could severely depress children's performance on language tests and even mask the knowledge of language that they possess. One especially dramatic example in the literature is the well-known study conducted by Tallal et al. (1996), in which children with LI participated in treatment designed to improve their temporal processing of auditory stimuli. Following 1 month of treatment, the children's gains on language tests represented the equivalent of 2 years of growth. A reasonable conclusion, and one endorsed at least in part by Tallal et al., is that by focusing on rapidly changing acoustic signals, the treatment, in effect, reinforced the children for attending to details, and these gains in attending to details enabled the children to perform on the posttreatment language tests at levels more in line with their actual (pretreatment) language knowledge. Put in terms more consistent with the Cowan (1999) model, the children's gains in attentional control through intervention may have enabled them to take greater advantage of the information in long-term memory during language testing.

More common is the case in which relatively poor scores on language tests reflect the joint effects of the processing demands of these tests and limitations in the children's language knowledge. However, even the limited language knowledge could have been the result of a lifetime of functioning with limited processing skills. This scenario seems in keeping with the Just and Carpenter (1992) view, as applied to children in the process of acquiring language. For example, processing limitations could result in incomplete processing of words and syntactic structures that appear in the speech stream. Such incomplete processing could lead to protracted development of language because these words or structures would have to be encountered more times than usual to be adequately processed and incorporated into the children's language system. A similar argument might be made by Baddeley et al. (1998), especially with regard to word learning.

We can also imagine how limitations in working memory could result in the types of "syntactic encapsulation" described by Just and Carpenter (1992). If working memory capacity is limited, it will prove more difficult to consider (i.e., to keep active) nonsyntactic information during syntactic computations. Consider sentences to be produced such as *The girl knew that the puppies jumped over the fence*. The choice between the appropriate *the puppies jumped* and the inappropriate *the puppies jump* does not lie in the relationship between *the puppies* and the following verb, as both *jumped* and *jump* are locally grammatical. Instead, the speaker must keep in mind nonsyntactic information during the formulation of this sentence, such as the temporal relationship between the events in the two clauses. A limited working memory might result in the loss of this information, leading to errors in the choice of verb form. To the extent that the children's composite language test scores reflected performance on items or subtests that required extralinguistic information along with linguistic information, our working memory measures might be expected to account for a considerable amount of the variance. As can be seen in Tables 5 and 6, our verbal working memory measures were, in fact, especially important in the prediction of the children's composite language test scores.

Our finding that processing measures contributed to the prediction of language test scores seems to have implications for clinical assessment and intervention. It appears that practitioners should pay careful attention to the processing demands that language assessment instruments might place on children. Low scores on language tests might reflect limited language knowledge, processing limitations, or both. In terms of intervention, it would appear appropriate to introduce new language material in ways that keep processing demands to a minimum. As children become better acquainted with this material, the processing requirements associated with the children's comprehension and production of the material might be systematically increased. Note that these activities are not designed to improve processing abilities;

rather they are intended to facilitate the children's acquisition of language knowledge even if limited processing looms as a potential obstacle.

Comorbidity?

Although nested Model 3 and Model 4 accounted for much of the variance in the children's composite language test scores, approximately 38% of the variance remained unexplained. There are at least three possible reasons for this finding. First, our processing speed and working memory measures, although representative, may not have covered all of the relevant processing operations that are involved in acquiring language or even in responding to items on language tests.

Second, processing limitations at an earlier age may have led to gaps in the children's language knowledge, which, in turn, may have invited errant hypotheses about language details that were maintained throughout childhood. This possibility allows that the children's processing speed and working memory showed some of the improvement that is expected with age (e.g., Kail, 1991). However, it also requires the assumption that some of the hypotheses formed about language are anchored to particular maturational periods and are not easily altered at later ages (e.g., Locke, 1994).

One plausible example of this state of affairs might be the oft-cited optional use of finite verb forms by children with LI (e.g., Rice & Wexler, 1996), a pattern that seems to persist to some degree into the school years (Rice, Wexler, & Hershberger, 1998). Tomasello (2003) has noted that some of the productions often associated with optional use, such as *Him running* and *Her do that* could have their origins in the input, as adult utterances such as *We saw him running* and *We watched her do that* contain these same sequences. TD children quickly proceed out of the optional stage of development. However, if children are faced with working memory limitations, it is possible that the final clauses of these adult utterances are processed but their links to the preceding portion of the sentences are lost. This could lead to the hypothesis that sentences such as *He's running* (heard in simple sentences) and *Him running* are equally permissible in the language. If hypothesizing finite verb morphology as obligatory is tied to a narrow maturational period, by the time the children's working memory capacities have expanded, optional use may have become relatively fixed in their grammars.

A third and very real possibility for the unexplained variance in our latent variable regression analyses is that some portion of children's language abilities are simply unrelated to processing skills even if children are weak in both areas. If optional use of finite verb morphology cannot be traced to incomplete processing of utterances in the input, this type of problem might be one such example.

It should be noted that even in such cases of comorbidity, processing limitations may play a role in children's day-to-day language functioning. For example, Leonard et al. (2002) found evidence, consistent with the proposals of Rice and Wexler (1996), that children with LI often alternate between appropriate use of finite verb morphemes (e.g., *The mouse is eating the cheese*) and the use of nonfinite clauses (e.g., *The mouse eating the cheese*). However, Leonard et al. also found that the degree to which the children "selected" the nonfinite option was related to the processing demands of the speaking task. Therefore, even if children's treatment of finite verb morphemes as optional has a source quite unrelated to speed or working memory, the degree to which they revert to the less mature form might not be free of the influence of processing limitations.

This last observation would seem to have clinical application. The processing demands of the assessment or intervention activity may have a bearing on children's comprehension or production performance even if the particular area of weakness is unlikely to have been caused by processing limitations in the first place. For example, during the assessment of a child's use of auxiliary *are* in a sentence such as *The boys are flying a kite,* the child might have less success with *are* if the preceding item were, say, *The girl fell down* than if it were *The Grinch is reading a book*. In the latter case, the syntactic frame needed for *The boys are flying a kite* might be more readily retrieved because of its use in the preceding item (*The Grinch is reading a book*), which could reduce processing demands and thus increase the likelihood of the child producing a version of the sentence that includes the auxiliary *are*.

Summary

Confirmatory factor analyses were used to compare alternative models designed to examine the dimensionality of speed and working memory measures obtained from 14-year-old children with and without LI. The models meeting our evaluation criteria treated speed and working memory as separable factors. Furthermore, nonlinguistic/nonverbal as well as linguistic/verbal processing factors emerged from these analyses. Latent variable regression analyses showed that each of the appropriate models accounted for 62% of the variance in the children's concurrent composite language test scores. These findings do not permit definitive conclusions, but certainly suggest that processing limitations can exacerbate children's language difficulties and, possibly, serve as one of its chief causes.

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Appendix A. Description of the 204 participants in the study, divided according to language (L)–nonverbal intelligence (NVI) profile.

	Profile			
	Typical L Typical NVI	**Low L Typical NVI**	**Low L Low NVI**	**Typical L Low NVI**
N	116	51	27	10
Sex				
Male	64	36	11	5
Female	52	15	16	5
Race				
White	104	44	21	9
Asian	2	0	0	1
Black	7	7	6	0
Hispanic	3	0	0	0
Mother's education (mean, in years)	13.7 (2.2)	13.1 (1.7)	12.5 (1.5)	13.4 (1.6)
CELF–3 Con & Dir (SS)	8.8 (2.7)	5.2 (2.1)	5.1 (2.2)	7.4 (1.7)
CELF–3 Sent Rep (SS)	8.2 (2.3)	4.6 (1.6)	4.6 (1.6)	6.8 (2.2)
CREVT (SS)	93.0 (11.0)	83.0 (8.5)	81.4 (6.0)	93.5 (6.5)
PPVT–R (SS)	97.7 (13.3)	84.3 (9.9)	78.4 (10.5)	83.2 (7.3)
WISC–III Perf (SS)	101.6 (9.7)	97.9 (10.3)	75.8 (5.8)	80.0 (3.7)
QRI–3 Oral (*z* score)	−0.14 (0.9)	−1.00 (0.57)	−1.10 (0.51)	−0.67 (0.67)
Lang test composite (*z* score)	−0.21 (0.74)	−1.53 (0.36)	−1.77 (0.66)	−0.78 (0.42)

Note. Values in parentheses are standard deviations. SS = standard score; CELF–3 Con & Dir = Clinical Evaluation of Language Fundamentals—Third Edition Concepts and Directions subtest; Sent Rep = Recalling Sentences subtest; CREVT = Comprehensive Receptive and Expressive Vocabulary Test; PPVT–R = Peabody Picture Vocabulary Test—Revised; WISC–III Perf = Wechsler Intelligence Scale for Children—Third Edition Performance scale; QRI = Qualitative Reading Inventory—3.

Appendix B. Description of response time and working memory tasks.

Task type	Description	Example stimuli	Measurement
Nonlinguistic speed			
Motor			
Tapping	Tap one or two keys as quickly as possible for 5s	Beginning of trial signaled by "Start" and tone; end of trial signaled by "Stop" and tone	ms per tap
Strike to signal	Strike a key in response to "***"	Trial signaled by "Ready," followed by "***" in 1, 2, or 5s	ms from onset of "***" to keypress
Cognitive			
Visual search	Strike one key if target is present, another if absent	Array of letter-like figures	ms from onset of array to keypress
Mental rotation	Strike one key if second figure matches target, another if mirror image	Pair of letter-like figures; figure on right of screen oriented 0°, 60°, or 120° from vertical	ms from onset of stimulus pair to keypress
Picture matching	Strike one key if two pictures match on criterion, another if not	Black-on-white drawings of animals, furniture, vehicles	ms from stimulus completion to keypress
Linguistic speed			
Truth value	Strike one key if picture matches sentence heard, another if not	Black-on-white drawings paired with sentences, e.g. *The man is washing the baby. The baby is being fed by the girl. The boy and the girl are drying the baby.*	ms from onset of auditory stimulus (sentence) to keypress
Grammaticality	Strike one key if sentence is correct, another if incorrect	**I think my new kitten are really cute./ I think our dog Sam is sleepy today.* *Yesterday I put my sister crib in the/ Yesterday we put the boat in the lake.* *You should give the truck the man./ You should put the dishes in the sink.*	Incorrect sentence: ms from onset of anomalous material to keypress; correct sentence: ms from onset of final word to keypress
Judge rhymes	Strike one key if stimuli rhyme, another if not	Black-on-white drawing of a pan followed by drawing of a can	ms from completion of second stimulus to keypress
Judge initial consonants	Strike one key if stimuli start with same sound, another if not	Black-on-white drawing of a pen followed by spoken word "pie"	ms from completion of second stimulus to keypress
Verbal WM			
Auditory WM	Repeat object labels in order, then repeat digits in order	List of digits and words presented via audio (e.g. "dog, 1, shoe, 8, 2, apple")	Standard scores
Nonword rep	Repeat nonsense words	Nonsense syllables one to four syllables in length (e.g. /tævatʃinaɪg/)	% of phonemes correctly repeated
Comp lang proc	Respond to semantic accuracy of sets of sentences (1–6) and recall last word of each sentence	Respond to semantic accuracy of "Sugar is sweet" and later recall the word *sweet*	No. of words correctly recalled
Gramm span	Respond to grammatical accuracy of sets of sentences (2–6) and recall last word of each sentence	Respond to grammatical accuracy of "Last summer my brother play baseball" and later recall *baseball*	No. of words correctly recalled
Nonverbal WM			
Spatial WM	Identify the one complex shape of three that is different and later recall the location of this shape	Identify the odd-one-out in six sets of three complex shapes presented on a computer screen and then recall the location of each	No. of locations correctly recalled

Note. Auditory WM = auditory working memory; Nonword rep = nonword repetition; Comp lang proc = competing language processing; Gramm span = grammaticality judgment span; Spatial WM = spatial working memory.