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Working Memory, Short-Term Memory, and Speech Rate as Predictors of Children's Reading Performance at Different Ages

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This study explored the contribution of 2 working memory (WM) systems (the phonological loop and the central executive) to reading performance in younger (9-year-old) and older (14-year-old) children. The results showed that (a) significant age-related differences in verbal and visual-spatial WM performance were maintained when articulation speed and short-term memory (the phonological system) were partialed from the analysis and (b) WM predicted age-related differences in word recognition and comprehension performance independent of the contribution of a short-term memory and articulatory rate. The results were interpreted as support for the notion that both the phonological and the executive systems are important predictors of age-related changes in reading but that these processes operate independent of each other in predicting fluent reading. Several implications of the results are discussed.

Age-related differences in children's reading performance are attributed to working memory (WM; e.g., Siegel, 1994; Swanson, 1996) or short-term memory (STM; e.g., Rapala & Brady, 1990; Roodenrys, Hulme, & Brown, 1993). WM is referred to as a processing resource of limited capacity, involved in the preservation of information while simultaneously processing the same or other information (e.g., Baddeley, 1986; Baddeley & Logie, 1999; Engle, Kane, & Tuholski, 1999; Just & Carpenter, 1992). STM is typically involved in situations in which small amounts of material are held passively (i.e., minimal resources from long-term memory [LTM] are activated to interpret the task, e.g., digits or word span tasks) and then reproduced in a sequential or untransformed fashion. That is, participants are asked to reproduce the sequence of items in the order they were presented (e.g., Daneman & Carpenter, 1980, 1983; Dempster, 1985; Klapp, Marshburn, & Lester, 1983; also see Gathercole, 1998, for a comprehensive review of the developmental literature on WM and STM).[1] Although age-related changes in WM and STM may be related to performance on reading measures, there is no consensus about which system (WM or STM) is more important in predicting age-related changes in reading, a central issue addressed in this study.

One model currently used to capture proficiency in memory as it applies to reading (as well as other domains) and age-related performance is Baddeley's (1986, 1996) multi-component model. Baddeley (1986, 1992) described WM as a limited-capacity central executive system that interacts with a set of two passive store systems used for temporary storage of different classes of information: the speech-based phonological loop and the visual sketch pad. The phonological loop is responsible for the temporary storage of verbal information; items are held within a phonological store of limited duration, and the items are maintained within the store through the process of articulation. The visual sketch pad is responsible for the storage of visual-spatial information over brief periods and plays a key role in the generation and manipulation of mental images. Both storage systems are in direct contact with the central executive system. The central executive system is considered to be primarily responsible for the coordinating activity within the cognitive system but also devotes some of its resources to increasing the amount of information that can be held in the two subsystems (Baddeley & Logie, 1999).

The majority of studies that have compared older and younger readers assume that STM measures capture a subset of WM performance, the utilization or operation of the phonological loop (see Gathercole, 1998; Gathercole & Baddeley, 1993, for a com-

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[1] Everyday examples of WM tasks would thus include holding a person's address in mind while listening to instructions about how to get there or perhaps listening to the sequence of events in a story while trying to understand what the story means. Everyday examples of STM tasks might include recalling a series of digits in order, such as a telephone number, immediately after their presentation. Although there is controversy concerning the nature of STM and WM tasks (see Engle, Tuholski, et al., 1999, for a review), there is some agreement that a transformation or inference is required on WM tasks (e.g., Baddeley & Logie, 1999). For the sake of parsimony, the present study views WM tasks as those that require some inference, transformation, and executive processing, whereas STM tasks require the storage of information with minimal ongoing processing requirements that vary from initial encoding (Daneman, 1987). Thus, tasks in the present study were selected on the degree to which some transformation of information would be required prior to output.

prehensive review). Some authors have even suggested that the phonological loop may be referred to as STM (e.g., Baddeley, 1986; Bisiacchi, Cipolotti, & Denes, 1989; Brown & Hulme, 1992; Dempster, 1985), because it involves two major components discussed in the STM literature: a speech-based phonological input store and a rehearsal process (see Baddeley, 1986, for a review). Others have argued, however, that STM and WM are distinct operations (e.g., Cantor, Engle, & Hamilton, 1991; Cowan, 1995; Daneman & Carpenter, 1980; Engle, Tuholski, Laughlin, & Conway, 1999; Swanson, 1996).[2] Regardless of whether STM tasks are synonymous with the phonological loop and therefore a subset of WM, research to date indicates that younger children appear to rehearse less and perform more poorly on tasks requiring the short-term retention of order information than do older children (e.g., Ornstein, Naus, & Liberty, 1975), suggesting inefficient utilization of the phonological rehearsal process (cf. Henry & Millar, 1993). Because younger children have smaller digit spans than do older children, it is possible they have basic inefficiencies in the storage of phonological input that influence higher level processing, such as reading comprehension. Previous research has shown that both children and adults use phonological processing during word recognition and reading comprehension (e.g., Coltheart & Laxon, 1990; Coltheart, Laxon, Rickard, & Elton, 1988; Herdman & LeFevre, 1992). Developmental differences in the phonological loop therefore might be expected to influence some aspects of word recognition (i.e., learning new words; Baddeley, Gathercole, & Papagno, 1998) but also the comprehension of prose, particularly when word order is crucial to meaning (e.g., Crain, Shankweiler, Macaruso, & Bar-Shalom, 1990).

Given that the phonological loop is partly controlled by the central executive system (i.e., the executive system shares some variance with the phonological loop), the development of reading may also be directly related to the controlling functions of the central executive system itself (Baddeley, 1992; Gathercole & Baddeley, 1993). The present study explores the possibility that executive processing plays a key role in mediating age-related performance in reading. We consider two competing models as an explanation of the role of the executive system in age-related reading performance in children: One focuses on processing efficiency at a phonological level, and the other focuses on constraints in the storage aspect of WM at a general processing level. What is at issue is not whether age-related differences in reading performance are related to the phonological system (see Gathercole, 1998, for a review) but whether age-related differences in reading can also be attributed to age-related changes in executive processing over and above the well-attested contribution of phonological processing to reading.

One model tested here is that the age-related influence of WM on children's reading is primarily moderated by processing efficiency at the phonological level. Several researchers attribute children's increases in WM span and reading to the phonological system (e.g., Perfetti, 1985; Rapala & Brady, 1990; Siegel, 1994; see Gathercole, 1998, for a review). One of the possible reasons WM span increases as a function of age is because older children can articulate items more rapidly at recall than can younger children. That is, increases in articulation rates up to the late childhood years are assumed to enhance the effectiveness of subvocal rehearsal processes and hence reduce the decay of memory items in the phonological store prior to output (e.g., Henry & Millar, 1993; Hulme, Thomson, Muir, & Lawrence, 1984).

Further, several studies also suggest that the phonological system, through the phonological loop (phonological store; subvocal rehearsal), influences the reader's verbatim memory capacity, which in turn supports comprehension (e.g., Perfetti, 1985). For example, McCutchen, Bell, France, and Perfetti's (1991) model of reading suggested that phonological codes are made available during word recognition and used to retain information in WM. Automatic activation of phonological codes is assumed to increase the likelihood that those codes are available in WM, which in turn frees resources for other reading processes (e.g., comprehension). These assumptions are consistent with a number of bottom-up models of reading that view the primary task of executive processing as one of relaying the results of lower level linguistic analyses upward through the language system (e.g., Shankweiler & Crain, 1986). Phonologically analyzed information at the word level is then transferred to WM storage, which in turn is then transferred (thus freeing storage for the next chunk of phonological information) upward through the processing system to promote on-line extraction of meaning.

There are clear expectations in the aforementioned model: Age-related changes in children's reading are related to the phonological system. Comprehension proficiency follows automatically from improvements in word skills, and therefore correlations between WM and reading comprehension should be significantly weakened if measures reflective of the phonological system are partialed from the analysis. This is, if age-related differences in reading performance (whether at the word recognition or comprehension level) and WM are moderated by the phonological system, then the relationship between reading and WM should be diminished when measures of the phonological system (e.g., articulatory speed) are partialed from the analysis. Unfortunately, the majority of studies that have tested this model have primarily relied on young children (those below age 8) or less skilled readers. These studies suggest that reading comprehension is compromised because inefficient phonological analysis creates a bottleneck that constricts information flow to higher levels of processing (e.g., Crain et al., 1990). However, it is necessary to test whether such a model can be generalized to children who are fluent readers. Thus, as an extension of this model we asked, "Does the WM span of children who are relatively fluent in word recognition skills rely on a phonological system, and does the phonological system influence high-order cognitive activities, such as executive processing and reading comprehension?"

[2] Clearly, both STM and WM tasks invoke controlled processes such as rehearsal. However, controlled processing on WM tasks emerges in the context of high demands on attention (e.g., maintaining a memory trace in the face of interference) and the drawing of resources from the executive system (see Engle, Kane, et al., 1999, pp. 311–312 for a discussion). Instructions in controlled processing emphasize maintaining information in the face of interference. Interference reflects competing memory traces that draw away from the targeted memory trace. In contrast, controlled processing on STM tasks attempts to maintain memory traces above some critical threshold. This maintenance does not directly draw resources from the central executive system. Instructions in controlled processing may emphasize perceptual grouping or chunking skills, skills at phonological coding, and rehearsal speed (see Engle, Kane, et al., 1999, for a review).

In contrast to the above model, the second model views executive processes as providing resources to lower order (phonological system) skills as well as monitoring a general system independent of those skills (e.g., Baddeley, 1986, 1992; Baddeley & Logie, 1999). This model assumes there is variance unique to particular systems of WM (executive processing, phonological coding) as well as some shared variance with these systems (see Swanson & Alexander, 1997, for further discussion). Thus, in the context of memory development, the model suggests that both a general (executive) and specific (phonological) system contribute significant variance to age-related differences in reading (cf. Gathercole, 1998; Gathercole & Baddeley, 1993; Swanson, 1999).

Conflicting findings exist as to whether the correlations between WM tasks and reading measures are primarily mediated by domain-specific processes or a general system (see Engle, 1996; Shah & Miyake, 1996, for a review). This lack of clarity makes it difficult to determine whether the mechanisms that mediate the link between WM and reading in children across age groups reflect the development of independent systems (such as verbal and visual-spatial systems as reflected in Baddeley's, 1986, model) or a common storage system. For example, Daneman and Tardif (1987) suggested that individual differences in WM are domain specific and not based on a common system. The primary evidence for their conclusion is that measures of verbal WM, not visual-spatial WM, are significant predictors of reading performance (see Engle, Cantor, & Carullo, 1992, for a review). Daneman and Carpenter (1980) also argued that the overall executive capacity of WM does not differ across individuals. Individuals differ, however, in the storage component of WM as a consequence of how much attention their reading processes require (see Engle, 1996, for a comprehensive review).

In contrast, Turner and Engle (1989) suggested that "working-memory may be a unitary individual characteristic, independent of the nature of the task in which the individual makes use of it" (p. 150). In support of a general capacity hypothesis, Engle and colleagues (e.g., Cantor et al., 1991; Engle et al., 1992) found that visual-spatial tasks correlated with reading scores as highly as did verbal WM tasks. Their findings suggest that WM capacity is not dependent on the particular strategy used to accomplish the task at hand, suggesting that visual-spatial and verbal WM measures tap the same underlying system.

In summary, the purpose of this study was to assess the contribution of executive processing to age-related changes in children's reading performance. We consider two possibilities: (a) the relationship between WM and reading across age is primarily mediated by the phonological system or (b) age-related changes in executive processing operate independent of the phonological system and therefore contribute unique variance to reading beyond the phonological system. Measures of the executive system were modeled after Daneman and Carpenter's (1980) WM tasks; the tasks demand the coordination of both processing and storage. Measures of the phonological system, however, include those related to articulation speed and STM. We assumed that although the WM tasks involve executive processing and therefore have a domain general function, they also require the coordination of visual-spatial or verbal information. This assumption is consistent with Baddeley's (1986, 1996) model, which views the central executive as coordinating information from the two subsystems (i.e., phonological and visual-spatial sketch pad). We assumed that age-related differences in STM and articulation speed are derivative or share a substrate of processes related to the phonological system (Baddeley, Lewis, & Vallar, 1984; Brown & Hulme, 1992). This is because a significant linear relationship between articulation rate and verbal memory span has been found in many experimental situations (e.g., Brown & Hulme, 1992), whether the differences in articulation rate are due to developmental increases in children (Hulme et al., 1984) or reading ability (McDougall, Hulme, Ellis, & Monk, 1994) or are due to the type of words (i.e., pseudowords and familiar words; Hulme, Maughan, & Brown, 1991). Further, articulation rates have been interpreted as a measure of how quickly words can be encoded and rehearsed within the phonological loop (McDougall et al., 1994). In short, the model assumes that participants who are fast articulators can maintain more items than can participants who are slow articulators.

The approach used in this study, as in others (e.g., Cohen & Heath, 1990; Johnston & Anderson, 1998; Turner & Engle, 1989), to assess whether a particular memory system plays the major role in mediating age-related differences in reading performance was to remove statistically its influence from the analysis. In this study, the influence of the phonological system (i.e., articulation speed) was partialed from the correlation between reading and WM. We reasoned that if WM and reading are primarily mediated by a phonological system, then the relationship between WM processing and reading performance should be minimized (i.e., correlation coefficients are nonsignificant) when measures related to the phonological system are partialed from the analysis. However, if age-related differences in executive processing also mediate the relationship between WM and reading, then the correlations between these two variables will remain significant when articulation is partialed from the analysis. We also assumed that because measures of articulation rate and STM draw resources from the phonological system, significant differences between age groups on STM measures would be eliminated when articulation speed was partialed from the analysis.

Two predictions are tested in this study. First, age-related changes in WM are mediated by an executive system that operates independent of the phonological system. Thus, age-related changes in WM will be sustained when measures of phonological processing (i.e., articulation speed) are partialed from the analysis. However, on the assumption that STM and articulation speed draw on the same processes, age-related changes in STM were expected to be substantially reduced when articulation speed was partialed from the analysis. Consistent with several studies (e.g., Conway & Engle, 1994; Turner & Engle, 1989), executive processing is defined in this study as the contribution of both verbal and visual WM tasks to the same reading task.

To this end, 9-year-old children's performance was compared with 14-year-old children's on measures of WM, STM, and articulation rate. This age group was selected to generalize to other studies that have included this broad sample to assess the influence of articulation speed on memory span (Cohen & Heath, 1990). We also selected this age group because we wanted to compare age-related changes in memory in children who are fluent readers. Previous studies linking reading, memory span, and articulation speed have primarily focused on beginning readers. These studies show weak to moderate correlations between memory span and articulation rates in children 7 years of age and younger (see Gathercole, 1998, pp. 6–7 for a review). This occurs because younger children's time-based strategies (i.e., rehearsal) are unstable (Gathercole, 1998). Thus, we selected an age level at which memory strategies are more stable to better assess the relationship between WM, STM, and articulation speed. Fourteen-year-olds were compared with 9-year-olds to determine whether the developmental improvement in memory span and reading was due to increased articulation speed.

Second, age-related changes in reading comprehension are mediated by both the phonological system and the executive system. We predicted that correlations between WM and comprehension would remain significant after we statistically removed the influence of articulation speed from the analysis, suggesting that the influence of WM operations on reading comprehension is related to processes independent of the phonological system. On the other hand, the correlations between STM and reading comprehension were expected to be nonsignificant after we partialed the influence of phonological processing measures (articulation speed) from the analysis. This is because the phonological system is assumed to mediate the relationship between reading comprehension and STM. We also consider the influence of STM and WM on word recognition. Previous studies (e.g., Swanson & Berninger, 1995) have suggested that STM is more important than WM in predicting word recognition, but this finding has not been considered across the age ranges found in this sample. On the basis of research with fluent readers (e.g., Engle et al., 1992; Herdman & LeFevre, 1992), however, we expected that both STM and WM measures will contribute significant variance to word recognition.

Method

Participants

Fifty students from the fourth grade and 50 students from the ninth grade were selected from a large Southern California public school district and served as participants in this study. Chronological age of the younger children was 9.58 (SD = 0.83), and chronological age of the older children was 14.89 (SD = 0.68). All children were initially selected on the basis of average scores on the California Achievement Test (in the range of the 45th to 75th percentile) in reading and mathematics. All participants were native speakers of English. Participants were also selected to represent the ethnic and gender breakdown of the school district, approximately 52% White, 29% Hispanic, 8% Black, and 8% Asian. In each age group, 29 participants were male and 21 were female.

Working Memory

Two verbal and two visual-spatial WM tasks were administered. The measures were selected from a normed-referenced test (Swanson, 1995), standardized across a broad age range. Validity and reliability of the measures with previous samples of children are reported in Swanson (1992, 1995, 1996). The WM tasks correlate significantly with Daneman and Carpenter's (1980, 1983) reading span and listening span task (seminal measure of WM) across several samples (correlations range from .50 to .86), and confirmatory analysis supports a factor structure consistent with Daneman and Carpenter's (1980) WM model (Swanson, 1992, 1995; Swanson, Mink, & Bocian, 1999). The measures are standardized, and coefficient alphas for the total sample (N = 1,630) with age partialed out vary from .80 to .92.

Verbal WM Measures

Sentence span. The sentence span task adapted by Swanson (1992) from Daneman and Carpenter (1980) was used. Here, children read a number of sentences presented in sets of two to five and are asked to recall the last word of each sentence in the set. Prior to target recall, children are also asked a simple comprehension question regarding material presented in one of the sentences (e.g., "What was canceled?" after listening to the sentence, "Both of the games were canceled because of trouble"). The location of the answer to the process question is varied between sentences with the restriction of never appearing in the last sentence of the set. Sentence span is defined as the total number of target words recalled when the process question is answered correctly. The reading level of the sentences is approximately 3.8 grade equivalent, and the KR_{20} reliability of the Swanson adaptation is greater than .90 (Swanson, 1992).

Auditory digit sequencing. This is a standardized task (Swanson, 1995) designed to measure numerical information presented in short sentences. For example, the participant is asked to pretend to be a taxi driver and told, "Suppose somebody wanted to have you drive them to the hospital located at 2–9 Maple Street." The process question ("Can you tell me the name of the street?") is followed by a recall question: "Tell me the numbers of the address of the hospital in order." The participant's score is the last set of numbers recalled correctly in sequential order whereby the process question (street name) was correctly answered. The number of digits to be recalled ranges from 2 to 14, and the names of the streets are common tree varieties.

Visual-Spatial WM Measures

Visual matrix. This standardized task (Swanson, 1995) requires the participant to remember visual sequences of dots within a matrix. The matrices are presented individually on cards, ranging from 4 squares and 2 dots to 45 squares and 12 dots. After the participant studies a card for 5 s, the card is removed and the participant is asked the process question: "Are there any dots in the first column?" After providing the answer, the participant is required to reproduce the pattern of dots in the correct boxes of a blank matrix. The number of matrices recalled correctly is the dependent measure, ranging from 0 to 11 matrices.

Mapping and directions. This standardized task (Swanson, 1992) requires the participant to remember sequences of directions on an unlabeled map. The administrator presents a street map composed of lines (streets) and dots (stop lights). After a 10-s study period, the participant is asked a process question: "Were there any dots in the first street?" The participant is then required to draw on another map the lines and dots he or she saw on the stimulus. The number of dots recalled (4–19) is the range of difficulty, and the number of maps correctly reproduced is the dependent variable.

Short-Term Memory

Four measures of STM were used. The digit span Wechsler Intelligence Scale for Children—III (WISC–III; WISC–III Manual, 1991) and word span tasks were used to measure verbal STM. Administration of the digit span task from the WISC–III followed the standardized instructions for the forward digit presentation. The word span task was presented in the same manner. The word span task was previously used by Swanson, Ashbaker, and Lee (1996). The word stimuli are one-syllable, high frequency words. In both tasks, participants were read increasing numbers of digits or words, which were recalled in exact order. The verbal tasks matched those used by Daneman and Carpenter (1980) and Turner and Engle (1989) to assess verbal STM.

Two visual STM tasks were presented. The simple sorting task consisted of reproducing a card array of abstract shapes. The stimulus cards included shapes taken from the Nonverbal subtest of the Cognitive Processing Test (S–CPT; Swanson, 1995). Sets of abstract shapes were shown in an array for 2 s. The cards were then gathered and shuffled by the experimenter. The participant was then given the cards and asked to reproduce the array correctly. The array involved presentation of abstract shapes of increasing difficulty (range is 2 to 10 shapes). For the location sorting task, two shapes (* and −) appeared on various locations of 3 × 5 cards. The cards were taken from the Spatial Organization subtest of the S–CPT. Stimulus cards were again presented in sets of 2 to 10. The procedures of presentation were similar to the simple sorting task. However, for this task, the stimulus cards had to be arranged by the correct location of the two shapes. Thus, the correct response included placing the cards in the correct array and position.

Articulation Speed

Articulation speed was measured by adapting the task and procedures reported in McDougall et al. (1994). Articulation speed was estimated by measuring the amount of time taken to read lists of words taken from the corpus compiled by Carroll, Davies, and Richman (1971). All participants were asked to read as quickly as possible each list of short (e.g., leaf, doll, pig), medium (e.g., pencil, sunset, candle), and long (e.g., elephant, basketball, umbrella) words while timed with a stopwatch (the list of words can be obtained from the authors). All participants were presented the same three word triads (each triad included eight words), which included all words for a given word length. Children were asked to repeat each triad 10 times as quickly as possible. The triads for each word length were presented in one block of trials. All children accurately identified the words for each word length. Articulation speed was defined as the average time taken to read all the word lists. The tape-recorded times obtained were transformed into an articulation rate in words per second for each word length.

Reliability

The reliability of the memory and speed measures were computed for this sample. Because the subsequent analysis used composite scores, the reliability of the WM measures and STM measures was calculated. Reliability measures on the total sample were calculated. Because reliability is inflated by when age is left to covary, the subsequent analysis partialed out the influence of age. Coefficient alphas, with the influence of age partialed from the analysis, were .81, .62, and .76 for the total WM (all four WM tasks), verbal WM (sentence span and auditory sequencing tasks), and visual-spatial WM composite score (visual matrix and mapping and direction tasks), respectively. Coefficient alphas, with the influence of age partialed from the analysis, were .79, .76, and .80 for the total STM (all four STM tasks), verbal STM (digit span and word span tasks), and visual-spatial STM composite score (simple sorting and location sorting tasks), respectively. Because children responded to all items on the articulation task, reliability estimates were also calculated for the articulation speed task. The reliability (Cronbach's alpha) for the articulation speed task was .77.

Cronbach's alpha was also used to calculate reliability for each composite score and each memory measure within each age group. For the older children, coefficient alphas were .81, .53, and .80 for the total WM, verbal WM, and visual-spatial WM composite score, respectively. Coefficient alphas were .86, .76, and .85 for the total STM, verbal STM, and visual-spatial STM composite score, respectively. For the individual tests, reliability estimates were .72 for sentence span, .89 for auditory digit sequencing, .92 for visual matrix, and .56 for the mapping and directions task. Reliability estimates were .52 for digit span, .89 for word span, .62 for simple sorting, and .67 for the location sorting task.

For the younger children, coefficient alphas were .73, .51, and .58 for the total WM, verbal WM, and visual-spatial WM composite score, respectively. Coefficient alphas were .86, .36, and .55 for the total STM, verbal STM, and visual-spatial STM composite score, respectively. Reliability estimates for individual tests were .46 for sentence span, .56 for auditory digit sequencing, .47 for visual matrix, and .50 for the mapping and directions task. Reliability estimates were .85 for digit span, .47 for word span, .86 for simple sorting, and .65 for the location sorting task. The reliability for the articulation task was .59 for younger participants and .81 for older participants.

As expected, composite scores yielded higher reliability coefficients than did single measures (increases in number of items increase the size of the coefficients), and therefore these scores were the primary dependent measures in the analysis. Further, these reliability coefficients are within an acceptable range for basic research (see Nunnally & Bernstein, 1994, pp. 264–265 for a discussion).

Standardized Reading Measures

Word recognition was measured by the Wide Range Achievement Test, Reading subtest score (WRAT–3; Jastak & Wilkinson, 1993). Reading comprehension ability was measured on the Woodcock Johnson Reading Mastery Test, Revised-Reading Comprehension subtest (WJRMT–R; Woodcock, 1987).

Procedure

The children participated in two experimental sessions. The reading tests (WJRMT–R Reading Comprehension, WRAT–3) were administered in the first session. Articulation speed, WM, and STM span tasks were administered in counterbalanced order in the second session. The span tasks were presented orally, with half the participants receiving the STM span tasks first and half receiving the WM span tasks first. Within each span task type, half of the children received the verbal or the visual tasks first. The word lists used to measure articulation speed were presented after the memory tasks. All testing was conducted by one experimenter. The experimenter (Margaret Howell) is a trained psychologist and has 10 years of experience administering individual standardized tests. Scoring was done by us and a graduate student unfamiliar with the students.

Results

Means and standard deviations of memory measures, word recognition, reading comprehension, and articulation speed are presented in Table 1. Also shown are the univariate analyses of variance (ANOVAs) with a Bonferroni correction for Type I error (alpha level of .05/11 = .005). To test linear combinations, the variables were organized conceptually for the subsequent analysis. The multivariate analysis of variance (MANOVA) showed that significant differences emerged between age groups on the four STM tasks, $F(4, 95) = 10.16$, $p < .001$, and four WM measures, $F(4, 95) = 55.01$, $p < .001$. The general pattern for the linear composite score across WM and STM was that the 14-year-old children significantly outperformed the 9-year-old children. When isolated tasks were considered, however, an exception to this pattern occurred on the simple sorting and the location sorting tasks (the 14-year-old children were equal to the 9-year-old children). An ANOVA of articulation speed performance showed that the 14-year-old group was significantly faster than the 9-year-old group.

WM Versus STM Performance

This analysis assessed whether age-related differences on the WM tasks were related to a general or a specific system. We predicted that if age-related differences in WM performance are related to the executive system, then significant differences between age-difference groups would occur on both verbal and visual-spatial WM measures but not on STM measures, when

Table 1
Means and Standard Deviations for Younger and Older Children

Variable	Younger Children *M*	Younger Children *SD*	Older Children *M*	Older Children *SD*	$F(1, 98)$ ratio	R^2
Reading recognition[a]	103.72	4.48	106.96	5.50		
Raw scores	50.24	2.28	76.66	4.13	1,389.97***	.93
Reading comprehension[b]	109.76	4.66	110.68	4.33		
Raw scores	56.14	3.98	79.58	3.11	1,075.00***	.91
Articulation						
Articulation speed	6.28	1.73	4.25	0.91	53.57***	.35
STM						
Digit span	3.60	0.60	4.70	1.29	29.50***	.23
Word span	3.44	0.57	4.58	1.19	36.81***	.27
Simple sorting	5.22	0.84	5.48	0.99	1.99	.02
Location sorting	5.00	0.60	5.36	0.96	5.00	.05
WM						
Sentence span	1.97	0.41	3.83	0.81	206.07***	.67
Auditory digit	3.82	1.10	4.54	1.50	7.48*	.07
Mapping	2.38	0.72	3.14	1.12	16.12***	.14
Matrix	4.74	1.06	5.66	1.45	13.06***	.12

Note. STM = short-term memory; WM = working memory.
[a] Wide Range Achievement Test, Reading subtest score. [b] Woodcock Johnson Reading Mastery Test, Revised-Reading Comprehension subtest score.
* $p < .05$. *** $p < .001$.

measures of the phonological system were partialed from the analysis. To investigate these possibilities, a 2 (9-year-olds vs. 14-year-olds) × 2 (memory span: STM, WM) × 2 (modality: visual, verbal) analysis of covariance (ANCOVA) with repeated measures on the last two factors was conducted on composite span scores. Composite scores were created by converting span scores to *z* scores (based on the total sample) for each verbal and visual-spatial task as a function of the type of memory task (WM vs. STM). Four composite scores included the mean *z* scores of tasks related to visual STM (simple and location sorting; $r = .63$, $p < .001$), verbal STM (digit span and word span; $r = .75$, $p < .001$), visual WM (mapping and visual matrix; $r = .66$, $p < .001$), and verbal WM (sentence span and auditory digit sequencing; $r = .47$, $p < .001$). The covariate was articulation speed, $F(1, 96) = 0.12$, $p > .05$. No significant two- or three-way interactions with the factor articulation speed reached significance (all *p*s > .05), satisfying an assumption of ANCOVA (e.g., equivalent slopes between age groups).

The ANCOVA indicated that the main effect for age group was significant, $F(1, 96) = 24.91$, $p < .0001$, $MSE = 1.49$, indicating that 14-year-old children outperformed 9-year-old children. A significant effect emerged for Age Group × Modality Interaction, $F(1, 96) = 10.89$, $p < .001$, $MSE = 1.30$. The least square mean *z* scores for 9-year-old and 14-year-old children were −0.35 versus 0.32 for the visual STM composite score, −0.92 versus 1.13 for the verbal STM composite score, −0.63 versus 0.94 for the visual WM composite score, and −0.98 versus 1.27 for the verbal WM composite score, respectively. No other significant effects emerged. A test of simple effects indicated that 14-year-old children outperformed 9-year-old children on all composite scores (all *p*s < .001), except for the visual STM composite scores, $F(1, 96) = 2.01$, $p > .05$. A Tukey test of least square means showed that relatively poorer performance emerged on verbal than on visual-spatial tasks (visual STM > visual WM > verbal STM = verbal WM) for 9-year-old children, whereas relatively poorer performance emerged on the visual STM task for 14-year-old children (verbal WM = verbal STM = visual WM > visual STM).

Because the partialing of articulation rates from the analysis did not eliminate group effects on either the WM or the STM tasks, a follow-up ANCOVA compared ability groups on WM performance (composite score that is the sum of *z* scores for WM tasks) when the influence of STM performance (composite score that is the sum of *z* scores for STM tasks) was partialed from the analysis. This was done because of the possibility that the STM composite score may better reflect the phonological system than scores related to articulation rates. The ANCOVA indicated that the main effect for age group was significant, $F(1, 96) = 20.63$, $p < .0001$, $MSE = 2.75$, indicating that 14-year-old children outperformed 9-year-old children. A significant effect emerged for the Age Group × Modality interaction, $F(1, 96) = 8.22$, $p < .01$, $MSE = .83$. The covariate, STM, was significant, $F(1, 96) = 17.39$, $p < .001$. The interaction of Group × STM did not reach reached significance, $F(1, 96) = 1.66$, $p > .05$, satisfying an assumption of ANCOVA.

The least square mean *z* scores for 9-year-old and 14-year-old children were −0.44 versus 0.36 for the visual WM composite score and −0.96 versus 0.69 for the verbal WM composite score, respectively. No other significant effects emerged. A test of simple effects indicated that 14-year-old children outperformed 9-year-old children on verbal WM, $F(1, 96) = 42.03$, $p < .001$, and visual-spatial WM composite scores, $F(1, 96) = 5.12$, $p < .05$. A Tukey test of least square means indicated that relatively poorer performance emerged on verbal than on visual-spatial tasks (visual WM > verbal WM) for 9-year-old children, whereas relatively comparable performance emerged between visual and verbal WM tasks for 14-year-old children (verbal WM = visual-spatial WM).

A final question that we addressed was whether age-related differences in verbal and visual-spatial WM reflect two separate independent systems or reflect two systems that draw on a general system. We assumed the two composite scores (verbal and visual-spatial WM) reflected shared variance (in this case variance related to a domain-general system) as well as unique variance (in this case domain-specific variance). To analyze these differences, we had to partition the variance. We used the CALIS (SAS Institute, 1990) program to create two first-order factors (the two verbal WM tasks reflect Factor 1 and the two visual-spatial WM tasks reflect Factor 2) to capture unique variance and a second high-order factor to reflect shared variance or domain-general performance among all the tasks. This forced second-order model was adequate (Bentler's comparative fit index = .98, root mean square residual = .007), and therefore factor scores were created from this model. The factor scores were compared between the two age groups with the influence of articulation speed partialed from the analysis. Factor scores were a linear composite of the optimally weighted variables based on the covariance matrix and the second-order factor model.

An ANCOVA on the factor scores indicated that age-related differences were significant for the domain-general (second-order) factor, $R^2 = .30$, $F(1, 96) = 25.61$, $p < .001$, $MSE = .60$; as well as the verbal domain-specific factor, $R^2 = .24$, $F(1, 96) = 20.00$, $p < .001$, $MSE = .28$; and the visual-spatial factor, $R^2 = .23$, $F(1, 96) = 20.32$, $p < .001$, $MSE = .38$. Thus, age-related differences in favor of 14-year-old children emerged for the domain-general (least square mean z score − LSM = .61 vs. −.43) as well as domain-specific verbal (LSM = .37 vs. −.26) and visual-spatial (LSM = .43 vs. −.30) factors.

In summary, the results show that age-related differences were pervasive across WM and STM measures. These age-related differences did not vary as a function of articulation speed. More important, age-related differences in WM performance were sustained when the influence of STM and articulation speed was partialed from the analysis.

Relations Between Reading, STM, and WM

The next analysis examined the relationship between reading and WM and reading and STM. We predicted that if executive processing from the WM system played an important role in accounting for age-related differences in reading comprehension, independent of the phonological system, then WM measures would predict reading comprehension performance after various measures of the phonological system have been partialed from the analysis. We examined this hypothesis through a series of hierarchical regression analyses in which STM, articulation speed, and WM were the independent variables and reading comprehension and word recognition were the dependent measures. Measures of word recognition were included in the analysis to determine whether the WM effects were isolated only to high-order reading tasks (comprehension). Prior to our regression analysis, the intercorrelations between WM and reading measures were examined.

The intercorrelations between STM (verbal and visual-spatial), WM (verbal and visual-spatial), articulation speed, word recognition (raw scores from the WRAT–3 Reading subtest), and comprehension (raw scores from the Comprehension subtest of the WJMT–R) performances are shown in Table 2. Because significant interactions emerged related to modality (verbal vs. visual-spatial) in the previous analysis, composite z scores as a function of modality were used in the analysis.

As shown in Table 2, an age contrast variable was also included in the intercorrelations. The 9-year-old versus 14-year-old contrast variable was coded 1 for the 14-year-old group and 0 for the 9-year-old group. We did not enter actual chronological age into the correlation, or the subsequent regression analysis, because we did not sample ages between 10.5 and 13 (Grades 5 to 8) and because the two groups had restricted age variance. Accordingly (also see Cohen & Cohen, 1983, pp. 190–198, for a rationale related to dummy coding and interpretation of partial correlations

Table 2
Intercorrelations Among Contrast Variables, Working Memory, Short-Term Memory, and Reading Measures With and Without Articulation Speed Partialed From the Analysis

Variable	1	2	3	4	5	6	7	8	9
Contrast									
1. Older vs. younger	—	.15	.44***	.32**	.54***	.93***	.95***	.04	.30**
Short-term memory									
2. Visual	.19	—	.49***	.38***	.41***	.22*	.27**	.22*	.45***
3. Verbal	.53***	.50***	—	.46***	.63***	.49***	.56***	.25*	.56***
Working memory									
4. Visual	.39***	.40***	.50***	—	.69***	.35***	.42***	.19	.50***
5. Verbal	.63***	.42***	.68***	.71***	—	.60***	.64***	.30**	.60***
Reading									
Raw scores									
6. Reading comp.	.95***	.25*	.57***	.41***	.68***	—	.94***	.39***	.45***
7. Reading recog.	.96***	.29**	.55***	.47***	.71***	.96***	—	.20*	.57***
Standard scores									
8. Reading comp.	.10	.23*	.27**	.21*	.32**	.38***	.22*	—	.52***
9. Reading recog.	.30**	.45***	.57***	.51***	.58***	.43***	.53***	.52***	—
Articulation									
10. Speed	−.59***	−.12	−.33***	−.23*	−.40***	−.58***	−.55***	−.10	−.11

Note. The left diagonal shows the intercorrelations among measures without the influence of word recognition and articulation speed partialed from the analysis. The right diagonal shows the correlations with articulation speed partialed from the analysis. Standard scores are based on age norms. comp. = comprehension; recog. = recognition.
* $p < .05$. ** $p < .01$. *** $p < .001$.

of a dummy variable), age was represented as a contrast variable. A positive coefficient for the contrast variable, when correlated with other variables, reflected an advantage for the 14-year-old participants. Also included are raw scores and standard scores (based on age) for reading comprehension and word recognition. Except for the contrast variable, all variables were transformed to z scores with a total sample mean of 0 and a standard deviation of 1.

The left diagonal in Table 2 shows the intercorrelations among measures without the influence of articulation speed partialed from the analysis. The right diagonal shows the correlations with articulation speed partialed from the analysis. There are four important results reported in Table 2.

First, articulation speed was significantly correlated with verbal STM, visual-spatial WM, and verbal WM but not visual-spatial STM, $p > .05$. Articulation speed was also significantly correlated with raw scores for reading comprehension and word recognition but not for standardized scores (scores that partial the influence of age) of reading comprehension and word recognition. The significant correlation between the span measures and articulation speed was consistent with the literature.

One could argue that the significant correlations between verbal WM and articulation speed and between visual-spatial WM and articulation speed emerged simply because both WM measures draw on a language system. We reasoned, however, that if both the verbal and visual-spatial tasks are drawing from the same language system, then the correlations between verbal WM and articulation speed should be nonsignificant (or at least substantially reduced) when visual-spatial WM was partialed from the analysis. In contrast to this argument, the correlation between verbal WM and articulation speed was significant, $r(98) = -.34$, $p < .001$, when visual WM was partialed from the analysis.

Second, the 14-year-old versus 9-year-old contrast variable was significantly correlated with verbal STM, visual-spatial WM, and verbal WM with articulation speed partialed out. Third, WM and STM measures remained significantly ($p < .01$) intercorrelated (rs ranged from .38 to .63) when articulation speed was partialed from the analysis.

Finally, the magnitude of the correlation between STM and reading and WM and reading was not reduced substantially when articulation speed was partialed from the analysis (rs range from .22 to .56 vs. .25 to .57 for nonpartialed and partialed coefficients on STM measures, respectively, and rs range from .35 to .64 vs. .41 to .71 for nonpartialed and partialed coefficients on WM measures, respectively). Further, the magnitude of the correlation between STM and standardized reading scores (scores standardized by age) and WM and standardized reading scores was not reduced substantially when articulation speed was partialed from the analysis (rs range from .23 to .57 vs. .22 to .56 for nonpartialed and partialed coefficients on STM measures, respectively, and rs range from .21 to .58 vs. .19 to .60 for nonpartialed and partialed coefficients on WM measures, respectively).

As a follow-up to the correlation analysis, we also analyzed the relationship between STM, WM, and reading within age groups. To simplify the reporting, composite scores (sum of z scores) were used for the STM and WM tasks. For the 9-year-old age group, the magnitudes of the correlation between STM and standardized word recognition and reading comprehension scores were $r(48) = .36$, $p < .01$, and $r(48) = .29$, $p < .05$, respectively. The magnitudes of the correlation between WM and standardized word recognition and reading comprehension scores were $r(48) = .45$, $p < .001$, and $r(48) = .20$, $p > .05$, respectively. For the 14-year-old age group, the magnitudes of the correlation between STM and standardized word recognition and reading comprehension scores were $r(48) = .63$, $p < .001$, and $r(48) = .30$, $p < .05$, respectively. The magnitudes of the correlation between WM and standardized word recognition and reading comprehension scores were $r(48) = .58$, $p < .001$, and $r(48) = .37$, $p < .01$, respectively. All coefficients between memory and reading within age groups were significant (ps $< .05$) with articulation speed partialed from the analysis, except for the correlation between WM and reading comprehension in the 9-year-olds, $r(48) = .20$, $p > .05$. A comparison was made between the two age groups on the magnitude of these correlations. Fisher's z_r transformation indicated that the magnitude of the correlation differed significantly between age groups for the correlation between STM and word recognition ($r = .36$ vs. $r = .63$), $z_r = 1.82$, $p < .05$. No other significant differences in the magnitude of the correlations emerged, ps $> .05$.

Predictions of Reading

These analyses assessed whether age-related differences in reading comprehension and word recognition were significantly mediated by articulation speed, STM, and WM. We examined the age-related variance in reading comprehension and word recognition before and after controlling the variance (R^2) associated with the scores of cognitive processing (e.g., speed, STM, WM). We used the difference between the estimates of age-related performance given by the change in R^2 to show the contribution of memory scores to the age-related differences in reading (see Salthouse, 1992, for a further rationale). Because this difference (increment in R^2 or R^2 change) was directly related to the degree to which age-related variance in reading was reduced when the mediator was controlled, we then have a measure of the importance of that mediator. Because age-related variance was entered last, the R^2 change represented the variance of the composite score beyond the previous effects. If age-related differences remained after the entry of the postulated variables, age-related variance was attributed to some unspecified effects.

The predictor variables of interest in this study for reducing age-related variance were related to articulation speed, STM, and WM. Criterion measures were z scores (converted from raw scores based on the total sample) from the reading comprehension and word recognition measures. Thus, several hierarchical regression analyses were conducted (a) to determine the mediator variables (e.g., articulation speed, STM) that substantially reduced age-related performance and (b) to determine which mediator variables significantly contributed to reading when the influence of other variables was partialed from the analysis. Because the order of entry is known to influence the outcome of regression analyses, several hierarchical models were tested. Further, because of the number of variables and models considered, alpha was set at .001.

For our first set of analyses, we wanted to determine the amount of variance in reading performance, which was accounted for by (a) age-related contrast alone (Model 1), (b) age-related contrast after articulation speed was partialed out (Model 2), (c) age-related contrast after STM was partialed out (Model 3), and (d) age-related contrast after WM was partialed out (Model 4). In the subsequent models (Models 5a to 5d), we also determined in Model 5 which variables related to verbal and visual-spatial STM. Verbal and visual-spatial WM contributed unique variance to reading comprehension and word recognition when the influence of other variables was partialed from the analysis.

The results of our regression analysis are presented in Table 3. The cumulative R^2 associated with the addition of variables entered into the regression equation is presented in the second column. The increment in R^2 associated with each additional variable appears in the third column. The F statistics related to the squared partial correlations appear in the fourth column. Inspection of Table 3 indicates that the total amount of variance related to the age contrast variable in predicting reading comprehension was 91% for reading comprehension and 93% for word recognition (Model 1). Of course, this high amount of variance was related to selecting a sample with large age differences. In the second analysis (Model 2), when articulation speed was entered first it accounted for 33% of the variance in reading comprehension and 31% in word recognition. For Model 3, the STM composite score contributed 23% of the variance in reading comprehension and 29% of the variance in word recognition. In contrast, Model 4 shows that WM contributed 35% of the variance in reading comprehension and 40% of the variance in word recognition.

When Models 1–4 are taken together, the largest reduction in the 9-year-old versus 14-year-old contrast variable occurred for Model 4. Specifically, the drop in variance accounted for by age was reduced from 91% (Model 1) to 37% (Model 4) following the statistical control of WM in reading comprehension, .37 = (.91 − .57)/.91. This WM composite score also reduced the age-related variance in word recognition from 93% to 40%, .93 − .55/.93. To determine whether the contributions were significantly greater for the WM processes than for the STM processes in mediating age-related variance in reading, a follow-up regression analysis was done. This follow-up tested whether those variables that had the lower R^2 (i.e., STM Model 3) varied significantly from Model 4 (i.e., WM). For example, in predicting reading comprehension, the regression analysis first removed (partialed) the main effects of STM and WM and then entered the cross-product interaction of the two variables into the equation (see Cherry & Park, 1993, p. 523; Hultsch, Hertzog, & Dixon, 1990, p. 363; for an application, also see Cohen, 1988, pp. 409–412). The interaction, partialed for the influence of main effects, is the source of interest because we determined whether STM showed differential predictive power across reading measures. Further, to determine the effect size for an interaction, it is necessary to analyze residual effects (i.e., partial out the influence of main effects; see Cohen,

Table 3
Hierarchical Regression Analysis for Reading Comprehension and Word Recognition

Predictor variable (order of entry)	Reading comprehension R^2	Increment	F	df	Word recognition R^2	Increment	F	df
Model 1								
Age	.91		1075.00***	1, 97	.93		1389.97**	1, 97
Model 2								
AS	.33		394.66***	1, 97	.31		460.57***	1, 97
Age	.92	.59	673.01***	1, 96	.93	.62	925.70***	1, 96
Model 3								
STM	.23		284.69***	1, 97	.29		593.42***	1, 97
Age	.92	.69	865.31***	1, 96	.95	.66	1368.24***	1, 96
Model 4								
WM	.35		431.87***	1, 97	.40		774.84***	1, 97
Age	.92	.57	712.39***	1, 96	.95	.55	1041.63***	1, 96
Model 5a								
AS, STM[a]	.50		31.86***	1, 96	.53		36.05***	1, 96
Verbal WM	.59	.09	121.78***	1, 95	.63	.10	214.02***	1, 95
Visual WM	.60	.01	5.40	1, 94	.63		1.92	1, 94
Age	.93	.33	416.36***	1, 93	.96	.33	735.58***	1, 93
Model 5b								
AS, WM[b]	.57		44.64***	1, 96	.60		47.51****	1, 96
Verbal STM	.60	.03	17.16***	1, 95	.63	.03	61.01***	1, 95
Visual STM	.60		3.89	1, 94	.63		4.17	1, 94
Age	.93	.33	416.36***	1, 93	.96	.33	735.87***	1, 93
Model 5c								
AS, STM	.50		31.86***	1, 96	.53		36.04***	1, 96
Visual WM	.52	.02	20.73***	1, 95	.56	.03	53.77***	1, 95
Verbal WM	.60	.08	107.05***	1, 94	.63	.07	162.17***	1, 94
Age	.93	.33	416.36***	1, 93	.96	.33	735.87***	1, 93
Model 5d								
AS, WM	.57		44.64***	1, 96	.60		47.51***	1, 96
Visual STM	.57		0.25	1, 95	.60		0.41	1, 95
Verbal STM	.60	.03	20.80***	1, 94	.63	.03	64.77***	1, 94
Age	.93	.33	416.36***	1, 93	.96	.33	735.87***	1, 93

Note. AS = articulation speed; STM = short-term memory; WM = working memory.
[a] Verbal and visual STM were entered first. [b] Verbal and visual WM were entered first.
** $p < .01$. *** $p < .001$.

1988, pp. 370–371). In this case, the STM × WM interaction did not approach significance, $F(1, 96) = 1.25, p > .05$. Thus, the R^2 values of .23 and .35 from Model 3 and Model 4 (see Table 3) were not significantly different. Because no significant differences were found for the larger R^2 models when compared with the smallest R^2, further testing was not necessary. Taken together, the above analyses provided no evidence that one process (e.g., STM, articulation speed) was more important than another (e.g., WM) in predicting reading comprehension and word recognition.

As shown in Table 3, we also evaluated in Model 5 the importance of each composite score in predicting reading comprehension and word recognition. On the assumption that articulation speed accounts for variance related to memory and reading, articulation speed was always entered first into the equation. To determine whether the memory measures contributed unique variance to reading, we assessed the relative contribution of each of the span measures (STM and WM) to reading by varying the presentation order. We also tested whether the influence of the span measures on reading emerged across domains (verbal and visual-spatial) or were isolated to a particular domain (e.g., verbal). As shown for Models 5a to 5d, articulation speed and the target measures were forced into each model variation first. The target measures, STM or WM, were alternated for entry into the regression equation.

As shown in Table 3, the regression models (5a and 5c) in which articulation speed and verbal and visual-spatial STM were entered first into the equation contributed significant variance to reading comprehension, $R^2 = .50$. Entering verbal WM before age added 8% to the model (Model 5c). Entering visual-spatial WM before age (Model 5a) contributed significant variance to the model, but significance did not meet the established alpha of .001; increment in $R^2 = .01$, $F(1, 94) = 5.40, p < .05$. Visual-spatial WM contributed significant variance (increment in $R^2 = .02$) to reading comprehension when entered before verbal WM (Model 5c). When articulation speed and WM (i.e., verbal and visual-spatial WM) were entered before STM (Models 5b and 5d), the simultaneous entry of these three variables significantly predicted reading comprehension, $R^2 = .57$. As shown in Model 5d, the entry of verbal STM before age into the equation contributed significant variance, whereas the entry of visual STM (Model 5b) before age did not. In summary, verbal WM variables and the verbal STM variable contributed significant variance to age-related changes in reading comprehension.

For word recognition, when STM was entered first (Models 5a and 5c), the amount of explained variance was 53%. Adding verbal WM in Model 5a increased the total variance to 63%. Further, as shown in Model 5c, the significant contribution of verbal WM was maintained when entered before age into the equation (increment in $R^2 = .07$). As shown, visual-spatial WM contributed no significant variance to word recognition when entered after verbal WM. When WM was entered before STM (Models 5b and 5d), 60% of the variance in word recognition was accounted for. Verbal STM accounted for 3% additional variance when entered before age (see Model 5d) into the equation. As shown, visual-spatial STM contributed no significant variance to word recognition.

We assumed that both verbal and visual-spatial WM draw from a common system that contributes important variance to reading tasks. Thus, a follow-up was done by entering the domain-general WM factor score (second-order factor discussed earlier) before age into the equation. That is, after articulation speed and STM were entered first, we entered the second-order domain-general WM factor. The increment in R^2 when entered before age was 3% for reading comprehension, $F(1, 95) = 40.06, p < .001$, and 4% for word recognition, $F(1, 95) = 89.69, p < .001$.

In summary, there were four important findings related to the regression analysis. First, no process variables in isolation were more important than another in predicting the age-related variance in reading. Although WM produced the largest variance when entered first into the equation (Model 4), the results were not statistically different when compared with STM (Model 2) and articulation speed (Model 2). Second, entry of articulation speed, STM, and WM into the regression model reduced the contribution of age-related variance by 65% for reading comprehension and 66% for word recognition. However, the complete model (Model 5) left a large amount of age-related variance (33%) in reading unaccounted for. Finally, verbal WM rather than visual-spatial WM contributed significant variance to word recognition and comprehension. However, the domain-general factor (a second-order factor that includes overlapping variance between verbal and visual-spatial WM tasks) contributed significant variance to both reading measures. In contrast, the influence of STM on reading was isolated to the verbal domain.

Discussion

The purpose of this study was to determine whether an executive system mediated age-related WM and reading performance, beyond age-related changes related to articulation speed and STM. We tested two models of WM and its influence on reading. One model suggested that phonological processes play a major role in predicting age-related changes in reading and that the influence of executive processing on reading is mediated by the phonological system. The other suggested that age-related improvements in reading are related to executive processing, independent of the influence of the phonological system. The results yield three clear findings in support of the second model.

First, WM contributed unique variance to word recognition and reading comprehension beyond that contributed by STM and articulation speed. The results show that the significant contribution of WM to word recognition and reading comprehension was isolated to the verbal tasks. A follow-up of these results, however, indicated that the second-order factor that drew variance from both the verbal and visual-spatial WM tasks significantly predicted both reading comprehension and word recognition. Thus, there is evidence that a domain-general WM system does contribute important variance to age-related changes in reading comprehension and word recognition beyond what is contributed by processes related to STM and articulatory speed. Regarding the assumption that STM and articulation speed tap a phonological system, the results clearly show that age-related differences in verbal and visual-spatial WM are not primarily due to age-related changes in the phonological system.

Second, age-related differences on WM and STM measures were sustained when we partialed out articulation speed from the analysis. More important, these age-related differences were pervasive across verbal and visual-spatial WM tasks, suggesting that age-related differences are domain general. Overall, there was support for the notion that age-related performance related to articulation rate cooccurred with age-related performance in STM and WM performance. However, the variance related to 9-year-old versus 14-year-old children on memory measures was not eliminated by partialing out the influence of articulation rate. In addition, the influence of articulation rate on the intercorrelations between STM, WM, and reading was minimal. These findings suggest that age-related changes in STM and WM have little connection with articulation speed.

Finally, age-related changes in WM were not redundant with age-related changes in STM. Age-related differences emerged on both verbal and visual-spatial WM measures even when STM performance was partialed from the analysis. These results are consistent with those of Daneman and Carpenter (1980) and others (e.g., Engle, Tuholski, et al., 1999), who have argued that STM tasks and WM tasks are inherently different, and whereas phonological coding might be important to recall in STM, it may not be a critical factor in WM tasks. It was also found that these measures are tapping different processes because both WM and STM contributed independent variance to reading.

Implications

There are four implications of our findings for current literature. First, bottom-up processes (e.g., the phonological system) are not the primary mediators between age-related increases in WM and reading. Of course, these results only apply to the age groups represented in this sample and may not apply to beginning readers or poor readers. The results do coincide, however, with some studies that suggest that phonological skills wane in importance in older children (beyond elementary school years; e.g., Scarborough, Ehri, Olson, & Fowler, 1998). Our findings further suggest that although skills associated with phonological processes (i.e., articulation speed and STM) are important to age-related changes in children who are fluent in word recognition, they are no more important than verbal and visual-spatial WM. That is, our regression analysis found that articulation speed, STM, and WM substantially reduced age-related variance in word recognition and comprehension, but no one process was more important than another in this reduction. Such a finding qualifies bottom-up models of reading of children by suggesting that if low-order processes related to STM moderate the influence of executive processing (WM) on reading performance, their effects may be indirect or minimal for children fluent in reading skills.

Second, articulation rate does not explain all of the variance in age-related memory performance. The results do confirm, however, that robust age-related differences emerge on the articulation speed measure. This finding is consistent with the literature that suggests that lower WM and lower STM in 9-year-olds than that of 14-year-olds are a function of lower articulation rates. However, it appears that these memory processes and articulation rates can develop somewhat independently of each other. There are additional studies that suggest nonredundance between these measures (e.g., Bishop & Robson, 1989; Cohen & Heath, 1990; Johnston & Anderson, 1998). For example, Cohen and Heath (1990) found that memory span and articulation rate correlated within two different age levels (one age level ranged from 10.2 to 11.7, and the other ranged from 17.3 to 18.9). However, span performance was not weakened between age groups when articulation rate was partialed from the analysis.

Third, our results show that in the context of reading, WM and STM operate independently of each other. A common opinion in the reading literature is that STM tasks are a proper subset of processes of which WM is capable. Further, these studies assume that developmental differences in executive processing are related to efficient low-order processing related to the phonological loop. For example, Crain and Shankweiler (1990) stated,

> Along with other researchers, we envision the verbal working memory system as having two parts . . . First, there is a storage buffer, where rehearsal of phonetically coded information takes place. This buffer has the properties commonly attributed to short-term memory: It can hold linguistic input briefly . . . The second component of working memory is a control mechanism, whose primary task is to relay results of lower level analysis of linguistic input upward through the system. (p. 542)

As a qualification to this view, however, the present analysis suggests that WM can operate independently of STM. This finding is consistent with other experimental work with normally achieving readers (e.g., Cantor et al., 1991) and poor readers (Swanson et al., 1996). The implication of this finding is that age-related changes in WM may cooccur with STM but also maintain some independence from the development of STM.

Role of STM and WM in Reading

Given the extensive literature linking verbal STM to reading, however, especially at the word recognition level (e.g., Jorm, 1983), some explanation of the importance of verbal STM to reading must be considered. We found that age-related increases in both word recognition and reading comprehension were significantly related to verbal STM. Current literature (e.g., Swanson & Berninger, 1995) suggests that verbal STM is strongly related to word recognition but less so to reading comprehension. STM draws on a phonological code (Salame & Baddeley, 1982), a code critical to learning new words (Baddeley et al., 1998). WM tasks, however, tap executive functioning, a skill critical to reading comprehension (Engle et al., 1992; Just & Carpenter, 1992). Studies with adult samples have established that WM is particularly important to high-level cognition, such as reading comprehension, whereas STM is less so (e.g., Daneman & Carpenter, 1980). Within this premise, we might expect WM to be a more important factor in age-related differences in reading comprehension than in STM. Consistent with this notion, we found that some STM processes, those related to visual-spatial STM, did not distinguish 9-year-old and 14-year-old readers. However, processes related to verbal STM clearly separated age groups as well as contributed unique variance to both word recognition and reading comprehension.

Thus, given that STM has played a major role in explaining age-related differences in reading, it is necessary to reconcile its role to WM, at least for the sample under study. An earlier study by Cantor et al. (1991) may clarify this relationship. Their study assessed the relationship between complex span measures of WM, measures of STM, and comprehension as measured by the verbal Scholastic Aptitude Test. Their results showed that two distinct factors, STM and WM, contribute significant variance to comprehension. In a more recent study, Engle et al. (1992) argued that STM is important to comprehension that involves surface coding (e.g., the recall of words in a phrase), whereas WM is important in comprehending the gist and complexities of reading comprehension. This interpretation is consistent with the present study. That is, although the WM measures in the present study were more highly related to comprehension than to STM, some meaningful correlations were found between STM and comprehension (coefficients ranging from .30 to .40; see Table 2). Further, standardized reading comprehension passages in this study were composed of questions that vary from literal to inferential, thereby capturing surface coding as well as the comprehension of gist.

Although a distinction can be made between STM and WM to reading, we recognize from current models of WM (Ericsson & Kintsch, 1995) that the distinctions between STM and WM are obscured because both systems can draw from an LTM source. Thus, the relationship between WM and LTM as well as STM and LTM must also be clarified. Parallel to Anderson, Reder, and Lebiere (1996) and Ericsson and Kintsch (1995), WM consists of temporary or permanent knowledge units in LTM that are currently active. On the other hand, STM is information maintained at a surface level that does not consciously rely on permanent knowledge structures for its operation (e.g., Engle et al., 1992). This independence of STM from LTM processing has been established in the literature (e.g., Geiselman, Woodward, & Beatty, 1982). However, it is reasonable to assume that if STM tasks are designed to share components of WM, then STM would correlate with LTM. Thus, in our study it is reasonable to assume that WM and STM can share some common variance with LTM. However, the results also clearly show unique variance between the systems in that substantial WM differences emerged between age groups when STM was partialed from the analysis.

Domain-Specific Versus Domain-General Contributions

Finally, the findings address several issues regarding whether a general or task-specific domain is related to individual and age-related differences in reading (Engle et al., 1992; Engle, Tuholski, et al., 1999; Just & Carpenter, 1992). We found that a domain-general system predicted age-related performance in reading comprehension and word recognition. We also found that when the shared variance between the verbal and visual-spatial WM tasks was not taken into consideration, the verbal WM tasks better predicted reading than did the visual-spatial tasks. The findings are important because authors (Just & Carpenter, 1992) have argued that the influences of WM on reading are domain specific (e.g., Miyake, Just, & Carpenter, 1994), whereas others have argued that the influence of WM on reading is domain general (e.g., Engle et al., 1992; Turner & Engle, 1989). Our findings suggest that, with the current sample, both views are correct when the unique variance related to a domain-general and domain-specific system is taken into consideration.

Thus, our results converge with studies on individual differences that suggest that general resources from a WM system play a critical role in integrating information during reading comprehension (e.g., Cantor & Engle, 1993; Engle et al., 1992) as well as those that highlight the importance of a domain-specific language system (e.g., see Miyake et al., 1994, for a review). These models explicitly posit a dual role of WM: (a) It holds recently processed text to make connections to the latest input, and (b) it maintains the gist of information for the construction of an overall model of passage comprehension. In terms of individual differences, if a reader has a large WM capacity for language, then the execution of various fundamental comprehension processes (e.g., word encoding, lexical access, syntactic and semantic analysis) does not delete the limited resource pool as much as for a reader with a smaller capacity (e.g., Miyake et al., 1994). As a result, readers with a larger WM capacity would have more resources available for storage while comprehending text. On the other hand, readers with a smaller WM capacity might have fewer resources available for the maintenance of information for comprehension. This view is supported by our findings and others (e.g., Engle et al., 1992), showing that both verbal and visual-spatial WM correlate highly with comprehension, and we suggest that this relationship holds (at least for children) even when the influence of the articulation speed and STM are partialed from the analysis.

Alternative Models

Taken together, the findings in this study indicate that constraints in a domain-general (executive) system contribute significant variance to age-related differences in reading beyond the contribution of the phonological system. There are, of course, alternative interpretations to the results that must be considered. One possibility is that 9-year-old children are less resistant to interference (see Dempster, 1993; Harnishfeger & Bjorklund, 1994, for a discussion of this model) than are 14-year-olds, and this inference accounts for age-related span differences (e.g., Hasher, Stoltzfus, Zacks, & Rypma, 1991) and age-related reading differences (e.g., Gernsbacher & Robertson, 1995). For example, the process questions in the current WM tasks may constitute a very temporary competing condition with storage. Further, because the WM tasks vary considerably in the types of processing questions the children are exposed to, the pervasiveness of age-related differences across such diverse measures may reflect a general interference condition. As a consequence, 9-year-old children, when compared with 14-year-old children, have difficulty preventing unnecessary information from entering WM. Therefore, they are more likely to consider alternative interpretations of material (e.g., those asked for in the processing questions) that are not central to the task. This interpretation fits several recent models that explain age-related differences in memory performance as related to inhibitory mechanisms (e.g., Dempster, 1993; Harnishfeger & Bjorklund, 1994), without positing some form of a capacity limitation.

Although we see the above model as a viable alternative to the results, we have two reservations. First, only performance by children who answered the process question correctly was analyzed. That is, if a process question was missed, the child's recall of previously stored information was not requested. This procedure is different from previous studies (e.g., Daneman & Carpenter, 1980) that have allowed a dissociation between the process question (i.e., it is not necessary for children to answer the process question correctly) and retrieval question in the analyses. Thus, there was an experimenter-imposed association between the process question and the retrieval question. This control also provided feedback to children related to the interpretation or relevance of the material to be remembered. Second, it seems to us that the concept of interference can be tied to a limited capacity model that allocates resources. That is, capacity constraints may underlie age-related differences in inhibitory efficiency. This has been suggested in the literature on aging and WM (e.g., Hasher et al., 1991). In short, 9-year-old children may use more capacity related to the executive system than do 14-year-old children to inhibit or resist potential interference from irrelevant items.

A second possibility that could be argued is that this study provides no direct measure of the mental coordination of resources across the verbal and visual-spatial WM task and therefore the results merely show that verbal and visual-spatial tasks draw finite resources from the same language system. This seems an unlikely interpretation because the significant correlations between verbal WM and articulation speed were sustained when visual-spatial WM was partialed from the analysis. If the visual-spatial WM tasks were merely tapping the verbal domain, partialing their influence from the analysis should have eliminated the significant correlations between verbal WM and articulation speed. Such was not the case in this study. Thus, it does not seem to us that a common language system moderated the results. Both tasks may, however, draw from a common source in LTM. That is, although the executive system coordinates the distribution of resources of the verbal and visual-spatial system, it also functions to access information from LTM (e.g., Baddeley & Logie, 1999; Ericsson & Kintsch, 1995). More specifically, as stated by Baddeley and Logie (1999), "a major role of working memory is retrieval of stored long-term knowledge relevant to the task at hand, the manipulation and recombination of material allowing the interpretation of novel stimuli, and the discovery of novel information" (p. 31). The hierarchical regression suggests that both verbal and visual-spatial tasks as well as the composite visual-verbal general WM score, contributed resources to reading comprehension and suggest that the tasks draw from a common resource in LTM.

In summary, future research should focus on the interaction between executive and lower order processing during the act of reading across a broad age span to disentangle the alternative interpretation of the results. It appears, however, that age-related differences emerge at both the basic phonological loop level and the central executive level of memory. Although age-related differences in WM were related to age-related differences in reading performance, our results suggest that both a general and a domain-specific system mediate this relationship. In addition, future research should also be directed toward developing WM and STM measures of high discriminant validity. Although several of the memory measures used in this study were drawn from standardized tests (i.e., Swanson, 1995), thereby providing norm referenced information in terms of reliability and validity, previous research has reported weak correlations among memory measures purporting to measure the same or a related process (Salthouse, 1990; also see Swanson, 1992, p. 474 for a review). In addition, few studies reporting a distinction between WM and STM report the psychometric qualities of the measures, suggesting that the distinctions between the processes may reflect a number of processes other than memory.

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