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DEVELOPMENT OF VISUAL-VERBAL INTEGRATION IN WORKING MEMORY DURING CHILDHOOD AND ITS RELATION TO LANGUAGE AND READING ABILITIES

by

M. KATRINA SMITH

Under the Direction of Byron F. Robinson

ABSTRACT

Research has demonstrated working memory improves during childhood and supports vocabulary, grammar, and reading development (Adams & Gathercole, 1995, 1996; Bowey, 1996; Gathercole & Baddeley, 1989, 1990). Prior to the addition of the episodic buffer in Baddeley's model of working memory (2000a), auditory and visual aspects of working memory were often treated separately without evaluating contributions from the ability to integrate the two forms of information. The present study was designed to investigate the development of visual-verbal integration in working memory and its role in language and reading development. Tests of receptive vocabulary, receptive grammar, and decoding ability were administered to 46 children between 6 and 10 years of age. Working memory was assessed with a paired associates task where stimuli varied based on modality and contributions from long-term memory were limited by using nonwords and unfamiliar images. Data from the same tests of language and working memory were also available for 58 children between 3 and 5 years of age (Robinson & Smith, 2005) and included in exploratory analyses. Developmental findings were consistent with previous studies in indicating the unimodal aspects of working memory improve

steadily across the entire age range examined. Growth curve analyses of cross-modal working memory, which taxed the episodic buffer, showed curvilinear growth where spans increased rapidly between 3 and 7 years of age then appeared to slow dramatically. Analyses of residuals support the notion of integrative growth above and beyond changes in unimodal working memory. Although cross-modal working memory did not make significant contributions to decoding ability, it accounted for 11% of unique variance in receptive grammar scores in school-aged children.

INDEX WORDS: Working memory, Development, Childhood, Visual-verbal integration, Language, Vocabulary, Grammar, Reading

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M. KATRINA SMITH

A Dissertation Submitted in Partial Fulfillment of Requirements for the Degree of

Doctor of Philosophy

Georgia State University

2005

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by

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May 2005

Dedication

I dedicate this work to my husband, who has supported me throughout my educational career without question or complaint.

I also dedicate this work to my parents, especially my father who now has a club member in the family.

Last but certainly not least… I dedicate this to my daughter, Nicole, who really knows how to come through in a pinch.

Thank you all.

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Development of Visual-verbal Integration in Working Memory During Childhood and Its Relation to Language and Reading Abilities

In 1974, Baddeley and Hitch proposed the construct of working memory, which built upon existing theories of short-term memory and suggested an individual could maintain a limited amount of information in an active form for a short period of time (Atkinson & Shiffrin, 1968; Howes, 1990; Miller, 1956; Waugh & Norman, 1965). Working memory addressed not only the temporary storage of items but also the processing necessary to manipulate those items. Subsequent research has elucidated the structure and function of working memory as well as its contributions to development in other cognitive domains such as language and reading (Ardila & Rosselli, 1994; Baddeley & Hitch 1974; Case, 1987; Case, Kurland, & Goldberg, 1982; Cowan, 1997; Daneman & Carpenter, 1980; Demetriou, Christou, Spanoudis, & Platsidou, 2002; Gathercole & Baddeley, 1989, 1990, 1993; Kemps, Rammelaere, & Desmet, 2000; Pascual-Leone, 2000; Windfuhr, & Snowling, 2001).

Since the construct was first proposed, several theories of working memory have been offered. One difference between theories that may be of particular importance when examining visual-verbal integration in working memory involves whether the models differentiate between the two types of information. Baddeley and Hitch (1974) made an explicit distinction between visual and verbal modalities in their model of working memory shown in Figure 1. The phonological loop processes auditory-based information, whereas processing of visually based information takes place in the visuo-spatial sketchpad (VSSP). The central executive is responsible for the coordination of information and attentional resources between the visual and verbal systems.

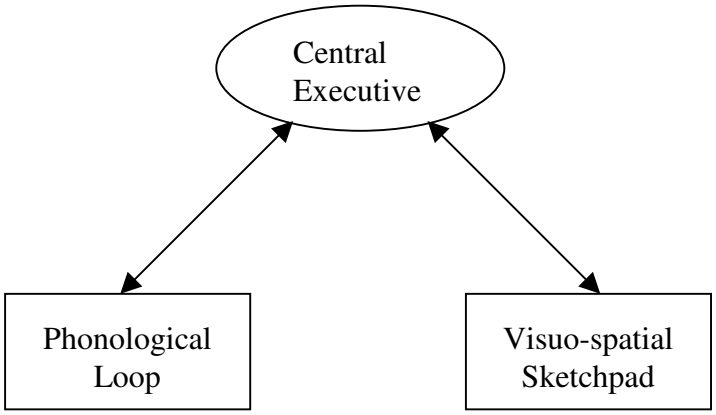

Figure 1. The 1974 Baddeley and Hitch model of working memory

Of the components proposed by Baddeley and Hitch (1974), the phonological loop has received the most attention. This system is dedicated to the temporary storage and processing of auditory or spoken information. The phonological loop supports two processes – articulatory storage and articulatory rehearsal. The primary means by which stored information is maintained in the phonological loop is subvocal rehearsal (Baddeley, 1990; Gathercole & Baddeley, 1993). Experimental tasks that require articulatory suppression have been used to examine this process (Duyck, Szmalec, Kemps, & Vandierendonck, 2003). Performance on verbal working memory tasks declines when participants engage in secondary verbal tasks that block subvocal rehearsal. Conversely, when the secondary task involves the VSSP, such as tapping blocks in a square, recall of verbal information is not affected to the same degree. Together this pattern of results support Baddeley and Hitch's claim that the phonological loop represents a distinct aspect of the working memory system that is separate from the visual system (Baddeley, 1990; Brandimonte, Hitch, & Bishop, 1992).

The VSSP is dedicated to the maintenance and manipulation of visual and spatial information. Although the visual and spatial aspects of the VSSP represent a single component, empirical evidence suggests that each involves discrete processes (Baddeley, 1990, 2000a; Hamilton, Coates, & Heffernan, 2003; Pickering, Gathercole, Hall, & Lloyd, 2001). Reports from lesion based studies reveal that the two types of information are processed in different areas of the brain with visual tasks tapping the occipital lobe, spatial tasks drawing from the parietal lobe, and coordination between the two taking place in the frontal lobes (Baddeley, 1990). Underlying processes that support maintenance and manipulation of information in the VSSP are not understood as well as corresponding rehearsal processes in the verbal system (Pickering, 2001). Logie (1995) suggested that rehearsal utilizes the spatial component of the sketchpad. Baddeley (2000a), on the other hand, suggested that visual rehearsal operates more like attention. It seems that the spatial aspect of the VSSP may be utilized in tasks that require serial recall and visual rehearsal may be more effective for storing a single complex pattern.

The third component, the central executive, was underspecified by the 1974 model when it was first developed (Baddeley, 2002). Research to date has primarily focused on defining this component and explicating its role in the model. The central executive is responsible for planning and coordination of attention during tasks with immediate processing demands and coordination of information between the visual and verbal systems. This component is important in complex tasks that require directing processing resources to several tasks simultaneously. Although the central executive may direct attention to the phonological loop and VSSP, it has no storage capacity and current conceptualizations of working memory place active integration of material outside of the central executive.

Although Baddeley and Hitch's (1974) model of working memory has been widely used and well respected in the literature, the model did not provide a satisfying account for the pattern of prose recall found among patients with amnesia who remembered more words in the form of a sentence than from a list of unrelated words (Baddeley & Wilson, 2002). In one case study, Baddeley (2000a) reports that a patient had a sentence span of five related words compared to a span of one when the words were unrelated. An explanation was needed that could account for this difference in span length. Baddeley suggested that the longer sentence span could not be due to the phonological loop because the sentence span exceeded the capacity of this component. Moreover, he expressed doubts that the improvement was stemming from the VSSP because this component is not efficient for the serial recall required in the task. Furthermore, he suggested that the central executive, which has no storage capacity, could not be responsible for the increased span for related words. So while it appeared that some form of chunking related to long-term memory was occurring, a modification to Baddeley and Hitch's model was necessary in order to specify the relation between long-term memory and working memory.

The three-component model (Baddeley & Hitch, 1974) also had difficulty accounting for differences in span length when participants were asked to verbally recall a list of words after presentation of either visual or verbal of items (Baddeley, 2000a). If the visually presented items were automatically recoded in phonetic form, articulatory suppression should have disrupted rehearsal to the same extent as when items were presented verbally. However, in studies with non-impaired adults, spans for visually presented lists were approximately two units smaller when participants engaged in articulatory suppression compared to performance without suppression. In contrast, spans for verbally presented lists were three or four units smaller. Similarly, when adults with neurological impairments were examined, participants with very

poor auditory recall (a digit span of 1) could recall more digits from a visually presented list (digit span of 4). This pattern of findings led Baddeley (2000a) to argue that the increased span length for visually presented material was more than an additive contribution from the VSSP and that visual and verbal information must be integrated.

Because the central executive has no storage capacity, a component was needed that would provide storage, support serial recall, and allow for integration from various sensory modalities. In 2000, Baddeley introduced a new component to his model, the episodic buffer, which served these functions. The modified model is shown in Figure 2 (Baddeley, 2000a, 2000b, 2001; Baddeley & Hitch, 2000). The refinements to the model served to more precisely describe the processes within the system and explicitly map out the links between the various components and long-term memory. Baddeley proposed that the episodic buffer would support storage and integration of information from the VSSP, phonological loop, and long-term memory (Baddeley, 2000a, 2000b, 2001, 2002, 2003; Baddeley & Hitch, 2000; Baddeley & Wilson, 2002). This component is responsible for the conversion of codes from different sources into a common form that creates a unitary 'episode'. The capacity of the system is limited because of the computational demands necessary to convert the various codes. Early research supports Baddeley's contention that the episodic buffer is distinct from other aspects of working memory (Alloway, Gathercole, Willis, & Adams, 2004; Gruber & von Cramon, 2003; Zhang et al., 2004).

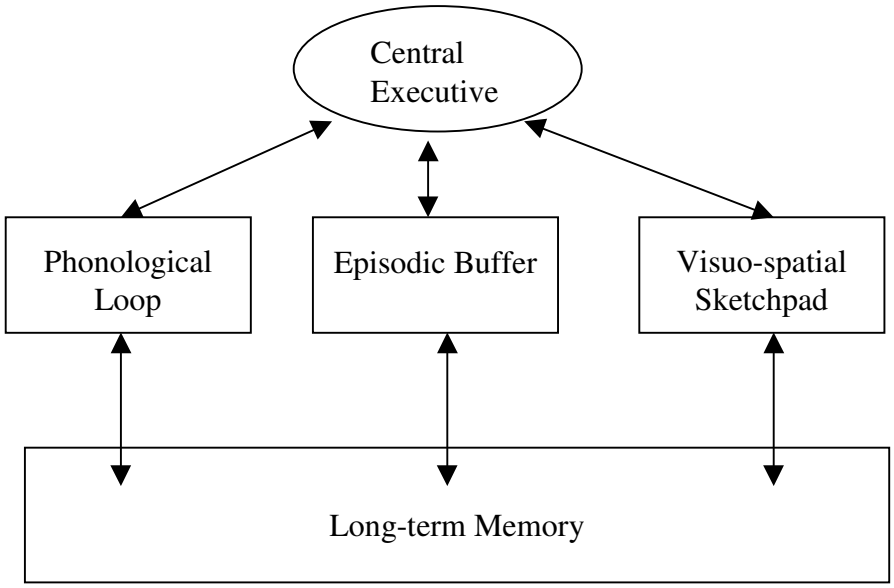

Figure 2. Baddeley's revised model of working memory

Baddeley (2001) proposed two ways to measure the capacity of the episodic buffer – constrained sentence span and prose recall. The constrained sentence span task involves maintaining the same basic syntactic structure while increasing the sentence length by adding function words. An example of a short sentence is "*Miko followed Kobe*". A longer sentence is "*The generous boy Kobe gave the nice girl Miko the new red ball*". According to Baddeley and Turk (as cited in Baddeley, 2001), sentence spans were 5 to 10 words longer than spans for unrelated lists of words. The ability to recall sentences was most disrupted when participants performed a concurrent task that tapped either the VSSP or central executive, whereas recall on lists of unrelated words was more disrupted when the concurrent task taxed the phonological loop. Baddeley argued that longer sentence spans were the result of contributions from multiple components of working memory. Similar findings were reported in a descriptive analysis of

memory for 2 patients with amnesia whose prose recall exceeded their memory span for lists of unrelated words (Baddeley & Wilson, 2002). These findings were used to generate the a priori hypothesis that prose recall span would consistently exceed span for unrelated words. Baddeley and Wilson confirmed their hypothesis in a larger sample of 23 patients with amnesia. The authors suggested that these individuals were able to remember a longer series of words related in the form of prose because it provided an organization that was supported by long-term memory and integrated with verbal information in the episodic buffer.

Integration from long-term memory, however, is only one aspect of the function of the episodic buffer. This component is also responsible for the integration of information from the visual and verbal systems. Although empirical studies of this process were not available, Baddeley suggested that visual-verbal integration should be similar to integration from long-term stores (Baddeley, 2000a, 2001; Baddeley & Wilson, 2002). Further, previous empirical studies suggest that the ability to integrate visual and verbal information may change dramatically during childhood.

Development of Working Memory

Numerous studies have examined age-related growth in children's working memory. More specifically, research has indicated that children's working memory spans increase steadily between 3 and 15 years of age (Case et al., 1982; Cowan, 1997; Dempster, 1981; Gathercole & Baddeley, 1993; Schneider & Bjorklund, 1998). Evidence presented in the context of the model proposed by Baddeley and Hitch (1974) provided the most specific picture of development within the individual verbal and visual working memory systems. This literature also provided clues as to what changes may be taking place within an integrative system.

Developmental Changes in the Phonological Loop

Existing research consistently indicates improvements in children's verbal working memory across the course of childhood (Case, 1987; Case et al., 1982; Cowan, 1997, 2000; Cowan, Nugent, Elliott, Ponomarev, & Saults, 1999; Dempster, 1981; Gathercole & Baddeley, 1993). Studies using digit span measures indicate a positive correlation with age (Ferguson, Bowey, & Tilley, 2002) with span increasing from approximately two digits for 2-year-olds, five digits for 7-year-olds, and seven digits in early adolescence (Case et al.; Dempster). Measures of word and letter spans reflect similar span lengths with 3-year-olds recalling about three words and 5-year-olds recalling approximately four words (Case et al.; Dempster). Findings from studies using tasks that require both storage and processing, such as backward digit span or operation spans (Daneman & Carpenter, 1980), also supported the idea of steady growth; however, spans are generally lower by approximately two units (Pascual-Leone, 2000; Schneider & Bjorklund, 1998). Although the literature supports developmental increases in verbal working memory, researchers are still investigating the mechanisms and processes that underlie these improvements.

Articulatory storage and articulatory rehearsal are the primary components of the phonological loop (Baddeley 1990, 2000a; Gathercole & Baddeley, 1993). Articulatory storage has been probed with two types of experimental tasks (Baddeley, 1990; Gathercole & Baddeley, 1993; Logie, Sala, Wynn, & Baddeley, 2000). In one type of task, the similarity effect is demonstrated when participants have more trouble recalling a series in which the items sound similar (B, D, G) than sequences with items that are phonetically distinct (F, T, X). In the second type of task, interference is introduced by presenting participants with irrelevant speech during list presentation. The former makes demands on storage by varying the distinction of the

information being held, and the latter taxes storage by requiring active attention while resisting interference (Baddeley, 1990; Gathercole & Baddeley, 1993; Logie et al.). Articulatory rehearsal has been assessed when participants demonstrate word length effects and suppression effects. Word length effects are exhibited when individuals remember a longer series of short words (1-syllable in length) than long words (5-syllables; Baddeley, Thompson, & Buchanan, 1975). Because it takes more time to articulate the longer words, the verbal working memory system is able to maintain fewer words (Baddeley et al., 1975, Dempster, 1981; Hitch, Towse, & Hutton, 2001). Suppression techniques require participants to perform two tasks at once. Usually this involves remembering a word list while repeating a short word like ‘the”. Suppression blocks the subvocal rehearsal process by using active speech, and the effect is that recall of verbal material decreases.

The role of articulatory storage in the development of the phonological loop has been supported with phonetic similarity effects for verbally presented material in children as young as 5 years of age (Halliday, Hitch, Lennon, & Pettipher, 1990); however, improvements in articulatory rehearsal seem to be the primary mechanism for growth (Gathercole & Baddeley, 1993; Hulme, Thompson, Muir, & Lawrence, 1984; Schneider & Bjorklund, 1998). Research has examined age-related changes in processes such as subvocal rehearsal and articulation rate. Children show steady improvement in the speed of verbal rehearsal, which allows more items to be stored (Baddeley et al., 1975; Case et al., 1982; Dempster, 1981; Hulme et al., 1984). As articulation rate increases and children are able to rehearse faster (either vocally or subvocally), span increases and word length effects become more pronounced (Gathercole & Baddeley, 1993). The word length effect has been found in children as early as 4 years of age (Hulme & Tordoff, 1989) suggesting that articulation rate is important as early as the preschool years. Over

the course of development, children increasingly rely on more sophisticated forms of rehearsal instead of faster repetition. For example, school-aged children are more likely to use subvocal rehearsal to keep memory traces active. By monitoring lip movements, Flavell, Beach and Chinsky (1966) demonstrated that 5-year-old children did not use subvocal rehearsal during the delay between presentation and recall. Explicit training in subvocal rehearsal, however, increased verbal memory span (Keeney, Cannizzo, & Flavell, 1967; Johnson, Johnson, & Gray, 1987). Overall, empirical studies support claims that verbal working memory improves during childhood and suggest that increases are due to more sophisticated and efficient processing of verbal information.

Developmental Changes in the VSSP

Literature focusing on the development of the VSSP has been relatively sparse. In general, this system appears to be in place early in development, and there seems to be an increase in the capacity of the sketchpad that parallels improvements in the phonological loop. Studies using pattern matrices and Corsi block tasks have demonstrated that VSSP spans improve steadily between the ages of 5 and 11 years (Pickering, 2001; Wilson, Scott, & Power, 1987). By 4 or 5 years of age, children can remember two- to three-item sequences of pictures (Gathercole & Baddeley, 1993). Before approximately 4 years of age, children are able to remember visual sequences, if the to-be-remembered items are sufficiently distinct (Conrad, 1971).

Although research has provided evidence that the capacity of the VSSP increases on a scale similar to that found in the phonological loop, improvements in the underlying processes that support the visual system have not been explored to the same degree as those in the verbal system. Processes analogous to articulatory storage and rehearsal have not yet been identified;

however, storage and rehearsal in the VSSP has been explored in a general manner (Pickering, 2001; Pickering et al., 2001). Hitch, Halliday, Schaafstal, & Schraagen (1988) examined storage in the visual system with tasks that involved similarity effects for visually presented material. Younger children had more difficulty when the pictures of items on a list resembled one another than when they were visually distinct. Studies have noted visual similarity effects with children as early as preschool age (Hitch & Halliday, 1983; Hitch et al., 1988; Hayes & Schulze, 1977) but not among older children around 10 years of age (Hitch & Halliday, 1983, Hitch et al., 1988). Older children have more trouble with recall when the verbal labels for the images have similar sounding names. Therefore, visual similarity effects decrease with age, whereas phonological similarity effects increase with age. Gathercole and Baddeley (1993) suggested these differences occur because young children use the visual system for rehearsal of visual information, but some time between 6 and 8 years of age, children begin using verbal system for rehearsal. One possibility is that developments in the episodic buffer support recoding of visual material into a verbal form.

Development of Visual-verbal Integration Within the Episodic Buffer

Does Integration Change Over the Course of Development?

Visual-verbal integration is important in tasks that make immediate memory demands in both sensory modalities. One example of this type of task is showing participants a set of pictures and asking them to verbally report the list of items. Broad theories of cognitive development provide a sound theoretical base for proposing that changes in integrative ability take place over the course of childhood. For example, Flavell (1977) presents cognitive development as a process of integration, specifically proposing that children's representations become more amodal. In terms of the processes underlying these changes, Flavell proposed that

the ability to control the focus of attention improves, which gives the child more flexibility in dealing with multiple types of information. This position is consistent with Piaget's concept of decentration where children become better able to deal with multiple aspects of a particular problem (Furth, 1969; Phillips, 1969). More recently, Mounoud (1996) wrote that development involved a change from separate to more integrated processing. Mounoud considers this a general change in cognition driven by neurological maturation and supported by the environment. This is consistent with the work of Janowsky and Carper (1996) that suggests brain maturation in the associative cortices may support integration.

Developmental theory provides general support for age-related improvements in integrative ability; however, the literature is lacking in terms of information that specifically addresses the issue of visual-verbal integration in a working memory or short-term memory context (Halliday et al., 1990; Hitch et al., 1988). No studies have directly examined development within the episodic buffer, but research on cross-modal paired associates, the phonological loop, and development of the VSSP provides clues about changes that might be expected. Frequently used tasks in these areas involve presenting children with a series of pictures and asking them to verbally recall the pictures in serial order (Conrad, 1971; Gathercole & Baddeley, 1993; Halliday et al., 1990). This task clearly makes demands in both visual and verbal systems. Age related differences were first noticed when children's performance was different than that predicted from adult models. When shown pictures, younger children appeared to rely on a visual code when remembering items whereas older children and adults tended to rely on a verbal code (Hitch et al., 1988; Kee, Bell, & Davis, 1981; Palmer, 2000).

Research hints that some type of shift in the coordination of visual and verbal information occurs between 6 and 10 years of age. The primary difference between the performance of

younger children and that of adults and older children seems to center around the spontaneous recoding of visual information into a verbal form. Prior to the introduction of the revised working memory model (Baddeley, 2000a, 2001), explanations of age-related changes in visual-verbal integration in working memory were somewhat piecemeal, and there was no clear theoretical framework. It may be possible to clarify findings from previous developmental, working memory, and paired associates studies by applying a developmental perspective to Baddeley's revised model of working memory. Many questions could be posed regarding the timing and nature of changes in visual-verbal integration within the episodic buffer.

When Does Integration Change?

Research suggests that visual-verbal integration may undergo substantial changes during middle childhood. For example, Flavell et al. (1966) asked 5-, 7-, and 10-year-old children to remember an array of seven pictures of common objects. Children were asked to reproduce this sequence by pointing to the same pictures. They found that older children were more likely to spontaneously use verbal rehearsal to recall visual sequences. Keeney et al. (1967) suggested there was a transition in the way that children rehearsed the sequences between 6 and 7 years of age. Although they had the ability to verbally rehearse, younger children do not consistently use verbal rehearsal for remembering the visual sequence.

Working memory literature offers additional support for the notion that processing of visual and verbal information changes during the elementary school years. In auditory working memory tasks, word length effects are found among older children and adults when articulatory time is increased. This seems to occur because the length of time that information can be maintained through subvocal rehearsal is limited, and the longer it takes to say the word, the fewer the number of words that can be recalled (Baddeley et al., 1975; Dempster, 1981; Hitch et

al., 2001; Hulme et al., 1984). Interestingly, children younger than 7 or 8 years of age do not demonstrate the word length effect when presentation comes from pictorial lists (Halliday et al., 1990; Hitch & Halliday, 1983). Younger children do, however, show word length effects as early as 4 years of age when presentation involves verbal lists. This indicates that children can use subvocal rehearsal; however, it is not until 7 or 8 years of age that they use verbal rehearsal when the original form of the information is visual. One explanation for this pattern is that younger children's integrative ability is not yet developed enough to support performance in tasks where they must effectively use information from both modalities simultaneously.

Word length effects no longer occur when participants engage in articulatory suppression, which interferes with verbal rehearsal mechanisms. When presenting visual lists to children around 5 years of age, having them repeat a short word aloud during rehearsal does not stop word length effects (Halliday et al., 1990). In contrast, children around 11 years of age no longer demonstrate word length effects when they engage in this type of articulatory suppression. This is similar to adult patterns indicated in Baddeley's work with the phonological loop (2000a).

Developmental data regarding the similarity effect provide further support for the notion that younger children do not use the verbal system for rehearsal of visual information. Phonological similarity effects are indicated when participants recall a longer list of items that have distinct sounds compared to the list length of items with similar sounds. This pattern is generally demonstrated by adults regardless of whether the series is presented in a visual or auditory form. With a visual presentation of items, Conrad (1971) found that prior to the age of 5 years, children did not demonstrate the phonological similarity effect shown in adults. Hitch and Halliday (1983) suggest that phonological similarity effects do not emerge until around 7 years of age when presentation of items is visual. If younger children recode pictures into their verbal

form, they should have more difficulty remembering lists in which the items sound similar because the verbal system provides the primary means of rehearsal and the items in this system are not very distinct. Instead, it seems that visual rehearsal takes place in a separate system. At some point, however, children change their rehearsal strategy and draw from both visual and verbal systems simultaneously.

Studies of visual similarity effects also support a change in visual-verbal integration. Visual similarity effects are indicated when participants have more difficulty recalling images that are visually similar than images that are visually distinct. Because adults automatically code visual information into its phonetic form, they do not typically demonstrate a visual similarity effect. A study by Hitch et al. (1988) indicated that children between 5 and 6 years of age were responsive to visual similarity. In contrast, 10-year-olds demonstrated more adult-like performance in that they were not sensitive to visual similarity in cases where the verbal labels for items were phonetically distinct. Again, the research indicates that younger children are not recoding the visual information into a verbal form. By 10 years of age, children use both forms of information in a manner similar to that seen in adults. In a review of the literature on the development of visuo-spatial working memory, Pickering (2001) specifically suggests that the change from visual to verbal processing is occurring around 8 years of age. Gathercole, Pickering, Ambridge, and Wearing (2004) suggest that the change in processing occurs around 7 years of age.

Framing Developmental Changes in Visual-verbal Integration in a Theoretical Model

Although most sources generally support the notion that children's ability to integrate visual and verbal information improves during development, almost no work focused on explicating the nature of these developments. According to the Baddeley and Hitch model of

working memory proposed in 1974, individuals recode visual information into its phonetic form (Gathercole & Baddeley, 1993). Because adults are so efficient at this recoding, under ordinary circumstances, the process of converting visual stimuli into its phonetic form appears automatic. Developmental data, however, have indicated that children below about 7 years of age do not easily recode information into a phonetic form if the stimuli involve presentation of pictures of familiar items (Conrad, 1971; Hitch & Halliday, 1983; Hitch et al., 1988; Hitch, Halliday, Schaafstal, & Hefferan, 1991; Pickering, 2001). The lack of recoding on the part of children has been credited to immaturity of the system and not examined in the context of the development of integrative abilities. However, using the revised model of working memory (Baddeley, 2000a, 2001), support for the integration of visual and verbal information could result from developments within the episodic buffer that support automatic recoding by providing efficient integration of visual and verbal information.

One problem with the available methods for measuring the episodic buffer is that they do not offer a good way to tease apart the relative contributions of visual-verbal integration from those of long-term memory. According to Baddeley, the process of integration for the two tasks previously described involves activating simultaneous representations in the VSSP and phonological loop. The visual and verbal systems, in turn, activate representations from long-term memory. The episodic buffer is responsible for combining the information from the verbal and visual systems with long-term memory. However, this assumes that long-term representations are equally available across individuals. This might not be the case when examining children across the elementary school years where differences in children's levels of long-term knowledge are expected. For example, they will have different levels of mastery of lexical items and syntactic structures. In this context, it is important to be able to separate out the

effects of knowledge base from integrative skills. Baddeley (2001) suggested that the episodic buffer could support direct integration between the VSSP and the phonological loop without contributions from long-term memory, but no measures were available to assess this hypothesis. Contributions from long-term memory could be limited in an experimental task by using novel words and images. In many ways, this type of task parallels aspects of the language learning process of children because, by design, the task requires the immediate, active association of novel visual and verbal information.

Contributions from Visual-verbal Integration in Working Memory to Other Domains of Development

Research on the development of working memory is important not only because it provides information about changes in the cognitive domain, but also because of its role in other domains. Studies have substantiated claims that verbal working memory, and to a lesser extent visual working memory, make independent contributions to language and reading development (Adams & Gathercole, 1995, 2000; Blake, Austin, Cannon, Lisus, & Vaughn, 1994; Duyck et al., 2003; Gathercole, 1995; Gathercole & Baddeley, 1989, 1990, 1993; Ellis & Sinclair, 1996). An interesting question is whether visual-verbal integration in working memory makes similar contributions to developments in language and reading.

Role of Visual-verbal Integration in Working Memory During Language Development

The argument that visual-verbal integration in working memory plays a role in language development rests on the assumption that, in general, working memory supports language learning (Adams & Gathercole, 1995; Ellis & Sinclair, 1996; Gathercole, Hitch, Service & Martin, 1997; Gathercole & Pickering, 2000; Gathercole, Service, Hitch, Adams, & Martin, 1999). Research has indicated that nonword repetition scores are an important factor in

explaining receptive vocabulary in children around 4 or 5 years of age. Working memory predicted approximately 15% of the variance in vocabulary performance in 4-year-olds and approximately 20% of the variance for 5-year-olds (Gathercole & Baddeley, 1989). Further, nonword repetition scores at 4 years of age predicted receptive vocabulary scores at 5 years of age (Gathercole & Baddeley, 1990).

In addition to contributing to vocabulary acquisition, working memory is important in grammar development (Adams & Gathercole, 1995, 1996; Willis & Gathercole, 2001). Adams and Gathercole (2000) indicated that working memory played a role in productive vocabulary, sentence length, and sentence complexity. The authors compared 4-year-olds matched on nonverbal abilities but who demonstrated either high or low levels of performance on a measure of phonological loop capacity. Their findings indicated that the sentences produced when children were describing sets of pictures were longer and more complex in the group of children with greater levels of phonological memory performance. Blake et al. (1994) found similar relations between working memory and sentence complexity in children between the ages of 2 and 5 years. Specifically, Blake et al. found that verbal working memory predicted the mean length of children's utterances (MLU) better than either mental or chronological age.

Studies that included measures of the VSSP also have indicated contributions to language development in typically and atypically developing children (Adams & Gathercole, 2000; Jarrold, Baddeley, & Hewes, 1998; Mervis, Robinson, & Pani, 1999). In a sample of 97 typically developing children between 4 and 5 years of age, Adams and Gathercole (2000) report a moderate association between Corsi block span and MLU and a strong association between Corsi block span and expressive grammar (Index of Productive Syntax [IPSyn], Scarborough, 1990) after controlling for nonverbal ability.

One way to understand the importance of visual-verbal integration to language development is to examine the language tasks that children face. For example, one aspect of vocabulary acquisition requires that children be able to associate a phonological representation with its corresponding visual referent. To label a ball, the child must remember the sound sequence of the word *ball* and associate those sounds with the spherical toy he or she sees. Initially, considerable amounts of working memory resources are needed to maintain both the visual and phonetic representations simultaneously. As children master the strategies needed to label basic objects and actions and extend those labels to multiple exemplars, they begin to direct their attention to the next linguistic task – mastering grammar.

During middle childhood, children have large vocabularies, are fairly proficient at learning words, and comprehend many syntactic structures; however, their linguistic development is far from complete. Children at this age are still acquiring new lexical items at a rapid rate and mastering more complex syntactic structures such as passives (Berko-Gleason, 2001; Tomasello & Brooks, 1999). In a passive sentence, the focus shifts away from the actor (as in the basic transitive sentence) and is placed on the patient. Comprehension of this type of sentence requires that the child hold in working memory several things simultaneously. He or she must comprehend the verbal labels referring to the participants and actions as well as the relative roles of the participants as actor and patient. The child also must apply those pieces of verbal information within an analysis of a visual scene and process information regarding the word order used in the sentence. In English, the passive construction requires the child to reverse the order of actor and patient relative to the more familiar transitive sentence. Further, when a child encounters a new scene, some novel features must be managed.

Developing comprehension of passive sentences illustrates the types of demands more advanced grammatical structures make on the working memory system. It is logical to propose that the child's developing memory system may be called upon to support language tasks that require association of an auditory representation with visual information from a complex scene. This activity requires integration of information from multiple sources. This type of processing brings into play the newest component of the Baddeley (2000a, 2001) model, the episodic buffer. If this component, which supports the integration of verbal and visual information, is growing and becoming more efficient, it is possible that it would make unique contributions to language development.

Although studies have consistently shown that working memory plays an important role in language, researchers have suggested that the role of the phonological loop in language varies over the course of development (Gathercole et al., 1999; Gathercole, Willis, Emslie, & Baddeley, 1992). Gathercole et al. (1992) reported that the phonological loop made a much smaller contribution to vocabulary performance for 8-year-olds than for 4-year-olds. During the preschool years, the capacity of the phonological loop is well suited for maintaining and manipulating very small amounts of information. Linguistic development during this period primarily involves increases in vocabulary size and managing short, relatively simple sentences. The phonological loop seems to support these types of linguistic tasks. As children become older, the process of word learning becomes more efficient and automatized, and there are fewer demands on the working memory system. A more efficient system for dealing with information in its temporary form should also support advances in the complexity of sentences that can be understood and produced. Studies have supported a link between the phonological loop and grammar development (Adams & Gathercole, 1995, 1996, 2000; Blake et al., 1994; Willis &

Gathercole, 2001). Age-related improvements in other aspects of working memory may also make an important contribution to the increasingly sophisticated linguistic tasks that a child faces.

Role of Visual-verbal Integration in Working Memory During Reading Development

Both visual and verbal working memory plays a role in reading development (Gathercole & Baddeley, 1993; Gathercole & Pickering, 2000; Leather & Henry, 1994; Meyler & Breznitz, 1998; Windfuhr & Snowling, 2001). The basic premise behind the theory that working memory contributes to reading development seems to be similar to that proposed in the domain of language development. Specifically, children's ability to maintain and combine phonological representations of the sounds that make up a word is important in reading tasks such as decoding and comprehension. In a longitudinal study of children from 4 to 8 years of age, Gathercole et al. (1992) reported moderate correlations between verbal working memory and decoding (as measured by word and nonword reading). Similarly, Gathercole and Pickering (2000) reported moderate to strong correlations between verbal working memory and literacy assessments for children between 7- and 8-years-old. Among a sample of 71 children between the ages of 7;0 and 7;11, Leather and Henry found that listening span was moderately correlated with reading comprehension even after accounting for simple verbal memory span. Meyler and Breznitz reported a similar pattern of association between visual working memory and decoding. Cumulatively, these studies provide compelling evidence for the role of visual and verbal working memory in reading development.

Decoding is important to the task of reading because of its fundamental nature. The child must be able to make the necessary connections between the orthographic code and the corresponding phonetic form. Making associations between printed letters and spoken phonemes

is the type of task that improvements in visual-verbal integration seem to support. Windfuhr and Snowling (2001) examined cross-modal paired associates learning and working memory in reading development between the ages of 7 and 11 years. They found that cross-modal paired associates learning was uniquely related to word and nonword reading decoding ability. After controlling for age, nonverbal ability, verbal ability, and phonological awareness, paired associates learning explained 8% of the variance in word reading scores and 2% of the variance in nonword reading scores. Both contributions were statistically significant ($p < .05$).

Specific Issues Examined in the Present Study

Predictions Regarding the Development of Visual-verbal Integration in Working Memory

The present study was designed to explore age-related changes in the separate visual and verbal aspects of working memory as well as developments in children's ability integrate visual and verbal information in working memory. Gains in unimodal visual and verbal working memory have been well documented in the literature (Case, 1987; Case et al., 1982; Cowan, 1997; Demetriou et al., 2002; Gathercole & Baddeley, 1993; Gathercole et al., 2004; Pickering, 2001; Kemps et al., 2000). It was expected that both aspects of unimodal working memory would improve steadily between 6 and 10 years of age.

Developmental improvements in visual-verbal integration are interpreted in the framework of the episodic buffer from Baddeley's model of working memory (2000a, 2001). The literature suggests that integrative ability should improve rapidly between 6 and 10 years of age (Conrad, 1971; Hitch & Halliday, 1983; Reznick, 1977); however, many questions remain regarding the developmental picture. Reports on the growth of separate visual and verbal systems imply that development is linear. In contrast, studies indicating a qualitative shift towards verbal processing of visual information suggest that growth curves may be nonlinear. Researchers have

proposed that children begin to spontaneously re-code visual information into its verbal form between 6 and 8 years of age. Based on this notion, it was expected that there would be rapid improvement in visual-verbal integration around 7 years of age with growth slowing after 8 or 9 years of age. If visual-verbal integration draws on a distinct aspect of working memory as Baddeley suggests (2000a, 2001), growth would also be present even after controlling for increases in the separate visual and verbal systems. Taken together, the analysis of development should provide a more comprehensive picture of changes in working memory and the mechanisms that underlie these improvements.

Predictions Regarding the Role of Visual-verbal Integration in Working Memory in Language Development

Studies have shown that the phonological loop supports both vocabulary and grammar development (Adams & Gathercole, 1995, 1996; Blake et al., 1994; Gathercole & Baddeley, 1989, 1990; Gathercole et al., 1999; Gathercole et al., 1992). The verbal working memory system makes such contributions because it deals with the same type of information that is the basis of spoken language; however, language is not limited to the spoken domain. The language learner must be able to relate the verbal labels to the participants, their roles, and the images that they see. Because of the overlap in demands placed on the visual and verbal systems, integrative ability may make a unique contribution to language development. One goal of the current study was to explore the relationship between visual-verbal integration in working memory and advancements in language.

It was predicted that vocabulary size increases between 6 and 10 years of age and, if present, the unique contributions to receptive vocabulary from working memory would decrease with age. Based on a review of the literature, performance on working memory tasks is most

predictive of vocabulary size at the early stages of acquisition. Because children between 6 and 10 years of age have mastered many of the skills needed to learn new words via spoken language, the demands on working memory may be minimal. Although working memory might make relatively small contributions to the more developed aspects of language, its importance may be most evident in contributions to emerging skills. In contrast, it was hypothesized that visual-verbal integration in working memory would make a unique contribution to receptive grammar ability after taking into account age and working memory performance on tasks that were limited to a single modality (unimodal working memory).

Predictions Regarding the Role of Visual-verbal Integration in Working Memory in Reading Development

The ability to integrate visual and verbal material in working memory might support the translation of an orthographic code into its corresponding phonological representations. The integrative aspect of working memory may be especially important for children who are just learning to read because the conversion of letters to associated phonemes is not yet automatized. Within the verbal domain, studies of the phonological loop have supported the notion that working memory is especially important during periods of acquisition in language development (Gathercole & Adams, 1993; Gathercole et al., 1992; Gathercole, Willis, Baddeley, & Emslie, 1994). It is logical to propose that integrative ability would make similar contributions during the acquisition of reading. In the present study, it was hypothesized that visual-verbal integration would make a unique contribution to decoding after accounting for age and unimodal working memory.

Method

Participants

Children between 6 and 10 years of age were recruited from five public schools to participate in the present study. All participants met the following eligibility requirements:

- visual acuity within normal limits or corrected to the normal range
- hearing within normal limits
- not receiving speech therapy services in the school system
- no diagnosed learning disabilities

Participants also were limited to children learning English as their primary language. A survey, completed by parents, provided information about children's exposure to written and oral languages (see Appendix A). Children were included only if the parents indicated exposure to English in the home at least 90% of the time. This decision was made because the novel auditory stimuli in the working memory assessments were developed based on phonotactic rules of the English language and might not be valid for testing children with a different primary language. Participants were also limited to children that had not been exposed to written languages that use a character system other than the Latin alphabet. The visual stimuli used in the working memory assessments were intended to be novel to children and consisted of Kanji characters.

After attaining parental consent, 46 children (23 males, 23 females) between 6 and 10 years of age were tested. The mean age of participants was 8;5 (*SD* = 1;3) with ages ranging from 6;0 to 10;9. Five additional children who were 11 years of age were also tested; however, these data were initially excluded because the current study was originally designed to examine children 6 to 10 years of age. In exploratory analyses, these data were included because the goal was to provide the broadest picture of development possible. Experimenters identified the

ethnicity of all of the children as White. This reflected the demographics of the participating elementary schools. Four of the five schools reported that less than 1% of their population was African American or American Indian. Three schools reported that more than 90% of their students were White. One school reported 18% of students were Hispanic, but most of the Hispanic children in this school did not speak English in the home. These four schools also reported that the percentage of students eligible to receive a free or reduced price lunch ranged from 38% to 58%.

Procedures

Testing took place in a quiet area at the school. The child was asked to give verbal assent to testing. Examiners addressed any questions that the children had about their participation. Each child was administered a battery of tests that assessed receptive vocabulary, receptive grammar, reading and working memory. The order of administration of the individual tests was randomized across participants. The standardized procedures provided in the test administration manuals of each measure were used for all children. Testing took approximately 1 hr 15 min to complete and took place during a single testing session.

Measures

Vocabulary Measure

Peabody Picture Vocabulary Test - Third Edition (PPVT-III; Dunn & Dunn, 1997). The PPVT-III is a commonly used standardized measure of receptive vocabulary for Standard American English. During testing, an examiner reads a single word, and the child is asked to select the picture that best illustrates the meaning of the word from an array of four black and white drawings. Scoring procedures described in the test administration manual were followed when determining children's raw and standard scores.

Grammar Measure

Test for Reception of Grammar (TROG; Bishop, 1989). The TROG is an individually administered, multiple-choice test designed to assess receptive grammar. During this test, an experimenter reads a word, phrase, or sentence, and the child is asked to select the picture that best represents the meaning of the stimulus item from an array of four drawings. Twenty grammatical constructions are assessed in four-item blocks. Raw scores reported on this measure represent the number of blocks in which the child answered all four items correctly.

Reading Measure

Woodcock Reading Mastery Test-Revised-Normative Update (WRMT-R/NU; Woodcock, 1998). The WRMT-R/NU is used to assess reading achievement and reading-related abilities in individuals between 5 and 75 years of age. This is an individually administered, norm-referenced assessment. The Word Attack and Word Identification sub-tests from the Basic Skills Cluster provided a measure of decoding skills. In both tasks, children read a list of words (or nonwords) aloud. Scoring procedures described in the test administration manual were followed when determining children's raw and standard scores.

Working Memory Measure

Paired Associates Intermodal Response Scale (PAIRS; Robinson & Smith, 2005): This measure assesses unimodal and cross-modal working memory in individuals over 3 years of age. Tasks limit contributions from long-term memory by using nonwords and unfamiliar images. Dollaghan's rules for generating the nonwords were used to create the novel verbal items used in this measure (Dollaghan, Biber, & Campbell, 1993; Dollaghan & Campbell, 1998). These rules follow the phonotactics of English while reducing the frequency of wordlikeness. Potential contributions of familiarity for the visual images were limited by selecting images that would not

be familiar to English speaking children. These images were Kanji characters that were difficult to verbally name.

The PAIRS battery includes four separate tasks. Examples of each task are included in Appendix B. For each task, the number of pairs presented increases until the child can no longer perform at above-chance levels. The number of pairs increases from one to a maximum of six pairs. The child's span score represents the highest number of pairs he or she can remember. The tasks are divided as follows based on the stimuli involved in each pair:

Unimodal tasks:

In the *unimodal verbal task*, participants are presented with an increasing number of nonword pairs. Recall of a pair is probed when the participant is given one member of a pair and asked to verbally report the corresponding target. This measure includes eight levels of performance. The first level includes a single pair of 1-syllable nonwords. If this was the highest level that the child completes, his or her span score is one. The second level includes one pair of 2-syllable nonwords and corresponds to a span score of two. The third level consists of two pairs of 1-syllable nonwords (span of 3). The next five levels (representing span scores of 4 to 8) include two to six pairs of 2-syllable nonwords.

In the *unimodal visual task*, participants are presented with pairs of side-by-side pictures of unfamiliar images that are difficult to verbally label. Recognition of paired items is probed when participants are shown one member of a pair and asked to select the corresponding image from a visual array that includes the target image and three distracters. Span scores are equivalent to the number of pairs presented.

Cross-modal tasks:

In both the *cross-modal task with verbal recall* and the *cross-modal task with visual recognition,* participants are presented with increasing numbers of nonword-unfamiliar image pairs. For the verbal recall task, participants are shown one of the unfamiliar images and asked to provide the associated verbal label. In the visual recall task, the participant is given one of the nonwords and asked to identify the target image from an array of four items. For both tasks, a span score of one indicates that the child passed a level that included an image paired with a 1-syllable nonword. On the second level, children are presented with one 2-syllable nonword-image pair (span of 2). On subsequent levels (spans of 3 to 7), children are presented with two to six pairs that utilize 2-syllable nonwords.

Results

Preliminary Analyses

Prior to analyzing the development of visual-verbal integration and its relation to language and reading, a descriptive analysis of all data was performed. Preliminary analysis included an examination of variable means and standard deviations, a check for outliers, and review of the distribution of scores and errors to insure that the data were appropriate for the planned inferential statistical analyses (see Table 1 for descriptive statistics). The distribution of raw scores on the reading tests was slightly skewed. A square root transformation normalized the distribution. There were, however, no meaningful differences in the findings (based on statistical significance) for either form of the data. For the sake of interpretability, the data reported reflect the original raw values. The preliminary analysis for all other variables indicated that they were approximately normally distributed and all other assumptions for the planned inferential analyses were met. Scores from the reading tests were excluded for 1 case because it was not clear that the

child understood the tasks, and scores on the nonword reading measure were identified as statistical outliers. In 3 cases, scores on the grammar measure were excluded due to administrator error and treated as missing data. Bivariate correlations between individual tests in the battery are shown in Table 2 below the diagonal. Partial correlations (after accounting for age) are shown in Table 2 above the diagonal.

Table 1

Mean Test Scores for Children between 6 and 10 Years of Age

Measure	N	Mean	SD
Language			
PPVT	45	108.80	9.85
TROG	42	102.29	15.48
Reading			
Word ID	45	114.64	11.49
Word Attack	45	115.82	12.43
Working memory			
Unimodal			
Verbal [a]	46	4.46	1.47
Visual [b]	46	1.52	0.89
Cross-modal			
Verbal recall[c]	46	3.52	1.03
Visual recognition[c]	46	5.67	1.45

Note. Scores on tests of language and reading represent standard scores.

Standard scores for reading tests based on age.

[a] maximum score of 8, [b] maximum score of 6, [c] maximum score of 7

Sample sizes: 6-year-olds (n = 4); 7-year-olds (n = 16); 8-year-olds (n = 11); 9-year-olds (n = 8); 10-year-olds (n = 7)

Table 2
Correlations

		Language				Reading				Working memory			
	Age	PPVT		TROG		Word ID		Word Attack		Unimodal		Cross-modal	
	(months)	raw	SS	raw	SS	raw	SS age	raw	SS age	verbal	visual	verbal	visual
PPVT													
raw	.87**		**.99****	**.20**	**.16**	**.23**	**.35***	**.21**	**.32***	**.01**	**.05**	**-.09**	**.18**
SS	.42*	.82**		**.18**	**.15**	**.18**	**.37***	**.16**	**.29**	**.02**	**.06**	**-.07**	**.16**
TROG													
raw	.52**	.54**	.36*		**.91****	**.33***	**.34***	**.43****	**.40***	**.10**	**.15**	**.40****	**.16**
SS	.16	.21	.20	.85**		**.20**	**.23**	**.29**	**.25**	**.05**	**-.01**	**.35***	**.13**
Word ID													
raw	.67**	.67**	.40**	.56**	.25		**.92****	**.88****	**.84****	**.16**	**.07**	**.10**	**.10**
SS age	-.44*	-.22	.11	.03	.14	.32*		**.80****	**.83****	**.11**	**.05**	**.07**	**.10**
Word Attack													
raw	.38**	.43**	.30	.54**	.32*	.86**	.50**		**.96****	**.16**	**.01**	**.22**	**.12**
SS age	-.42*	-.22	.06	.09	.16	.29	.87**	.64**		**.11**	**.06**	**.21**	**.16**
Working memory													
unimodal													
verbal	.32*	.28	.15	.25	.09	.33*	-.05	.26	-.04		**.07**	**.20**	**.15**
visual	.58**	.53**	.29	.40**	.08	.43**	-.22	.23	-.20	.24		**.17**	**.29**
Cross-modal													
verbal	.11	0.05	-.02	.39**	.36*	.15	.01	.25	.14	.23	.30*		**.00**
visual	.13	.20	.19	.21	.16	.16	.03	.16	.09	.18	.01	.20	

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).
values below the diagonal are bivariate, above the diagonal in bold are partial correlations controlling for age

Developmental Analyses

The examination of age related improvements in working memory span involved a descriptive, visual analysis of data and a regression-based growth curve analysis (trend analysis) for the PAIRS measure. Composite scores were computed for the two unimodal working memory tasks by adding the unimodal verbal and unimodal visual spans together. Span scores from the two cross-modal measures were added together to form a composite cross-modal span score. Composite scores provided a way to balance the possible effects of task demands for the measures and allow a direct comparison of unimodal and cross-modal performance. Therefore, both composite spans included one task in which the child needed to generate a verbal label (recall) and one task where the child needed to choose the target image from an array of four items (recognition). Separate regression analyses were performed for each of the following dependent variables: composite scores from the unimodal tasks and cross-modal tasks, each task separately, and residuals of composite cross-modal span after accounting for composite unimodal span.

Growth in Unimodal Working Memory Between 6 and 10 Years of Age

Analysis of growth on composite scores from unimodal tasks.

The first set of analyses was aimed at examining growth in unimodal working memory. A trend analysis was performed using composite unimodal scores as the dependent variable and age as the independent variable. As Figure 3 shows, children's combined unimodal visual and verbal spans increased steadily between 6 and 10 years of age. A hierarchical regression indicated that there was a significant linear trend (F (1,44) = 16.43, $p < .001$). Composite unimodal span improved approximately 0.78 units per year. There were no significant curvilinear trends.

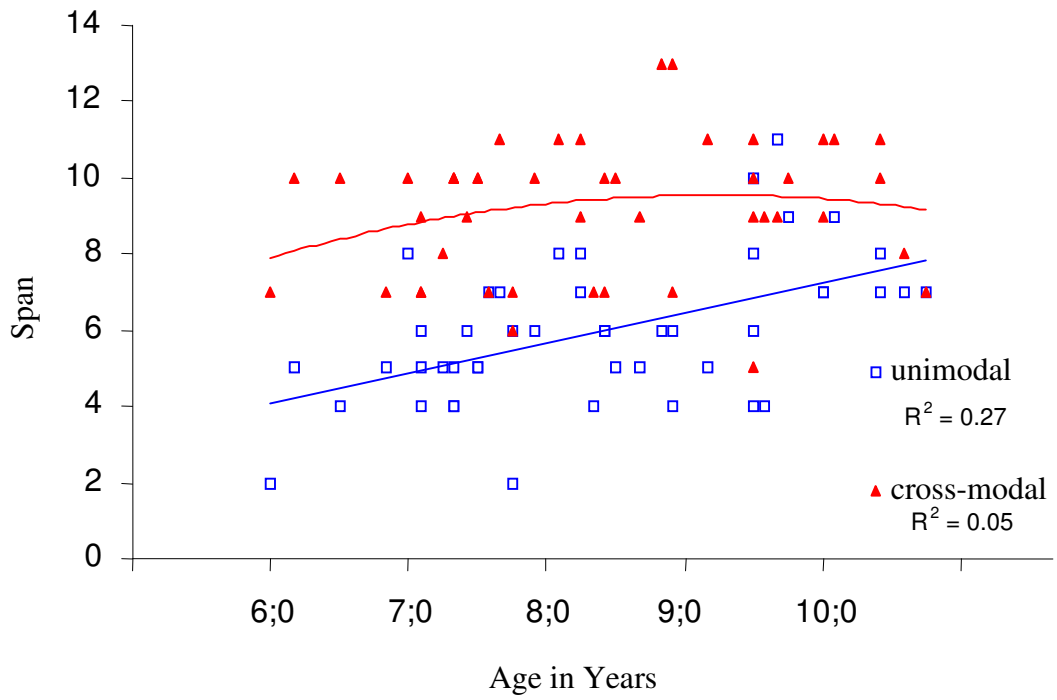

Figure 3. Growth of Unimodal and Cross-modal working memory span (composite scores) in children 6 to 10 years of age.

Analysis of growth on individual unimodal tasks.

Growth also was examined for the individual unimodal tasks. As shown in Figure 4, spans on the verbal unimodal measure increased from a mean of 3.5 units for 6-year-olds to a mean of 4.9 units for 10-year-olds. Spans on the unimodal visual task increased from an average of 0.5 units for 6-year-olds to an average of 2.6 units at age 10 years. A hierarchical regression indicated that the linear model provided a significant fit to the data from the unimodal verbal task (F (1,44) = 4.99, p = .03) with span increasing approximately 0.37 units per year. The linear trend also provided a significant fit to the data from the unimodal visual task (F (1,44) = 22.51, p

< .001) with children's span increasing at a rate of approximately 0.41 units per year. There were no significant curvilinear components. Given the rates of growth indicated for the linear models, children's unimodal verbal and visual working memory spans increased by approximately one pair every 2 to 3 years.

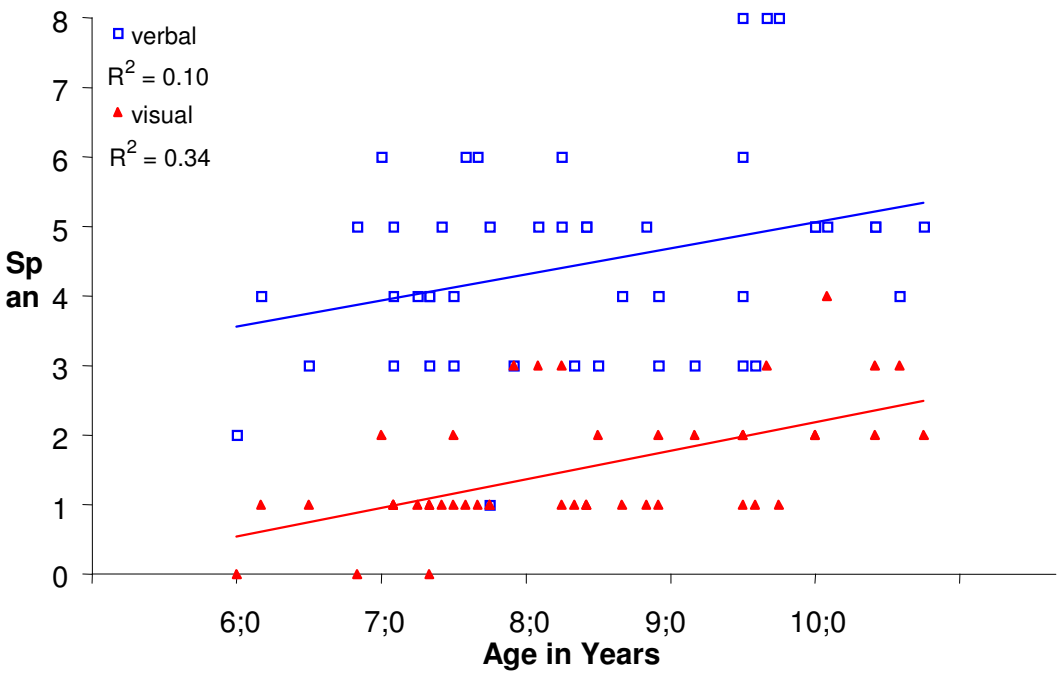

Figure 4. Growth of unimodal working memory between 6 and 10 years of age.

Growth in Cross-modal Working Memory Between 6 and 10 Years of Age

Analysis of growth on composite scores from cross-modal tasks.

Age related growth in cross-modal span was also examined. A visual analysis of the data shown in Figure 3 suggested that there was slight improvement in composite cross-modal scores between 6 and 10 years of age. Mean composite cross-modal span scores increased from 8.5 units for 6-year-olds to 9.5 units for 10-year-olds; however, a hierarchical regression yielded no significant linear component (F (1,44) = 1.19, p = .28) or curvilinear components.

Analysis of growth on individual cross-modal tasks.

Another set of analyses was performed to examine performance on the individual cross-modal tasks. Data from the cross-modal task with verbal recall shown in Figure 5 suggested slight improvements at a rate of approximately 0.13 units per year; however, performance reached ceiling levels for some of the children over 7 years of age. On the cross-modal task with visual recognition shown in Figure 6, there were neither floor nor ceiling effects, and slight growth was suggested (at a rate of approximately 0.10 units per year). A regression analysis of the growth in the two cross-modal tasks failed to reach statistical significance (cross-modal task with verbal recall (linear: F (1,44) = 0.55, p = .46; cross-modal task with visual recognition (linear: F (1,44) = 0.71, p = .41). Analyses also indicated that there was no significant deviation from linearity.

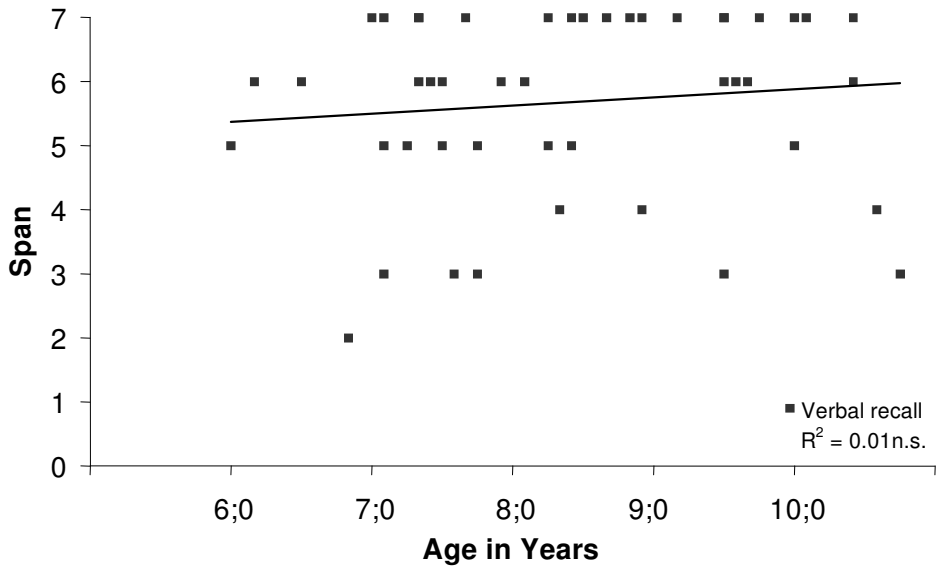

Figure 5. Growth of cross-modal working memory task with verbal recall between 6 and 10 years of age.

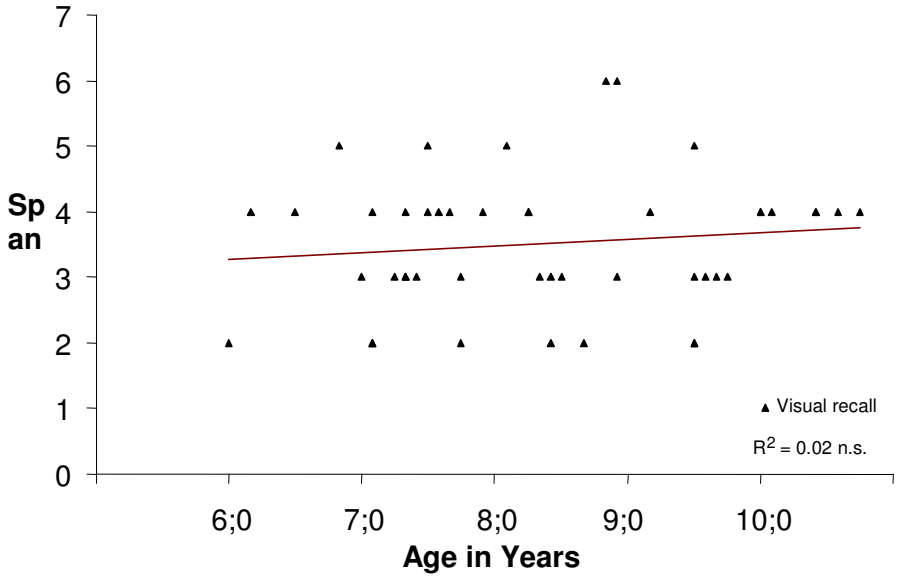

Figure 6. Growth of cross-modal working memory task with visual recall between 6 and 10 years of age.

Analysis of growth of residual cross-modal span after accounting for unimodal span.

A statistically significant correlation between unimodal and cross-modal composite span scores was found (r (46) = .38, p = .01; partial correlation controlling for age pr (46) = .35, p = .02). One possible explanation for the lack of statistically significant growth in cross-modal working memory was that effects stemming from unimodal working memory were masking the growth on the cross-modal measures. In order to examine whether this was the case, a regression analysis of growth in cross-modal composite span after controlling for unimodal composite span was conducted. The regression analysis yielded no significant linear or curvilinear trends (linear: R^2 = .03; F (1,44) = 1.19, p = .28).

Relation to Language Development

The relation between visual-verbal integration and vocabulary ability among school-aged children was examined using a regression approach. The dependent variable representing receptive vocabulary in the regression analysis was raw scores on the PPVT-III. Using hierarchical regression, age was treated as a covariate and entered in the first step. Next performance on the unimodal visual and verbal paired associates tasks was taken in to account. These measures represent the contributions of the phonological loop and the VSSP to vocabulary size. In the final step of the regression, scores on the two cross-modal tasks were added. Performance on these two tasks represented contributions from visual-verbal integration. These analyses indicated that, whereas receptive vocabulary size increases with age, neither unimodal nor cross-modal working memory contributed to receptive vocabulary between 6 and 10 years of age (see Table 3).

The relation between grammatical ability and visual-verbal integration was examined in a similar manner. First, the effects of age were taken into account, and then performance on the

two unimodal paired associates tasks were taken in to account. Finally, performance on the two cross-modal tasks was entered into the regression. The analysis indicated that age and cross-modal span each made a unique contribution to raw grammar scores (see Table 4). The same pattern of effects was found when PPVT-III scores were entered prior to the working memory tasks. Vocabulary scores explained 3.0% of the variance in TROG scores (F (1,38) = 1.66, p = .21) after controlling for age. The proportion of variance accounted for by unimodal and cross-modal spans did not change.

Table 3

Regression of Age and Working Memory on Receptive Vocabulary for Children between 6 and 10 Years of Age (N = 45)

Step	Variable Added	R^2_{Total}	R^2_{change}	β
1	age	.75**	.75**	.85**
2	Unimodal spans	.75**	.00	
	verbal			.00
	visual			.01
3	Cross-modal spans	.76**	.01	
	verbal recall			-.05
	visual recognition			.09

Note. *p < .05, **p < .01.

β's reported in this table are from the final step of the regression

Table 4

Regression of Age and Working Memory on Receptive Grammar for Children between 6 and 10 Years of Age (N = 42)

Step	Variable Added	R^2_{Total}	R^2_{change}	β
1	age	.27**	.27**	.44**
2	Unimodal spans	.29**	.02	
	verbal			-.01
	visual			.04
3	Cross-modal spans	.40**	.11*	
	verbal recall			.34*
	visual recognition			.14

Note. *$p < .05$, **$p < .01$.

β's reported in this table are from the final step of the regression

Relation to Reading

The relation between visual-verbal integration and reading ability also was analyzed using a regression approach. The dependent variables in the regression analyses were raw scores from the Word Attack test (nonword reading) and the Word ID test (word reading). Analysis proceeded in a hierarchical fashion (see Table 5). First, age was regressed on the raw scores from each reading test (word and non-word). Next performance on the unimodal visual and verbal paired associates tasks was taken into account. These measures represented the contributions of the phonological loop and the VSSP to decoding ability. In the final step of the regression,

performance on the two cross-modal tasks was added. Neither unimodal nor cross-modal working memory span made significant contributions to raw scores on the word and nonword reading tests. Adding raw PPVT-III scores as a covariate in addition to age did not effect the results of the regression analysis. The addition of raw TROG scores as a covariate did not alter the relative contributions of unimodal or cross-modal working memory, but grammar did account for an additional 6% of the variance in word reading (F (1,38) = 4.73, p = .04) and 16% of the variance in nonword reading scores (F (1,38) = 8.49, p < .01) after controlling for age. A similar pattern of results was found when standard scores were used in place of raw scores. One difference between the regressions using raw and standard scores was that when standard scores were used, receptive vocabulary made significant contributions to both word and nonword reading scores. Neither unimodal nor cross-modal span explained a significant proportion of variance.

Table 5

Regression of Age and Working Memory on Reading for Children between 6 and 10 Years of Age (N = 45)

		Word ID		
Step	Variable Added	R^2_{Total}	R^2_{change}	β
1	age	.45**	.45**	.61**
2	Unimodal spans	.47**	.02	
	verbal			.10
	visual			.02
3	Cross-modal spans	.47**	.01	
	verbal recall			.05
	visual recognition			.06

		Word Attack		
Step	Variable Added	R^2_{Total}	R^2_{change}	β
1	age	.14**	.14**	.37*
2	Unimodal	.17	.02	
	verbal			.10
	visual			-.09
3	Cross-modal	.21	.05	
	verbal recall			.20
	visual recognition			.12

Note. *$p < .05$, **$p < .01$.

β's reported in this table are from the final step of the regression

Discussion

Working Memory: Theoretical Issues and Insights from Development

General Changes in Working Memory and the Unimodal Systems

Results from a growth curve analysis using composite scores from two unimodal paired associates tasks (verbal and visual) in the present study are consistent with earlier studies in indicating a steady improvement in overall working memory span between 6 and 10 years of age (Case, 1987; Case et al., 1982; Cowan, 1997; Schneider & Bjorklund, 1998). When each unimodal task was analyzed separately in the present study, verbal span scores indicated that children were able to work with approximately two pairs of 1- or 2-syllable nonwords at 6 years of age and could work with three or four pairs of 2-syllable nonwords by 10 years of age. Children's visual span scores were near floor levels (between zero and one pair) at 6 years of age and increased to approximately two or three pairs by 10 years of age. Although not all models specify a separation between visual and verbal forms of working memory, researchers have implied a distinction. Cowan's model (1997) does not explicitly differentiate between visual and verbal working memory, yet he acknowledges that the supporting evidence, such as selective interference in performance and differences in neurological processing, is compelling. Pascual-Leone (2000) also discusses differences between visual and verbal working memory that he suggests involve experiential and learning factors as opposed to different memory structures. Baddeley and Hitch (1974; see also Baddeley, 2000a, 2001) propose separate systems in working memory dedicated to the processing of unimodal visual and verbal information. Empirical studies suggest that span increases should be found when examining visual and verbal working memory separately (Demetriou et al., 2002; Gathercole & Baddeley, 1993; Gathercole et al., 2004; Kemps et al., 2000; Pickering, 2001).

The Episodic Buffer as a Framework for Understanding Changes in Integration

Prior to the addition of the episodic buffer in Baddeley's model of working memory (Baddeley, 2000a, 2001; Baddeley & Hitch, 2000; Baddeley & Wilson, 2002), researchers assumed that when an individual saw a picture of a familiar object, the verbal label was automatically available in the phonological loop. This assumption was based on findings from studies using older children and adults; however, when samples included 4- and 5-year-olds, it appeared that younger children did not automatically generate verbal labels (Halliday et al., 1990; Hitch & Halliday, 1983; Hitch et al., 1991). The lack of automaticity on the part of younger children was credited to immaturity, but researchers did not further delineate the issue (Pascual-Leone, 2000). A more precise explanation might be that development in the episodic buffer supports integration of information from different sources. Thus far, empirical studies of the episodic buffer have been limited to exploring integration from long-term memory in adults with impaired memory function (Baddeley & Wilson, 2002) and typically developing children between 4 and 6 years of age (Alloway et al., 2004). Alloway and colleagues argued that the buffer is functioning in 4-year-olds, correlated with age, and distinct from the phonological loop and central executive, but they did not address development of the component or direct integration from the visual and verbal systems.

Instead of postulating the existence of an episodic buffer that supports integration, it could be argued that children use the central executive to rapidly switch attention between the visual and verbal systems. In situations where children must report a verbal list of visually presented items, the differences between younger and older children might be the result of underlying improvements in the ability to shift attention between the modalities instead of drawing from a common code. The literature has generally supported an increase in the

efficiency of the central executive over the course of development (Gathercole & Baddeley, 1993). Children become better able to coordinate and maintain attention as well as plan and monitor behavior. However, the central executive has no storage capacity and does not provide a means for maintaining multiple links between items. Therefore, it is the episodic buffer as opposed to the central executive that is called upon when task demands, such as those in the cross-modal paired associates task used in the present study, require the active storage and processing of both visual and verbal forms of information.

Further support for the existence and distinction of the episodic buffer comes from neuroimaging studies. Based on the Baddeley model (2000a, 2001), when information enters working memory it is routed to a modality specific component. Processing of information from each modality is associated with different areas of the brain. Using functional magnetic resonance imaging (fMRI), Gruber and von Cramon (2003) found that visual working memory tasks were processed in the bilateral prefrontoparietal area, and verbal working memory was associated with activity in the left premotor and parietal regions. Integration, however, seems to require more than separate processing of visual and verbal information. The information must be linked in some way, and those links maintained. One way of doing this is for a memory system to convert the modality specific codes to a common code that is accessible to both systems (Kee et al., 1981). Baddeley (2000a, 2001) suggests that the episodic buffer is responsible for conversion to an amodal format. Gruber and von Cramon propose that amodal storage within the episodic buffer is localized in the right middle frontal gyrus and bilaterally along the anterior/middle intraparietal sulcus. Whereas discrete areas were identified for amodal storage, nonspecific processing associated with the central executive was widely distributed and did not seem to involve a specific locale. Also using fMRI, Zhang et al. (2004) indicated that cross-

modal information was stored and processed in the right middle and superior frontal gyri; bilateral prefrontal, right premotor, and temporo-parietal junction (TPJ); and left superior parietal cortices.

Findings from the Present Study Interpreted in the Context of the Episodic Buffer

In the cross-modal paired associates tasks used in the present study, children were presented with both visual and verbal forms of information. The tasks required that children not only maintain both types of information but also remember the connections between items. Under Baddeley's model of working memory (2000a, 2001), the ability to store and manipulate these visual-verbal pairs utilizes the episodic buffer (A. D. Baddeley, personal communication, September 29, 2003). Findings from the present study did not support age-related increases in the capacity of the episodic buffer. Although the analysis of growth between 6 and 10 years of age suggested improvements in children's unimodal span, changes in cross-modal span failed to reach statistical significance.

One difference in performance on the two cross-modal tasks was that spans on the verbal recall task seemed to be approaching ceiling levels. Between 8 and 11 years of age, mean spans were approximately five pairs, and over half of the children scored the maximum span of six pairs. In contrast, spans on the visual recognition task averaged between two and three pairs, and no child had a span of six pairs. Given that children were reaching ceiling levels on the cross-modal task with verbal recall, it is possible that the task was not sensitive to growth after 8 years of age. However, at some point there will be a limit to the number of items that can be maintained. It is not unreasonable to propose that children are nearing a true ceiling in the capacity of the episodic buffer because, in order to manage six pairs, children must store and manipulate 12 items along with the relationship between the paired items.

One of the weaknesses of the present study was the lack of 6-year-olds in the sample. While efforts were made to find first-graders between 6;0 and 6;11, very few were available. This was due, in part, to public school requirements that specify that children must be born before a certain date in order to enroll. With testing taking place near the end of the school year, most children that were 6-years-old at the beginning had passed their seventh birthday by the time of testing. Of the 16 7-year-olds that participated in the present study, 8 were within 4 months of their seventh birthday. Having more data about the development of visual-verbal integration between 6;0 and 6;11 might have resulted in reaching statistical significance for cross-modal growth curves in the present study.

One reason for restricting the sample used in the present study to children 6 to 10 years-of-age was to insure that all participants had received formal instruction for at least one year. This was important because of possible effects of formal education on the processes under investigation in the present study, particularly reading. Direct instruction in reading, vocabulary, and grammar, at least should, impact children's performance in these domains above and beyond developmental improvements based solely on chronological age. Empirical evidence supports this position (Morrison, Griffith, & Fraizer, 1996). Although the rationale for restricting the sample to children who had experienced formal instruction in a public school setting seemed sound, perhaps a better strategy would have been to include a broader range of ages.

Before concluding that cross-modal working memory does not change over the course of childhood, the possibility that growth was occurring earlier than predicted was examined in an exploratory manner. A possible explanation for the lack of growth in visual-verbal integration between 6 and 10 years was that the age range sampled was not sufficient to capture the underlying picture of development because growth was occurring earlier than the literature

suggested. If this were the case, children's cross-modal spans may be leveling off by middle childhood. Fortunately, it was possible to explore this prospect.

Exploratory Analyses

Data from 58 children between 3;0 and 5;11 years of age (11 males; 47 females) were available from another study (Robinson & Smith, 2005). The mean age of participants was 4;2 (*SD* = 0;9) with ages ranging from 3;2 to 5;9. Experimenters identified the ethnicity of children and indicated that the sample included 10 African American children, 2 Hispanic children, 43 White children, 2 children that were identified both African American and White, and 1 child whose ethnicity was not identified. By combining these data with those from the present study, it was possible to explore development from a much broader perspective. The 3- to 5-year-old children were recruited from daycare centers and private schools located in a large metropolitan area in the southern United States. The eligibility criteria were the same as those described in the present study. Children in the Robinson and Smith study completed a battery of tests that included the PPVT-III, TROG, and PAIRS measures. In addition, the battery included one standardized measure of expressive language, four measures of visual and verbal working memory, and play sessions. Reading tests were not administered to the younger sample. The test battery was administered in two to four sessions on different days using the same procedures as those in the present study. Descriptive statistics for these data are provided in Table 6 in Appendix C. Data from the two studies were combined along with data from five 11-year-olds that were tested in the present study but not included in analyses because the study originally specified an age range of 6- to 10-year-olds. Growth was re-analyzed in the manner described in the results section of the present study. The results of these analyses are included in Appendix C.

These analyses were exploratory and provided important hints about the underlying changes that may be taking place in visual-verbal integration.

When the age distribution was expanded to include children between 3 and 11 years of age, a compelling developmental picture emerged. Based on this picture, it appears that children's integrative ability may change substantially between 3 and 11 years of age; however, much of this growth may occur before 7 or 8 years of age. As the quadratic growth curve suggests, by seven or eight years of age, the rate of growth in visual-verbal integration may be slowing (or leveling off). Details of the results of growth curve analyses are presented in Appendix C. The findings related to the picture of growth provided by the two cross-modal tasks were quite consistent in terms of age at which scores were stabilizing. In both cross-modal tasks, the developmental trajectories indicated that growth occurred rapidly between 3 and 7 years of age. Mean spans on the cross-modal task with verbal recall increased at a rate of approximately 0.9 units per year between 3 and 7 years of age. During this time, spans on the cross-modal task with visual recognition grew at a rate of approximately 0.7 units per year. Between 8 and 11 years of age, there were no substantial improvements on either cross-modal task.

A possible interpretation of the findings regarding development is that the age-related differences that were found were the result of combining separate samples from the present study and Robinson and Smith (2005). Following this line of reasoning, several possibilities could be offered. First, children tested in the present study might simply reflect a sample from the higher end of a normal distribution. Conversely, the sample from the Robinson and Smith study might reflect a sample from the lower portions of the distribution. It might also be argued that differences in the samples were reflective of differences in the quality of education that children

were receiving. A third alternative is that differences in testing procedures created systematic differences in performance.

One difference between the two samples was the recruitment strategy. It was possible that because one sample was drawn from an urban/suburban area and the other sample was drawn from a rural area. Children in one group may have been higher functioning than those in the other group. Given the pattern of results, this would suggest that the children in the present study had overall higher levels of performance on the measures administered. To a certain extent, this possibility could be examined informally by comparing the available standard scores from the tests of vocabulary and grammar. For both samples, the mean standard scores were very close to 100 and standard deviations were very close to 15, which are the standardization values reported for both measures. A tentative comparison of standard scores on the vocabulary and grammar measures suggested that there was not a statistically significant difference between standard scores for these groups (based on the results of an independent samples t-test). This might seem to suggest that both samples reflected a group that was fairly representative (neither unusually high or low on the distribution) and there was a range of ability levels similar to what would be expected in a large population of children.

Another possible source of differences between the two samples might have been related to the quality of education each group was receiving. If this were the case, it would suggest that children in the present study might be at an advantage because of more effective education. To a certain extent, differences in education could not be controlled. Around 6 years of age, most children in the United States begin their formal education in elementary school. Prior to this, children's care and education takes place in a variety of contexts. A child may be cared for in the home, participate in childcare outside of the home, or receive some type of early education. As it

related to the exploratory analyses, the most salient difference between the samples was that the children tested in the present study had begun elementary school, which represents a part of the typical developmental process for many children in the American culture. If the changes in integration were the result of instruction, it may not nullify the findings that suggest age-related changes in visual-verbal integration. To the extent that it was possible, efforts were made to ensure that education was uniform (hence, the choice of recruiting from public schools as opposed to private schools where more variability may exist in instructional practices). To the extent that it was not possible to control differences in education, recruitment in both studies was aimed at sampling a variety of individual settings. Children in the present study were recruited from seven public schools in two rural school districts. Children in the Robinson and Smith (2005) study were recruited from five different contexts near a large urban area. Some of the facilities were primarily focused on childcare while others were focused early education and used different methods of instruction.

It could also be argued that the difference in the administration of the test batteries accounted for the differences in visual-verbal integration. The test battery in the Robinson and Smith (2005) study was more extensive and time consuming. If the cross-modal tasks were administered at the end of the test battery in the Robinson and Smith study but at the beginning of the battery in the present study, it could be argued that the lower scores were the result of the children being tired. The order of administration of tests was randomized across children in both studies in order to minimize systematic effects due to test order. Also, standardized procedures were used in test administration and all examiners received extensive training in testing with children. For example, administrators were trained to recognize signs of fatigue. To avoid fatigue and being sensitive to the limitations in younger children's ability to stay on task for extended

periods of time, the test battery in the Robinson and Smith study was administered over several sessions.

Implications for Baddeley's (2000) Model of Working Memory and Conceptualizations of the Episodic Buffer

Baddeley (2000a) suggests that, although direct integration of information from the phonological loop and VSSP was not specified in the revised model of working memory, future studies may demonstrate the need for additional pathways linking the two systems directly to the episodic buffer. The results of the present study support this addition. Although empirical studies of the buffer are beginning to emerge in the literature, the focus has been on integration from long-term memory (Alloway et al., 2004; Baddeley & Wilson, 2002). In both studies, the authors claimed that the increase in span length on measures of prose recall and sentence repetition was the result of a reduction in the demands placed on working memory when items were presented in sentence form. This format makes chunking easier, and the participant is able to draw on their long-term knowledge of how sentences are structured. Similarly, studies from the working memory and paired associates literatures may have been tapping integration from long-term memory (Halliday et al., 1990; Hitch & Halliday, 1983; Hitch et al., 1991; Hitch et al., 1988). Many of these studies used pictures of familiar items. Other studies (Windfuhr & Snowling, 2001) used novel words and pictures, but the task for children was one of learning the pairs of items.

One problem with the previous studies, particularly those with children, is controlling for the individual's level of familiarity with the stimulus items. Children's long-term knowledge base changes over the course of childhood; however, the previous studies did not address how

familiar children were with the stimulus items or sentence forms. Therefore, it is not clear how much of the integration was from long-term memory and how much reflected direct integration from the separate visual and verbal systems. A possible explanation is that the age-related differences found in earlier studies were due to differences in children's levels of long-term knowledge as opposed to differences in working memory. Older children, who were more familiar with the verbal labels of the stimulus items and sentence structures, were able to integrate information from long-term memory while younger children could not. When there is little or no support from long-term memory, the child has no choice but to rely on less efficient visual rehearsal strategies or maintenance rehearsal (in the case of sentences). This account does not, however, provide much insight into why the changes observed did not take place until 6 to 8 years of age. If the line of logic was followed, either children did not have long-term representations of the stimulus items and sentences or the episodic buffer was not sufficiently developed to support integration until middle childhood.

The design of the present study differed from previous studies in that attempts were made to limit the potential contributions from long-term memory by using nonwords and unfamiliar images. Further, heavy demands were placed on the capacity of the system when children had to store and process a substantial quantity of information from both visual and verbal modalities. It could be argued that the most efficient solution to the memory demands is direct integration from the visual and verbal systems. Data from the current study and exploratory analyses are consistent with the notion that children may be able to integrate visual and verbal information with limited long-term representations, and their ability to integrate may begin much earlier than previous studies seem to suggest. Whereas previous studies propose that children begin integrating between 6 and 8 years of age, the data presented in Appendix C suggest that as early

as 3 years of age children may be integrating. Perhaps a better way to interpret the findings from the previous studies is to do so in the context of a model that includes direct integration from the phonological loop and VSSP as well as integration from long-term memory. From this perspective, findings from earlier studies showing older children and adults use verbal coding for serial recall of pictures of familiar items may reflect changes in the working memory system that are supported by developments in integrative ability. Although data from the present study did not indicate significant changes in cross-modal working memory span for children between 6 and 10 years of age, the developmental trends noted in the exploratory analyses suggest that this may be the case.

Explaining Changes in Visual-verbal Integration in Working Memory

General increases in the capacity of the working memory system may contribute to developmental improvements in visual-verbal integration. Pascual-Leone (2000), Baddeley (2000a, 2000b), and Cowan (1997; Cowan et al., 1999) seem to agree that the capacity of working memory increases during childhood. These theorists have also examined changes in processing ability that may support capacity increases. Researchers such as Case, Halford, Hulme, and others use a more abstract definition of capacity and suggest that the *total capacity* remains constant but more efficient processing allows the system to store more items. Regardless of whether the increases stem from increases in processing efficiency or storage capacity, the net result is the same; the child is able to remember more items. Improvements in children's ability to integrate visual and verbal information may also be related to an increase in the capacity of each separate system (Conrad, 1971; Demetriou et al., 2002; Gathercole & Baddeley, 1993; Gathercole et al., 2004; Gathercole et al., 1994; Kemps et al., 2000; Pickering, 2001). As the child can hold more of each type of information in working memory, the capacity necessary to

hold pairs of cross-modal information may also increase. Improvements in verbal rehearsal may support growth in the verbal aspect of cross-modal working memory (Hitch et al., 2001; Hulme et al., 1984). Similarly, the visual aspect of cross-modal working memory may be supported by improvements in rehearsal within the visual system (Logie, 1995, Baddeley, 2000a).

In exploratory analyses, age-related changes in cross-modal working memory span were examined after statistically controlling for unimodal visual and verbal span. The analysis of residuals suggested that, at least until 8 years of age, growth in cross-modal span was occurring above and beyond changes in unimodal span. This finding supports the idea that, although the separate visual and verbal systems may play a role in the development of the episodic buffer, unimodal working memory does not entirely account for performance on tasks that require integration. Further, these results are consistent with empirical studies suggesting that the episodic buffer is a separate component of working memory (Alloway et al., 2004; Gruber & von Cramon, 2003; Zhang et al., 2004).

Role of the Episodic Buffer in Language Development

How Working Memory Contributes to Language Learning

One commonality across language learning opportunities is that the experiences are temporally limited. When a child encounters a new word, exposure to the auditory stimulus may be limited to a fraction of a second. Without the ability to form a temporary representation of the word, it is impossible to create a long-term representation. For example, the child must maintain the sound sequence corresponding to *boat* (/b/ /o/ /t/) while creating a long-term representation that includes a link between the phonological representation of the word and its meaning. Gathercole and Baddeley (1993) suggest that children with better verbal working memory form more distinct and durable memory traces and are more likely to establish semantic links between

new words and their referents. Grammar development might place greater pressure on the verbal system when the child must temporarily store and process several words as well as the relationships and actions expressed in the sentence.

Working memory also contributes to language development by supporting maintenance of the visual referent. Although exposure to the visual stimulus may be limited in duration, in many cases objects remain available in the visual field. Following the example of a child learning the word "*boat*", he or she may still be looking at the object while they are forming the long-term representation. For this reason, visual working memory might play a relatively small role in vocabulary development. For sentence comprehension however, the ability to form a temporary representation of the visual scene may be important. For even a simple sentence such as "*The dog found the bone*", the child must maintain representations of the dog and bone. In addition, the child must represent the action of finding, which is no longer visually available.

The relative contributions from each unimodal system seem sound from a logical standpoint. Verbal working memory plays a more considerable role in language development because this type of memory system is important for dealing with the demands of learning a spoken language. However, visual working memory is not inconsequential. Language often is used to refer to a visually based experience. Therefore, both unimodal memory systems should support language development. However, in some situations, the ability to efficiently integrate the two forms of information in the episodic buffer may provide a contribution to language development above and beyond that from the unimodal working memory systems. For example, comprehending a sentence places demands on both the visual and verbal working memory systems to provide a temporary representation of the sounds of the words and the visual scene as well as the links between the visual and verbal information.

Integrating the Existing Literature and Findings From the Present Study

Studies have shown that both verbal and visual working memory make separate contributions to the growth of vocabulary during early childhood (Adams & Gathercole, 1995, 2000; Blake et al., 1994; Duyck et al., 2003; Gathercole & Baddeley, 1989, 1990, 1993; Gathercole et al., 1997). Among school-aged children in the present study, unimodal working memory did not account for variance in raw vocabulary scores after controlling for age. This finding was not surprising in light of previous studies that suggested unimodal verbal working memory does not make significant contributions to vocabulary development in older children (Gathercole et al., 1992). It is possible, however, that unimodal working memory is still important for older children when the language task is more demanding, such as during the learning of a second language. Typically, greater demands are placed on the working memory system during the acquisition of a new skill, in this case a second language, because more resources are needed as schemas are built and revised.

Research also supports a relationship between unimodal working memory and grammar development during early childhood (Adams & Gathercole, 2000; Blake et al., 1994). However, the findings from Adams and Gathercole (2000) suggest that that the relationship between unimodal verbal working memory and grammar development may be difficult to isolate. The authors (2000) compared the productive language development of two groups of 4-year-olds with good or poor nonword repetition skills. Differences between the group's MLU (based on morphemes) were statistically significant (High Nonword Group $M = 8.29$ ($SD = 3.44$) compared to Low Nonword Group $M = 6.04$ ($SD = 1.73$) (F (1,28) = 5.12, $p < .05$)). Although MLU is often used as an index of grammar development, it is less sensitive to syntactic complexity at later points in development (Scarborough, 1990). Adams and Gathercole (2000) also compared

groups by using a measure of grammatical development designed to quantify the complexity of sentences (Scarborough). Interestingly, differences between total IPSyn scores did not reach statistical significance (F (1,28) = 2.79, $p > .05$). In further analyses, three of the four subscales of the IPSyn yielded no significant differences between the groups.

Data from the present study did not support a significant contribution to grammar from unimodal working memory among school-aged children. After accounting for age, unimodal working memory accounted for 1.9% of the variance. One difference between these findings and those reported previously demonstrating a significant relationship between unimodal working memory and grammatical development is that earlier studies examined productive grammar among preschool aged children, whereas the current study assessed receptive grammar among school-aged children. It is possible that producing more complex sentences places greater demands on the working memory system than comprehension because the child must devote additional resources to speech output processes.

Previous research explored the role of unimodal working memory in language development rather extensively, but very little is known about the role of cross-modal working memory. In vocabulary development, the contributions from the episodic buffer might be limited. Although the child may need to integrate visual and verbal information, the amount of material is limited to a single pairing. The most substantial contributions from the episodic buffer were expected in the domain of grammar development. An aspect of grammar where visual-verbal integration may be important is in situations that involve combining a scene (whether actually viewed or imagined) with a series of words that expresses the meaning of the scene (Croft, 1998; Goldberg, 1995). For example, in order to comprehend a simple transitive sentence such as ‘Nicole kicked the ball” , a child must maintain a verbal representation of the complete

sentence. Visual-verbal integration may help the child establish links between the elements of the sentence and a visual representation of a girl using her foot to move a spherical object. The episodic buffer may be important in this process by supporting the linking of the visual and verbal information. The data from the present study indicated that cross-modal working memory span explained almost 12% of the variance in raw grammar scores for school-aged children after controlling for age, vocabulary, and unimodal working memory. This finding suggests that the episodic buffer makes a unique contribution to receptive grammar development during middle childhood above and beyond the contributions from the phonological loop and VSSP.

Role of the Episodic Buffer in Reading Development

The findings of the present study did not support the hypothesized relationship between visual-verbal integration and reading. Neither unimodal nor cross-modal working memory made significant contributions to word or nonword reading scores for children 6 to 10 years of age. This might suggest that working memory does not play a substantial role in learning to read; however, two issues deserve some comment. Although visual-verbal integration did not make a significant contribution to decoding, it is possible that the episodic buffer still contributes through integration from long-term memory. Second, the measure of reading used in the present study was restricted to decoding skills in school-aged children. This represents only one aspect of learning to read in a group of children that have already begun formal instruction. Perhaps, visual-verbal integration makes a greater contribution to other aspects of reading or at earlier points in development.

Findings regarding the relationship between visual-verbal integration and decoding skills stand in contrast to those used to formulate the hypotheses in the current study (Windfuhr & Snowling, 2001). A key difference between the current study and Windfuhr and Snowling's

study is the type of cross-modal task used in each study. Windfuhr and Snowling used a cross-modal paired associates learning task where the goal was to associate novel word/picture pairs for long-term recall. The cross-modal task used in the present study required immediate storage and processing while contributions from long-term memory were limited. Within the context of Baddeley's working memory model (2000a, 2001), it is possible that the working memory support noted in the literature comes from integration from long-term memory instead of direct integration from the phonological loop and VSSP. Perhaps children were taking advantage of patterns they were already familiar with during the reading tasks.

Decoding skills were chosen over other aspects reading development because of the logical relations between visual-verbal integration and the task of associating a series of letters with their phonetic counterparts. It was hypothesized that integration of visual images of words and nonwords with corresponding phonological representations might utilize the episodic buffer. It is possible that the age range used in the present study was not specific enough to capture the developmental period in which integration makes its greatest contribution to decoding. The sample collected in the current study consisted of children that had at least 1 year of formal reading instruction in public schools, and most had been reading for several years. Perhaps a closer examination of decoding at the earliest stages of reading development, before formal instruction begins, could better specify the role of the episodic buffer.

Another possibility is that working memory's contribution, particularly from the episodic buffer, is to comprehension as opposed to decoding. The analysis of cross-modal working memory contributions to grammar development suggested that the episodic buffer was more important when the language-learning task was more complex. Perhaps the buffer similarly supports the more complex aspects of reading development. Whereas unimodal working memory

might contribute to decoding during the preschool years and at the beginning of formal instruction, the episodic buffer might support developments in comprehension during the elementary school years.

Conclusions

Research has demonstrated that working memory supports children's development in a variety of other areas, such as general IQ, reading, language development, and higher cognitive functioning (Ardila & Rosselli, 1994; Gathercole & Baddeley, 1989, 1990, 1993; Windfuhr, & Snowling, 2001). The present study suggests that visual-verbal integration may be a unique part of this support system. The findings from the present study and exploratory analyses may have important implications for understanding the development of working memory. The data suggest not only a picture of growth in the unimodal systems, but also changes in the ability to integrate information, which Baddeley suggests involves the episodic buffer (2000a, 2001). Age-related improvements in the buffer and the mechanisms that underlie these improvements may have implications for additions to the model that may be necessary. Specifically, the findings support the addition of new pathways in Baddeley's model indicating direct integration of material from the phonological loop and VSSP. The present study provides some initial information about the development of a process that, to date has been relatively unexplored. The findings from the present study add to the developmental literature not only by exploring whether visual-verbal integration changes over the course of childhood, but also examining how this process may support development in other domains. This work could be used to extend the extant research regarding the support to language development that working memory provides. To this point, most research in this area has focused on contributions from the phonological loop with no regard for the contribution stemming from the ability to integrate visual information into

phonological representations. Analyses support the notion that visual-verbal integration may play a role in language learning above and beyond that of unimodal working memory. Findings related to the possible role of visual-verbal integration in the development of decoding skills, and in reading development more generally, highlight the need for further examination in this domain.

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Appendix A

Screening Information

Child's Name _____

Date of Birth: _____

Does your child have any known learning disabilities? _____ yes _____no

Does your child have any hearing or speech problems? _____ yes _____no

Does your child have any uncorrected vision problems? _____ yes _____no

Would you say that English is your child's primary language (the first language that they learned)?

Is any language other than English spoken at your house? _____yes _____no

If so, what language(s)? _____

If other languages are spoken at your house, what percentage of the time is your child exposed to English? _____

Is your child able to read any language other than English? _____yes _____no

If so, what language(s)? _____

Appendix B

Examples of items used in the working memory measure

Design: This measure included four tasks designed to assess unimodal and cross-modal working memory performance. The tasks were divided as follows based on the stimuli involved in each pair:

Unimodal tasks:

Verbal task : Pairs included two non-word auditory stimuli. Test phase required the presentation of the audio stimulus and recall of the auditory stimulus.

Visual task: Pairs include two unfamiliar visual images. Test phase required the presentation of the visual stimulus and recognition of the visual stimulus.

Cross-modal tasks:

Cross-modal task with verbal recall: Pairs included one auditory (non-word) stimulus and one visual (unfamiliar image) stimulus. Test phase required the presentation of the audio stimulus and recognition of the visual stimulus.

Cross-modal task with visual recognition: Pairs included one visual (unfamiliar image) stimulus and one auditory (non-word) stimulus. Test phase required the presentation of the visual stimulus and recall of the auditory stimulus.

Unimodal Tasks

Verbal task:

Stimulus items: (The child was presented with pairs of nonwords)

væsub – tʃuvidʒ

vededʒ - naɪteb

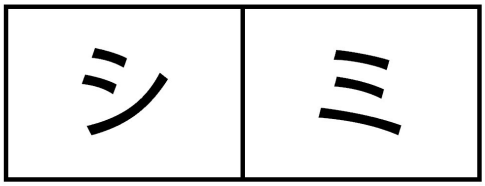
Test phase: (Then the child was presented with the test item)

Which word went with naɪteb?

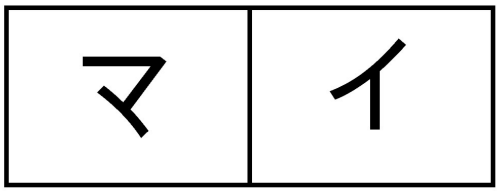
Visual task

Stimulus items: (The child was presented with pairs of images)

Pair 1



Pair 2



Test phase: (The child was shown the test item and the response array at the same time. The experimenter asked which one of the array went with the test item. The experimenter pointed to each item in the array and the single test item while asking about the paired items.)

Test item

シ

Response array

ワ	マ
ミ	イ

Cross-modal tasks

Stimulus items: (For both cross-modal tasks, the child was presented with nonword-image pairs)

Pair 1:

tʃudof

Pair 2:

vaɪvik

Cross-modal task with verbal recall:

Test phase: (Then the child was presented with the test item and asked which word went with the test image.)

Test image

ヌ

Cross-modal task with visual recognition:

Test phase: (The child was shown the response array and asked which image went with the test word. The experimenter pointed to each item in the array while asking about the paired items.)

Test word

vaɪvik

Response array

ト	ヌ
サ	オ

Appendix C

Exploratory Analyses Examining Working Memory Growth Between 3 and 11 Years of Age

Preliminary analysis included an examination of variable means and standard deviations, a check for outliers, and review of the distribution of scores and errors to insure that the data were appropriate for the planned inferential statistical analyses (see Table C1 for descriptive statistics). The preliminary analysis indicated that the data were approximately normally distributed and all other assumptions for the planned inferential analyses were met. The goal of the analyses presented in this appendix was to explore whether age-related changes in working memory might be occurring yet were not identified in the present study.

Growth in Unimodal Working Memory Between 3 and 11 Years of Age

Analysis of growth on composite scores from unimodal tasks.

General trends in unimodal working memory growth were examined using composite scores calculated in the manner described in the main body of the present paper. As shown in Figure C1, composite unimodal working memory span scores improved dramatically and steadily between 3 and 11 years of age. Regression analyses indicated that the linear function provided a statistically significant fit to the data (F (1,97) = 177.62 $p < .001$). The addition of curvilinear components did not provide a better fit. Based on the linear model, composite span scores increased at a rate of 0.87 units per year (Figure C1).

Table C1

Mean Test Scores for Children between 3 and 11 Years of Age

Measure	N	Mean	SD
Language			
PPVT	53	104.68	16.90
TROG	30	98.03	11.21
Working memory			
Unimodal			
Verbal only[a]	49	1.88	1.55
Visual only[b]	54	0.31	0.54
Cross-modal			
Verbal recall[c]	51	2.82	1.51
Visual recognition[c]	52	1.35	1.17

Notes:

Scores on tests of language represent standard scores

[a] maximum score of 8

[b] maximum score of 6

[c] maximum score of 7

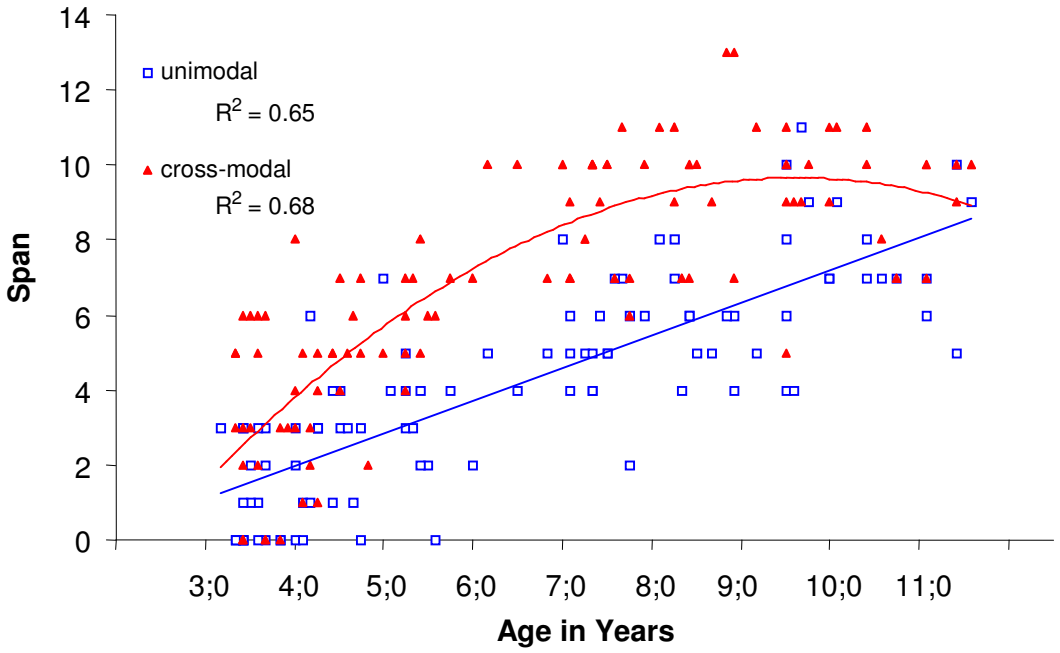


Figure C1. Growth of Unimodal and Cross-modal working memory span (composite scores) in children 3 to 11 years of age.

Analysis of growth on individual unimodal tasks.

Growth in unimodal working memory span for children between 3 and 11 years of age was also examined for the two individual unimodal tasks. As Figure C2 shows, there was an increase in the unimodal verbal span scores. Mean spans of unimodal visual working memory also increased. Results of the regression analyses indicated that the linear modal provided a statistically significant fit for the unimodal verbal task (linear: F (1,98) = 88.45, $p < .001$) and unimodal visual task (linear: F (1,103) = 138.89, $p < .001$). There were no significant departures from linearity for either task. Based on the linear model, unimodal verbal scores improved by approximately 0.56 units per year, and unimodal visual spans improved at a rate of approximately 0.29 units per year.

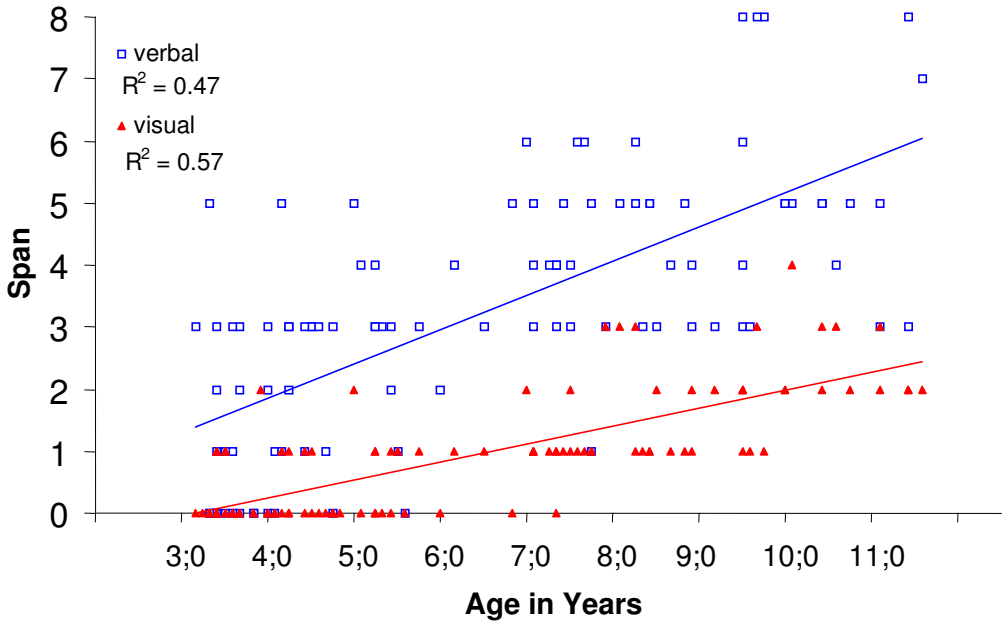


Figure C2. Growth of unimodal working memory in children 3 to 11 years of age.

Growth in Cross-modal Working Memory Between 3 and 11 Years of Age

Analysis of growth on composite scores from cross-modal tasks.

In contrast to the developmental picture when looking at children 6 to 10 years of age, statistically significant growth in cross-modal working memory was indicated when the sample included children between 3 and 11 years of age. A visual analysis of the data shown in Figure C1 suggested that cross-modal span increased steadily until 7 or 8 years of age when growth began to slow. Between 3 and 7 years of age, cross-modal span increased at the rate of approximately 1.5 units per year. Mean composite cross-modal scores increased from 2.9 for 3-year-olds to 6.0 at 5-years-old and 8.8 for 7-year-olds. Between 8 and 11 years of age, there was little change in composite cross-modal spans. Scores fluctuated with means ranging from 9.7 for 8-year-olds, 9.3 for 9-year-olds, 9.5 for 10-year-olds, and 9.2 for 11-year-olds. This fluctuation

suggested a slight decrease in scores (at a rate of 0.15 units per year) during this period. It is unlikely that cross-modal spans truly decrease after 8 years of age. It is more likely that spans growth is reaching asymptotic levels. A hierarchical regression indicated that the linear and quadratic models were significant (linear: $R^2 = .59$, F (1,98) = 140.90, $p < .001$; quadratic: $R^2 = .68$, F (2,97) = 104.78, $p < .001$). The quadratic term significantly increased fit above and beyond the linear model (R^2_{change} from a linear to quadratic model was 0.09, F (1,97) = 28.76, $p < .001$).

Analysis of growth on individual cross-modal tasks.

A set of analyses was performed to examine the growth on the individual working memory tasks using the combined samples from the present study and the Robinson and Smith (2005) study. In both cases, the same developmental trajectory is suggested as shown in Figure C3 where cross-modal span improved rapidly up to around 7 years of age and then leveled off in terms of growth. On the cross-modal task with verbal recall, mean span increased from 3 years of age to 7 years of age. Between 8 and 11 years of age, cross-modal spans with verbal recall fell slightly at a rate of approximately 0.1 pairs per year. Similarly, on the cross modal task with visual recognition, mean scores increased between 3 and 7 years of age. A regression analysis using data from the cross-modal task with verbal recall indicated that the linear and quadratic models were statistically significant (linear: $R^2 = .48$, F (1,100) = 92.76, $p < .001$; quadratic: $R^2 = .56$, F (2,99) = 62.40, $p < .001$). The addition of the quadratic term resulted in a significantly better fit to the data (R^2_{change} from a linear to quadratic model was 0.08, F (1,99) = 17.10, $p < .001$). Similarly, data from the cross-modal task with visual recognition indicated that both the linear and quadratic models yielded a statistically significant fit (linear: $R^2 = .47$, F (1,101) = 90.94, $p < .001$; quadratic: $R^2 = .54$, F (2,100) = 59.20, $p < .001$). Again, the quadratic term

provided a significantly better fit above and beyond the linear model (R^2_{change} from a linear to quadratic model was 0.07, F (1,100) = 14.93, $p < .001$).

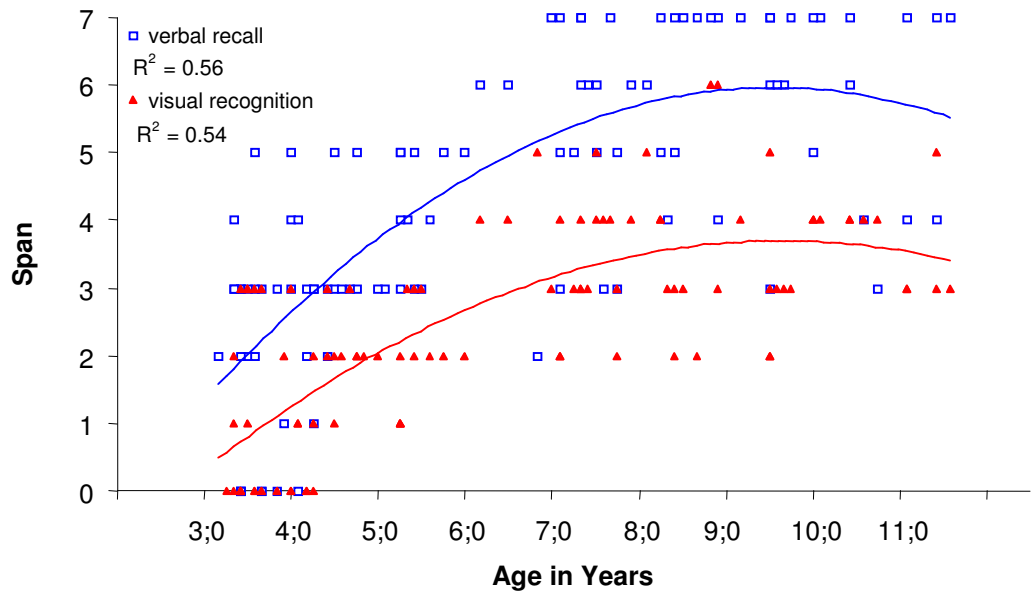


Figure C3. Growth of cross modal working memory in children 3 to 11 years of age

Analysis of growth of residual cross-modal span after accounting for unimodal span.

A set of analyses using the data from children between 3 and 11 years of age was performed that provided information about age-related growth of visual-verbal integration above and beyond the contributions from growth of separate visual and verbal systems. A visual analysis of the data shown in Figure C4 suggested that even after controlling for growth in unimodal working memory, unstandardized residuals of children's cross-modal spans improved in a curvilinear fashion from 3 to 11 years of age. Growth curve analysis of residual span scores indicated that the linear function was statistically significant between 3 and 11 years of age

(linear: R^2 = .09, F (1,95) = 8.88, p < .01). The addition of the quadratic term represented a significantly better fit to the data than the linear model (R^2_{change} from a linear to quadratic model was 0.11, F (1,94) = 13.33, p < .001). Statistically significant improvements in cross-modal span scores that were above and beyond the growth in unimodal span were suggested until approximately 7 years of age. In contrast, differences in cross-modal span between 7 and 11 years of age seemed to reflect the underlying growth in unimodal span.

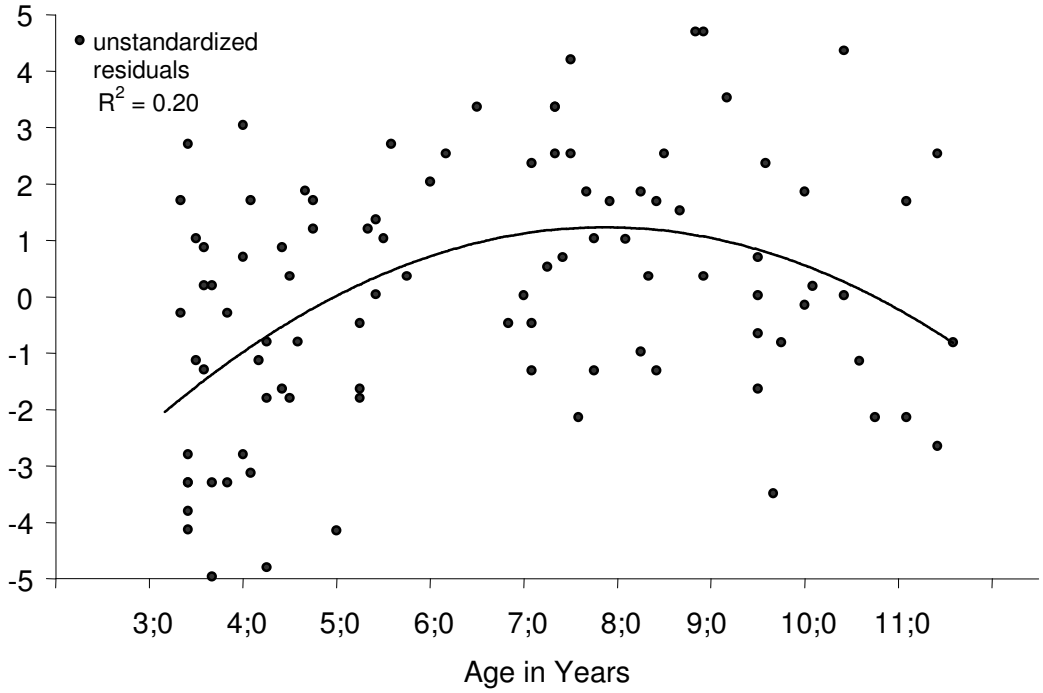


Figure C4. Growth of Residual Cross-modal working memory span in children 3 to 11 years of age.