Developmental Psychology
2004, Vol. 40, No. 2, 177–190

0012-1649/04/$12.00 DOI: 10.1037/0012-1649.40.2.177

The Structure of Working Memory From 4 to 15 Years of Age

Susan E. Gathercole
University of Durham

Susan J. Pickering, Benjamin Ambridge,
and Hannah Wearing
University of Bristol

The structure of working memory and its development across the childhood years were investigated in children 4–15 years of age. The children were given multiple assessments of each component of the A. D. Baddeley and G. Hitch (1974) working memory model. Broadly similar linear functions characterized performance on all measures as a function of age. From 6 years onward, a model consisting of 3 distinct but correlated factors corresponding to the working memory model provided a good fit to the data. The results indicate that the basic modular structure of working memory is present from 6 years of age and possibly earlier, with each component undergoing sizable expansion in functional capacity throughout the early and middle school years to adolescence.

In adults, short-term memory appears to be served by a number of interacting and highly specialized temporary memory systems. The broadest and most influential account of short-term memory is provided by the working memory model (Baddeley & Hitch, 1974). At the heart of the model lies the central executive, a system responsible for a range of regulatory functions including attention, the control of action, and problem solving (Baddeley, 1996). A new component, the episodic buffer, has recently been fractionated from the central executive; this is a multidimensional representation system capable of integrating temporary representations from other cognitive systems including components of working memory (Baddeley, 2000). The two other main components of working memory are slave systems specialized for the manipulation and retention of material in particular informational domains. The phonological loop consists of a phonological short-term store and a subvocal rehearsal process (Baddeley, 1986). The phonological store holds material in a phonological code that is subject to rapid decay. The rehearsal process recodes nonphonological inputs (such as pictures or printed words) into a phonological form that gains entry to the phonological store, and also refreshes decaying representations in the store. Finally, the visuospatial sketchpad stores material in terms of its visual or spatial features (Baddeley & Lieberman, 1980; Logie, 1986). It has recently been suggested that this slave system may be fractionated into a separate visual store and a more active spatial control process (Della Sala, Gray, Baddeley, Allemano, & Wilson, 1999; Logie, 1995).

Substantial evidence for the basic tripartite model of working memory is provided by experimental and neuropsychological dissociations between the putative components (see Baddeley & Logie, 1999, for a review). In recent years, the working memory model has been further supported by neuroimaging and neuropsychological studies of working memory that have identified distinct neuroanatomical loci for working memory systems (see Henson, 2001, and Vallar & Papagno, 2002, for reviews). Activities linked with the central executive function are associated with a variety of regions within the frontal lobes and also some posterior (mainly parietal) areas (Collette & Van der Linden, 2002; D'Esposito et al., 1995; Manoach et al., 1997; Owen, Evans, & Petrides, 1996). The phonological loop is served by a neural circuit in the left hemisphere spanning inferior parietal areas (serving phonological storage) and more anterior temporal frontal areas (associated with rehearsal), including Broca's area, premotor cortex, and the sensory motor association cortex (Henson, Burgess, & Frith, 2000; Smith & Jonides, 1997; Smith, Jonides, & Koeppe, 1996). Finally, spatial short-term memory (a component of the visuospatial sketchpad) is associated with right-hemisphere activation in occipital and inferior frontal areas (Smith & Jonides, 1997).

The working memory model has also proved to be a useful framework for characterizing the development of short-term memory (see Gathercole, 1999, 2002, for reviews). Almost all measures of short-term memory show a steady increase from the preschool years through to adolescence (Case, Kurland, & Goldberg, 1982; Dempster, 1985; Hulme, Thomson, Muir, & Lawrence, 1984; Isaacs & Vargha-Khadem, 1989; Siegel, 1994).

In the case of the phonological loop, a major source of the sizable increase in memory capacity as children grow older is the increased rate of rehearsal that enables the child to maintain increasing amounts of verbal material in the phonological store (Hulme et al., 1984). Before 7 years of age, spontaneous rehearsal does not reliably occur (see Gathercole & Hitch, 1993, for a

---

Susan E. Gathercole, Department of Psychology, University of Durham, Durham, England; Susan J. Pickering, Benjamin Ambridge, and Hannah Wearing, Department of Psychology, University of Bristol, Bristol, England.

This research was supported by a program grant on Working Memory and Learning Disability awarded by the Medical Research Council of Great Britain to Alan Baddeley and Susan E. Gathercole.

We thank the pupils and staff of the following schools in England that participated in the study: St. Anne's Infant and Junior Schools, Brislington, Bristol; St. Joseph's RC Primary School, Fishponds, Bristol; Raysfield Infant and Junior Schools, Chipping Sodbury; St. Thomas More School, Bristol; and Chipping Sodbury Secondary School.

Correspondence concerning this article should be addressed to Susan E. Gathercole, Department of Psychology, University of Durham, Science Laboratories, South Road, Durham, England DH1 3LE, United Kingdom.

review); in younger children, the phonological loop therefore consists of the phonological store only. Further factors implicated in the development of phonological memory capacity include changes in the speed of memory scanning during retrieval (Cowan et al., 1998) and of output processes (Cowan et al., 1992).

Short-term memory for visual material that is recodable into phonological form, such as pictures of familiar objects, undergoes an important developmental shift during the early school years. Children younger than 7 years typically rely on the visuospatial sketchpad to support recall of the physical forms of such stimuli. Older children, however, tend to use the phonological loop to mediate immediate memory performance where possible, and so recode the visual inputs into a phonological form via rehearsal (e.g., Hitch & Halliday, 1983; Hitch, Halliday, Schaafstal, & Schraagen, 1988). The basis of the steady increase across the childhood years in scores on tests of visuospatial short-term memory that use material that is not phonologically recodable is not as yet fully understood (e.g., Pickering, Gathercole, Hall, & Lloyd, 2001). One possibility is that the developmental increases reflect changes in the storage capacity of the visuospatial sketchpad per se (Logie & Pearson, 1997). Alternatively, they may relate to other age-related changes such as increasingly effective deployment of strategies, accumulating long-term knowledge relating to visuospatial structures, or increased support by the central executive (see Pickering, 2001, for a review). A further continuing area of debate concerns whether visual and spatial short-term memory reflect distinct subsystems of the visuospatial sketchpad that follow independent developmental trajectories or constitute a single integrated system (Logie & Pearson, 1997; Pickering, 2001; Pickering et al., 2001).

Developmental changes in the central executive have been investigated largely in the context of complex memory span paradigms that impose simultaneous processing and storage demands. An example of such a paradigm is reading span, in which participants process successive sentences in order to make a response such as a veracity judgment in each case and then recall the final word of each of the sentences in sequence (Daneman & Carpenter, 1980). Although, for many years, performance on complex memory span tasks was considered to be limited by the capacity of the central executive alone, it has been suggested more recently that the processing component of verbal complex memory span tasks is supported by the central executive, whereas storage is provided by the phonological loop (Baddeley & Logie, 1999; Duff & Logie, 2001; see also, LaPointe & Engle, 1990; Lobley, Gathercole, & Baddeley, 2003).

An alternative theoretical approach to complex memory span is that it taps a general working memory capacity that limits both processing and storage (e.g., Daneman & Carpenter, 1980, 1983; Engle, Cantor, & Carullo, 1992; Swanson, 1999). Consistent with this view is Case et al.'s (1982) suggestion that the developmental increase observed in memory span performance across the early and middle childhood years reflects a decrease in the processing demands of memory tasks as the child develops that releases additional resources to support storage. Resource-sharing models such as this one have, however, been challenged by reported absences of the predicted trade-offs between processing and storage in complex span tasks (e.g., Towse & Hitch, 1995; Towse, Hitch, & Hutton, 1998, 2002). Another possibility is that the crucial determinant of complex span performance is not processing difficulty but the amount of time elapsed between presentation of a memory item and its subsequent retrieval (e.g., Hitch, Towse, & Hutton, 2001). By this account, increased processing duration in younger children would result in greater delays and hence temporal decay, leading to lower span scores.

Because studies of the development of working memory have focused largely on changes taking place within individual components of the model, relatively little is known about the organization of the working memory system more generally and whether this changes with age. A small number of studies have investigated relationships across components of working memory in children. Data reported by Pickering, Gathercole, and Peaker (1998) indicated that at both 5 and 8 years of age, the phonological loop and the visuospatial sketchpad were independent of one another. In a study of 6- and 7-year-old children, Gathercole and Pickering (2000) reported evidence that the central executive and the phonological loop were separable but moderately associated with one another, consistent with the adult model of working memory. Visuospatial short-term memory, on the other hand, was not dissociable from central executive function, which suggests that it may not represent an independent entity, at least at this point in development (see also Wilson, Scott, & Power, 1987). Jarvis and Gathercole (2003) tested 11- and 14-year-old children on both verbal and visuospatial complex memory span measures as well as storage-only tasks associated with the phonological loop and the visuospatial sketchpad. At both ages, both verbal and visuospatial aspects of short-term memory (whether based on complex span or storage-only measures) were independent of one another.

In the present study, we had two principal aims. The first aim was to chart changes in performance across age for individual tasks in order to establish whether there are significant differences in the developmental functions associated with the components of working memory. At present it is not known whether the developmental increases in task performance are equivalent across the different components. The second aim was to establish whether the structural organization of working memory changes across the childhood years. There are several reasons to anticipate that this may be the case. The working memory model was constructed on the basis of evidence from studies of adult participants. The modular structure of working memory evident in adults may not, however, be in place at earlier stages of development. It has been argued that younger children's performance may be supported by more domain-general systems that become increasingly differentiated as knowledge and skills develop. Thus, although modular systems may represent the end point of development, they do not necessarily characterize the intermediate stages (Bishop, 1997; Karmiloff-Smith, 1998; Willis & Gathercole, 2001). For example, it is possible that performance by very young children on tasks known to tap either the phonological loop or the visuospatial sketchpad in adults may reflect the operation of less highly specialized working memory subsystems such as the central executive. The fractionated modular system characterizing adult working memory function may emerge only later in development, once specialized domain-specific skills and knowledge structures have been constructed.

Conversely, the specific informational domains served by the two slave systems (the phonological loop and the visuospatial sketchpad) may be supplemented to an increasing extent by the developing central executive in older children. The principal neuroanatomical area associated with central executive function, the frontal lobes, has a developmental span that extends over a much longer period than that of other brain areas, from birth to adolescence (Nelson, 1995, 2000). With increasing age, children may be able to take greater advantage of the flexible strategic and processing resources provided by the central executive to enhance the limited storage capacities of the loop and the sketchpad systems. By this account, a greater degree of interdependence between functioning of the executive and either or both of the two slave systems should be observed in older children. There are several ways in which this developmental trend could manifest itself. One possibility is that associations between central executive measures and both phonological and visuospatial short-term memory may increase in strength in older age groups. Alternatively, a distinct central executive may be present in older age groups only, with younger children relying only on the domain-specific storage resources of the phonological loop and the visuospatial sketchpad.

Our study sought to address these issues relating to the nature of developmental change in working memory in a large sample of children between the ages of 4 and 15 years. Over 700 children were assessed on measures associated with the three major components of the working memory model, which were taken from the Working Memory Test Battery for Children (Pickering & Gathercole, 2001). This battery was constructed in order to provide a theoretically based analysis of working memory skills suitable for use with children 4 years of age and older. Where possible, we chose the tests incorporated in the battery on the basis of substantial convergent evidence that they provide valid tests of one particular component of working memory, drawing upon the relevant experimental and neuropsychological research literature as well as developmental research (Gathercole & Pickering, 2000). We considered this approach to provide a more secure theoretical basis for interpreting test results than drawing upon less widely used or novel paradigms. The battery provides multiple tests associated with the central executive, the phonological loop, and the visuospatial sketchpad. In all cases, a span procedure was adopted in which the memory demands were increased to the point at which the individual child could no longer perform accurately. A major advantage of the span procedure is that it enables the same basic test structure to be used over a wide age range, with comparable sensitivity at different ages.

Three tasks (digit recall, word recall, and nonword recall) assessed the children's abilities to store and immediately recall sequences of spoken items. These measures are in common usage as measures of the phonological loop and are referred to here as verbal storage-only tasks. Three further tasks imposed both processing and storage demands and can be classified as complex memory span tasks. In each case, verbal recall was required. The backward digit recall test involved children recalling sequences of digits in reverse order (see, e.g., Morra, 1994). In the listening recall test, children listening to a series of short sentences verified each one by responding "yes" or "no" according to whether the statement was true or not and then recalled the final list item of each sentence in sequence (Daneman & Carpenter, 1980). In the counting recall test, children counted the number of dots in a series of arrays and then recalled the tallies in sequence (Case et al., 1982). According to Baddeley and Logie (1999), complex memory span tasks such as these place demands both on the central executive (for processing) and the phonological loop (for storage). Finally, three tests involving the storage of visual or spatial material (i.e., the visuospatial sketchpad) were administered. Spatial short-term memory capacity was tapped by block recall, which involved recall of a series of blocks on a three-dimensional array that were tapped by the test administrator (De Renzi & Nichelli, 1975), and by memory for a route drawn through two-dimensional mazes of increasing complexity (Pickering et al., 2001). Visual short-term memory was assessed by the Visual Patterns Test, a task that involves recall of shaded segments in two-dimensional patterns (Della Sala et al., 1999; Della Sala, Gray, Baddeley, & Wilson, 1997).

Method

Participants

Children attending five schools (three primary schools and two secondary schools) in southwest England participated in this study. The three urban schools and two rural schools were selected to represent the demographic profiles of schools in the United Kingdom as a whole and closely approximated average national performance on National Curriculum and General Certificate of Secondary Education indicators (see Pickering & Gathercole, 2001, for further detail). The children were sampled randomly from the following year groups: reception, Years 1 through 6, Year 8, and Year 10. The present analyses are based only on the children for whom data were collected on all measures. This sample consisted of 43 four-year-olds (17 boys and 26 girls), 101 five-year-olds (57 boys and 44 girls), 91 six-year-olds (51 boys and 40 girls), 96 seven-year-olds (47 boys and 49 girls), 63 eight-year-olds (30 boys and 33 girls), 98 nine-year-olds (49 boys and 49 girls), 101 ten-year-olds (48 boys and 53 girls), 37 eleven-year-olds (17 boys and 20 girls), 45 thirteen-year-olds (20 boys and 25 girls), 14 fourteen-year-olds (8 boys and 6 girls), and 47 fifteen-year-olds (19 boys and 28 girls). No exclusionary criteria were applied at recruitment—all available children on the days of testing with appropriate parental consent participated in the study.

All children completed the following tests: backward digit recall, word list recall, nonword list recall, block recall, and the Visual Patterns Test. The listening recall, counting recall, and mazes memory tests were not administered to children in the two youngest year groups (4- and 5-year-olds) because the task demands were too difficult.

Procedure

Each child was tested individually in three sessions conducted over a period of between 5 and 10 days. Testing took place in a quiet room in school. Nine tests were administered to each child: eight subtests of the Working Memory Test Battery for Children (Pickering & Gathercole, 2001), and the Visual Patterns Test (Della Sala et al., 1997). Three tests involved verbal storage only and are associated with the phonological loop (digit recall, word list recall, and nonword list recall). Three measures were designed to tap the visuospatial sketchpad (block recall, the Visual Patterns Test, mazes memory). The remaining three tests involved complex memory span associated with both the central executive and the phonological loop (backward digit recall, listening recall, and counting recall). The order of test administration was held constant across children and was designed to vary the nature of the memory demands experienced within each session.

The *digit recall* test involves the presentation of spoken sequences of digits that the child is asked to recall in correct serial order. Lists constructed randomly and without replacement from the digits ranging from 1 to 9 are spoken by the tester at the rate of one digit per second. Following a practice session, a maximum of six lists is presented at each length. List length is increased by one if the child recalls four lists at that length correctly. If the first four trials are correct, the child is credited with correct recall of all six lists at that length, and the next list length commences. Testing commences with single-digit lists and continues until three lists of a particular length are recalled incorrectly. The number of lists correctly recalled is scored. The mean test–retest reliability coefficient for this measure is .81.

The span procedure outlined for the digit recall test is shared by all other tests except the Visual Pattern Test. The *word list recall* and *nonword list recall* tests differ from digit recall only in the nature of the list items (words or nonwords). In each case, stimulus items are monosyllabic words with a consonant–vowel–consonant structure, and no stimuli are repeated. Items must be recalled with full accuracy (i.e., with all three phonemes correct) and in the correct serial position. Mean test–retest reliability coefficients are .72 for word list recall and .56 for nonword list recall.

In the *listening recall* test, the child listens to a series of short sentences, judges the veracity of each sentence in turn by responding "yes" or "no," and then recalls the final word of each of the sentences in sequence. Test trials begin with a single sentence and increase by a single sentence following the span procedure outlined above. The mean test–retest reliability coefficient for this measure is .61. In the *counting recall* test, the child is required to count the number of dots presented in a series of arrays (saying the total number aloud) and to recall subsequently the dot tallies in the order that the arrays were presented. A display booklet is placed in front of each child that consists of several pages, each showing an area that contains either three, four, five, or six red dots. Test trials begin with a single array of dots and increase by one further array following the span procedure outlined above. The mean test–retest reliability coefficient on this measure is .61. The *backward digit recall* test is identical to the digit recall test in all respects except that the child is required to recall the sequence of spoken digits in reverse order. Practice trials are given in order to ensure that the child understands the concept of "reverse." The mean test–retest reliability coefficient is .62.

In the *block recall* test, the child views nine wooden cubes located randomly on a board. The test administrator taps a sequence of blocks, and the child's task is to repeat the sequence in the same order. Testing begins with a single block tap and increases by one additional block following the span procedure outlined above. The mean test–retest reliability coefficient for this measure is .53. In the *mazes memory* test, the child views on each trial a two-dimensional line maze with a path drawn through the maze. The test administrator traces the line with her or his finger in view of the child. The same maze is then shown to the child without the path, and the child is asked to recall the path by drawing it on the maze. Maze complexity is increased by adding additional walls to the maze, following the span procedure outlined above. The mean test–retest reliability coefficient for this measure is .62.

The final test, the Visual Patterns Test (Della Sala et al., 1997), provides a measure of visual short-term memory originally developed for use with adults but that has recently been standardized for use with children (Pickering & Gathercole, 2001). The test involves the participant viewing two-dimensional grids composed of filled (black) and unfilled (white) squares for 3 s. An empty grid is then presented in which the participant has to mark the filled squares in the studied pattern. The complexity of the grid is increased until recall falls below threshold levels of accuracy.

Results

Elimination of Outliers

Tests for univariate and multivariate normality were conducted for each of five age groups within the sample: 4–5 years, 6–7 years, 8–9 years, 10–11 years, and 13–15 years. These age groups were chosen in order to provide sufficient sample sizes for the multivariate analyses reported below. Within each age group, univariate normality was assessed and outliers identified as follows. First, Mahalanobis D^2 values were computed for all memory scores, and cases with D^2 probability values $< .001$ were eliminated. Skewness and kurtosis values for each measure were then computed. On measures with values that either fell below –1.00 or exceeded 1.00 for either score, children with scores more than 3 standard deviations from the mean for the age group were excluded. A total of 18 children were excluded from all subsequent analyses on this basis, resulting in the following group sizes: 4–5 years, $n = 144$; 6–7 years, $n = 184$; 8–9 years, $n = 154$; 10–11 years, $n = 132$; 13–15 years, $n = 105$. Skewness and kurtosis values fell between -1.00 and 1.00 for all variables in each of these groups.

Descriptive Statistics and Multivariate Analyses of Variance

The mean scores for each measure are shown in Table 1 by age group (in years) and gender. A series of multivariate analyses of variance (MANOVAs) was performed on each set of measures associated with each of the three components of working memory, as a function of age in years (4 to 15 years) and gender. The MANOVA performed on the three verbal storage-only measures yielded a highly significant effect of age ($p < .01$) but no significant effect of gender ($p > .05$) and no significant interaction between age and gender. Separate MANOVAs were performed on the visuospatial measures for the 4- and 5-year-old children and the children 6 years of age and older because one of these measures (mazes memory) was completed only by the older children. In addition to highly significant effects of age in each case ($p < .01$), a significant gender effect was found for the older age group, reflecting the superior performance of boys on two of the measures: the Visual Patterns Test ($p < .05$) and block recall ($p < .01$). The gender effect was not significant, however, in the corresponding analysis performed on the younger age group ($p > .05$). In the MANOVA performed on the three complex memory span measures for the children 6 years and older, there was a highly significant effect of age ($p < .001$) and no significant effect of gender ($p > .05$). The same pattern of significance was also observed in the analysis of variance performed on the single complex memory span measure (backward digit recall) for the 4- and 5-year-old children. The pervasive age effects found in these analyses reflect the increasing memory scores in the older age groups.

This pattern of increasing levels of performance in successive age groups is demonstrated in Figure 1, which plots mean z scores for each year group, calculated on the basis of all children for whom data were available on each measure. All nine tests yielded broadly similar developmental functions, with performance increasing linearly from 4 to 14 years in general and leveling off between 14 and 15 years. The only marked departure from this profile was observed for the Visual Patterns Test, on which scores reached an asymptotic level at 11 years.

Z scores for the three tests associated with each subcomponent were averaged to provide a composite at each age (in years). The complex memory span score for the 4- and 5-year-old children was based only on their backward digit recall z score, and their visuospatial composite score was the average of the two such tests they completed—block recall and the Visual Patterns Test. Very similar linear functions were obtained in each case: for verbal storage-only, $y = 242x - 1.275$, $r^2 = .971$; complex memory span, $y =$

Table 1
Mean Test Scores as a Function of Age and Sex

Age (years)	Sex	*N*	Working memory measure Digit recall	Word recall	Nonword recall	Block recall	Visual patterns	Mazes memory	Backward digit recall	Listening recall	Counting recall
4	M	25	19.8	13.7	10.0	15.4	5.3	—	5.6	—	—
	F	17	19.5	13.9	8.6	15.1	6.0	—	5.8	—	—
5	M	44	22.0	14.6	9.8	20.1	8.2	—	8.0	—	—
	F	57	23.1	15.2	10.3	19.9	8.8	—	8.8	—	—
6	M	40	24.7	16.5	12.2	21.5	10.6	10.7	9.7	8.4	15.4
	F	49	25.5	17.2	12.7	21.8	11.1	8.8	10.5	8.9	16.4
7	M	49	26.4	18.1	11.9	23.7	13.3	13.9	11.4	9.6	19.2
	F	46	25.6	18.6	12.3	24.0	14.0	13.6	12.0	10.4	19.0
8	M	32	26.5	18.8	13.1	25.2	15.8	18.5	12.3	11.5	21.7
	F	30	27.2	19.4	13.5	25.4	15.1	16.7	13.0	11.1	22.0
9	M	47	27.5	20.2	13.8	26.1	17.2	21.0	12.8	12.0	22.6
	F	45	28.2	20.0	13.6	25.6	15.4	18.2	13.0	11.6	22.8
10	M	51	29.2	20.6	14.2	27.8	19.8	22.3	14.2	12.7	24.8
	F	46	29.5	22.0	14.7	27.2	18.6	19.5	14.2	12.7	24.3
11	M	19	29.5	21.1	14.0	28.7	20.6	24.0	15.6	12.8	23.2
	F	16	32.6	21.6	14.4	29.0	21.1	22.8	17.6	14.3	25.1
13	M	25	32.5	22.9	16.2	30.6	20.5	28.6	18.2	14.7	27.4
	F	20	34.0	25.0	16.7	29.9	18.8	28.0	18.5	15.0	27.2
14	M	6	37.3	25.5	19.2	29.7	22.2	28.7	19.0	15.7	29.5
	F	8	33.6	24.0	16.8	29.1	20.1	28.0	19.5	14.8	28.3
15	M	28	33.8	24.0	17.5	33.6	23.1	30.5	18.8	17.8	29.3
	F	18	36.0	24.4	18.2	31.9	19.2	28.5	17.9	15.3	28.2

Note. Dashes indicate that 4- and 5-year-olds were not given those tests because the task demands were too difficult for them. M = male; F = female.

$269x - 1.521$, $r^2 = .969$; visuospatial memory, $y = 251x - 1.453$, $r^2 = .979$.

Correlational Analyses

For the purpose of correlational analysis, the children were grouped into five age groups consisting of more than 100 children each to provide satisfactory statistical stability. Table 2 provides descriptive statistics for each measure for each of these age groups and for the entire group of 6- to 15-year-old children who completed all tests.

The simple correlation coefficients for the 6- to 15-year-old children, shown below the diagonal in Table 3, were all significant at the .001 level. However, these coefficients are inflated by the large variation in age in this group. In order to adjust for this, partial correlation coefficients were calculated with age in months partialed out, and these are shown above the diagonal in Table 3. The three verbal storage-only measures associated with the phonological loop (digit, word, and nonword recall) shared moderately high partial correlations with one another (partial *r*s ranging from .38 to .49; mean partial $r = .45$). These measures were correlated rather less highly (although still at highly significant levels) with the complex memory span measures (partial *r*s ranging from .18 to .41; mean partial $r = .30$) and only weakly with the three visuospatial memory measures (partial *r*s ranging from .06 to .19; mean partial $r = .11$). Partial correlations between the three visuospatial measures (block recall, visual patterns, and mazes memory) were

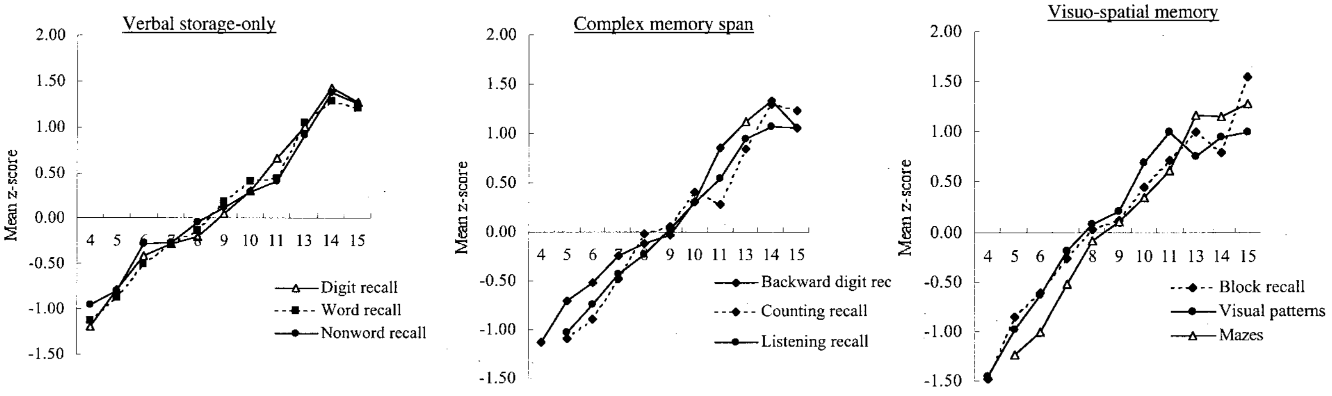


Figure 1. Mean *z* scores as a function of age for each measure, grouped by task type.

Table 2

Descriptive Statistics for Working Memory Measures as a Function of Age Band

Measure	Age (in years) 4–5 (*n* = 144)	 6–7 (*n* = 184)	 8–9 (*n* = 154)	 10–12 (*n* = 132)	 13–15 (*n* = 105)	 6–15 (*n* = 575)
Backward digit recall						
M	7.69	10.92	12.77	15.08	18.50	13.75
SD	3.15	3.11	3.20	3.66	5.67	4.70
Listening recall						
M	—	9.34	11.64	12.91	15.19	11.84
SD	—	3.05	3.00	2.37	2.94	3.54
Counting recall						
M	—	17.56	22.36	24.40	28.19	22.36
SD	—	4.59	4.30	4.35	4.17	5.80
Digit recall						
M	21.69	25.58	27.47	29.75	34.10	28.60
SD	4.10	3.63	3.46	4.28	5.66	5.14
Word recall						
M	14.52	17.61	19.71	21.17	24.10	20.18
SD	3.01	3.59	3.25	3.32	3.95	4.12
Nonword recall						
M	9.85	12.39	13.52	14.39	17.20	14.00
SD	2.68	2.92	2.56	2.63	3.74	3.38
Block recall						
M	18.56	22.77	25.64	27.84	31.31	26.26
SD	4.30	3.67	3.38	3.45	4.48	4.79
Visual patterns						
M	7.67	12.29	15.95	19.64	20.70	16.50
SD	3.24	4.23	4.52	5.05	4.73	5.68
Mazes memory						
M	—	11.76	18.81	21.63	28.94	19.05
SD	—	5.95	5.39	5.73	4.38	8.16

Note. Dashes indicate tests not taken by 4- and 5-year-olds.

moderate in magnitude (ranging from .31 to .45; mean partial r = .37). These measures correlated more weakly with the complex memory span measures (partial rs ranging from .22 to .32; mean partial $r = .26$). Partial correlations between the three complex memory span measures (backward digit recall, counting recall, and listening recall) were low to moderate in strength (rs ranging from .29 to .33; mean partial $r = .30$).

Confirmatory Factor Analyses

One of the principal aims of this study was to investigate the structural organization of working memory across the wide range of ages of the children participating in this study. Specifically, we wished to evaluate the extent to which the children's performance on these nine tasks corresponded to the basic three-factor model of

Table 3

Correlation Matrix for Working Memory Measures for 6- to 15-Year-Olds: Simple Correlation Coefficients Below the Diagonal and Partial Correlation Coefficients (With Age Controlled) Above the Diagonal

Variable	1	2	3	4	5	6	7	8	9	10
1. Age (months)	—									
2. Digit recall	**60**	—	**49**	**38**	**13**	**14**	6	**41**	**34**	**30**
3. Word recall	**55**	**66**	—	**48**	**17**	**19**	9	**29**	**33**	**31**
4. Nonword recall	**50**	**57**	**62**	—	**8**	**7**	**11**	**29**	**23**	**18**
5. Visual patterns	**58**	**43**	**44**	**35**	—	**45**	**34**	**23**	**32**	**27**
6. Block recall	**66**	**48**	**49**	**38**	**66**	—	**31**	**23**	**22**	**27**
7. Mazes memory	**75**	**48**	**46**	**44**	**62**	**66**	—	**22**	**27**	**30**
8. Backward digit recall	**59**	**62**	**52**	**50**	**49**	**53**	**56**	—	**33**	**28**
9. Listening recall	**60**	**58**	**55**	**46**	**56**	**53**	**59**	**57**	—	**29**
10. Counting recall	**66**	**58**	**58**	**45**	**55**	**59**	**64**	**56**	**57**	—

Note. Decimal points have been omitted. Coefficients in bold are significant at the .05 level (with $df = 572$).

working memory (Baddeley, 1996; Baddeley & Hitch, 1974). In order to address this issue, we conducted a series of confirmatory factor analyses (CFAs) using the EQS statistical package (Bentler & Wu, 1995). CFA is a method for testing specific hypotheses relating to the factor structure of a correlation matrix and is appropriate for situations in which there is an a priori model on interrelations between variables to be tested against the data. In the present case, this model consists of three factors, corresponding to the central executive, the phonological loop, and the visuospatial sketchpad. Note that as this model incorporates bidirectional associations between the factors (following Baddeley, 2000), structural equation modeling of the data set (with directional paths between factors) was not appropriate. Formally, the CFAs reported here correspond to the measurement model component of a structural equation model.

The weak and nonsignificant correlations between the verbal storage-only and visuospatial measures are consistent with the hypothesis that the phonological loop and the visuospatial sketchpad components of working memory are independent of one another. Whether the verbal storage-only and complex memory span measures should load on a single factor or two separate but highly associated factors is less clear: The verbal storage-only measures were more highly correlated with one another than with the complex span tasks, which suggests separable factors, but the complex span measures were as closely associated with the verbal storage-only measures as with each other. This raises the possibility that the latent model underlying these observations consists of two rather than three factors: a visuospatial factor and a further factor supporting performance on both the verbal storage-only and verbal complex span tasks. The two alternative models are represented in Figure 2. CFAs corresponding to each of the two models were tested for each age group in order to identify which model provides the better account of the data. The data from the 4- and 5-year-old children were not included in these analyses: As 4- and 5-year-olds were tested only on a single complex memory span measure, they did not supply sufficient data to identify a latent construct associated with complex span.

Note that, ideally, we would like to construct a three-factor model in which the verbally based complex memory tasks load on both a phonological loop and a central executive factor, reflecting the current theoretical analysis of these paradigms. However, it is not possible to test such a model using this method of analysis, because each factor has to be uniquely identified with at least two observed variables. The present solution of associating the complex span measures only with a single common factor represents the closest practical approximation to this ideal model.

An initial three-factor CFA was performed on the data for all 6- to 15-year-old children. The reliability of each variable as a factor indicator can be computed by squaring the standardized factor loadings for each measure. This procedure yielded the following values: backward digit recall (Factor 1), .540; listening recall (Factor 1), .564; counting recall (Factor 1), .594; digit recall (Factor 2), .682; word recall (Factor 2), .661; nonword recall (Factor 2), .507; Visual Patterns Test (Factor 3), .598; block recall (Factor 3), .645; mazes (Factor 3), .686.

For each age group, Mardia's (1970) multivariate kurtosis coefficient was below 3, meeting the multivariate normality assumption required for this method of analysis (Bentler & Wu, 1995). The input to each model was the raw data for an age group. The correlation matrices for the groups are provided in Table 4. Several measures of the goodness of fit of each model to the data are reported, following recommendations by McDonald and Ho (2002). The chi-square value reflects the degree of association between the model and the data. A nonsignificant value indicates

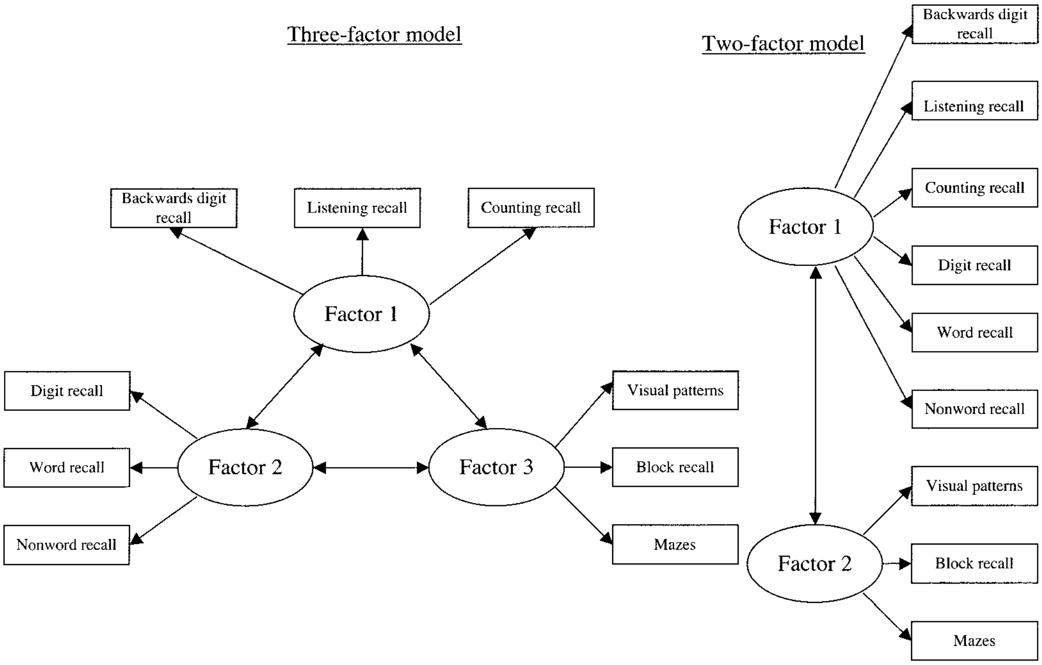


Figure 2. Structure of the three-factor and two-factor models of working memory.

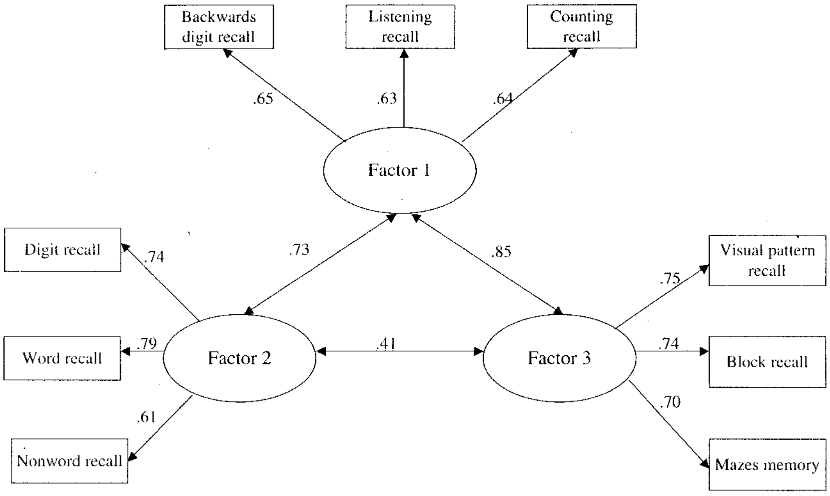
Table 4
Partial Correlation Coefficients (Age Controlled) Above the Diagonal for Each Age Band (Decimal Points Omitted) and Standardized Residuals for Three-Factor Model Below the Diagonal

Variable	1	2	3	4	5	6	7	8
4–5 years								
1. Digit recall	—	**62**	**51**	**39**	**36**	**46**		
2. Word recall		—	**51**	**34**	**32**	**40**		
3. Nonword recall			—	**19**	**20**	**26**		
4. Visual patterns				—	**40**	**44**		
5. Block recall					—	**42**		
6. Backward digit recall						—		
6–7 years								
1. Digit recall	—	**54**	**42**	**24**	14	9	**38**	**35**
2. Word recall	−.02	—	**58**	**22**	**17**	**14**	**30**	**24**
3. Nonword recall	−.04	.06	—	**15**	**15**	**18**	**27**	**31**
4. Visual patterns	.06	.05	−.06	—	**50**	**37**	**34**	**30**
5. Block recall	−.02	.00	−.05	.03	—	**41**	**25**	**28**
6. Mazes memory	−.05	.00	−.02	−.03	−.01	—	**27**	**36**
7. Backward digit recall	.06	.02	−.05	.02	−.07	−.01	—	**37**
8. Listening recall	.05	−.06	.01	−.01	−.02	.08	.03	—
9. Counting recall	.08	.01	−.11	.02	.02	.03	.02	−.05
8–9 years								
1. Digit recall	—	**45**	**28**	4	**15**	0	**31**	**25**
2. Word recall	.01	—	**49**	**19**	**21**	11	**20**	**39**
3. Nonword recall	−.06	.02	—	2	3	6	**27**	**29**
4. Visual patterns	−.06	.05	−.09	—	**42**	**24**	10	**34**
5. Block recall	.04	.05	−.09	.02	—	**24**	**31**	**26**
6. Mazes memory	−.09	.02	−.01	−.02	−.03	—	9	**30**
7. Backward digit recall	.11	−.08	.05	−.10	.09	−.05	—	**33**
8. Listening recall	−.04	.00	−.01	.06	−.05	.11	−.01	—
9. Counting recall	.11	−.01	.01	−.10	−.01	.03	.05	−.01
10–11 years								
1. Digit recall	—	**43**	**39**	9	17	10	**33**	**42**
2. Word recall	−.01	—	**39**	10	15	−9	**19**	**29**
3. Nonword recall	−.03	.07	—	**22**	14	**24**	**34**	**26**
4. Visual patterns	−.04	−.04	.07	—	**42**	**35**	**26**	**25**
5. Block recall	.02	.05	.03	.00	—	17	**22**	**20**
6. Mazes memory	−.05	−.16	.15	.02	−.04	—	13	−2
7. Backward digit recall	.00	−.10	.04	−.01	.04	.01	—	**32**
8. Listening recall	.07	−.01	−.04	−.03	.02	−.14	.08	—
9. Counting recall	−.06	.06	−.01	.01	.04	.17	−.30	−.10
13–15 years								
1. Digit recall	—	**57**	**43**	16	12	**22**	**51**	**42**
2. Word recall	−.02	—	**50**	15	**23**	11	**41**	**38**
3. Nonword recall	−.01	.08	—	9	1	6	**35**	14
4. Visual patterns	.01	−.01	−.01	—	**39**	**30**	17	**27**
5. Block recall	−.03	.07	−.07	.05	—	**37**	13	3
6. Mazes memory	.06	−.05	−.05	−.07	.03	—	**37**	15
7. Backward digit recall	.06	.00	.03	−.09	−.12	.10	—	**32**
8. Listening recall	.04	−.04	−.12	.06	−.16	−.06	−.01	—
9. Counting recall	−.02	−.06	−.09	.13	.05	.06	−.04	.08

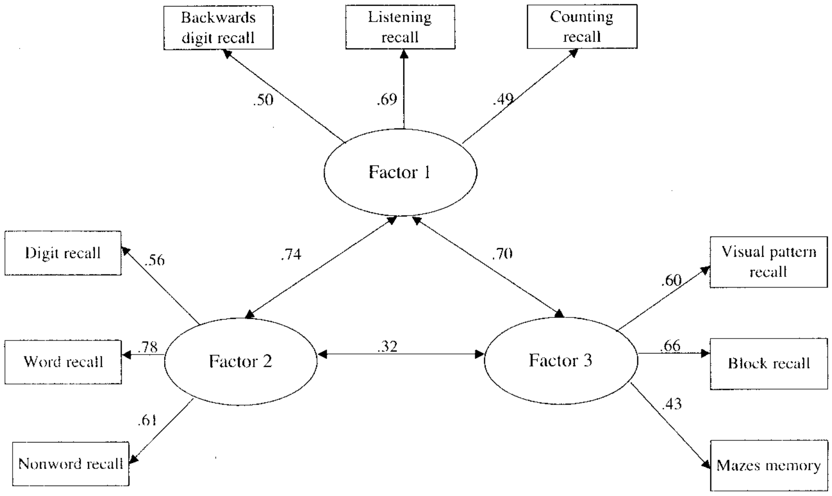
Note. Partial coefficients printed in bold are significant at the .05 level.

that there is no significant difference between the model and the data and is a desirable indicator of an excellent fit. Note that with large sample sizes, it is widely recognized that it can be difficult to achieve nonsignificant chi-square values even for the best-fitting models. The adequacy of alternative models can be compared by calculating the significance of the difference between their chi-square values, a procedure that was adopted in the present case to compare the two- and three-factor models. The comparative fit index (CFI) provides a global measure of fit, ranging between 0 and 1. As a rule of thumb, CFI values in excess of .90 are considered to be satisfactory. The root mean square error of approximation (RMSEA) provides a further index of fit. Model solutions with RMSEAs below .08 are considered acceptable; values below .05 indicate a good fit. Standardized residuals (discrepancies between a model and the data, for each measure) provide valuable insight into the more local aspects of goodness of fit, with larger residuals indicating areas of model mismatch with the data. Standardized residuals for the three-factor model depicted in Figures 3 and 4 for each age group are shown below the diagonals of the relevant matrices in Table 4.

The statistics for the two- and three-factor models for each age group, and for the comparison of the two models in each case, are shown in Table 5. The three-factor models (summarized in Figures 3 and 4) provided significantly better fits to the data than the two-factor models for all four age groups ($p < .001$ for the 6- to 7-year-old group, the 8- to 9-year-old group, and the 10- to 11-year-old group and $p < .05$ for the 13- to 15-year-old group). For all four age groups, the two-factor models differed significantly from the data, with chi-square probability values $> .05$. For the three youngest age groups, CFIs were $< .9$; a satisfactory CFI of .91 was obtained for the 13- to 15-year-old group. RMSEA values were unsatisfactory for all four groups, exceeding .08. In contrast, the three-factor model met conventional requirements for satisfactory fits across each age group, with CFIs $> .90$ and RMSEAs $< .08$. It should be noted, however, that the chi-square value for the three-factor model was nonsignificant ($p > .05$, indicating no significant difference between the model and the data) only for the 13- to 15-year-old group. The significance of the value for the three younger age groups, in combination with their otherwise satisfactory fit statistics, is a relatively common feature

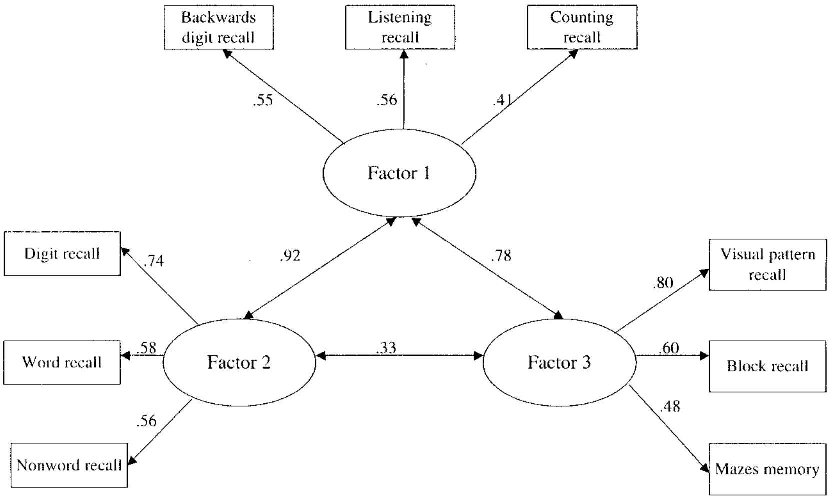


6 / 7 years

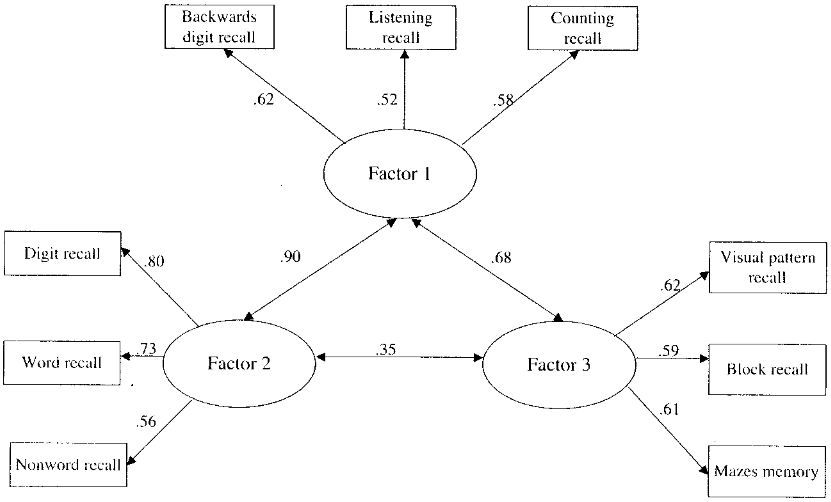


8 / 9 years

Figure 3. Factor loading and factor covariances for the three-factor models for the data for the 6- to 7-year-old and 8- to 9-year-old age groups.



10 to 12 years



13 to 15 years

Figure 4. Factor loading and factor covariances for the three-factor models for the data for the 10- to 12-year-old and 13- to 15-year-old age groups.

of best-fitting models with large sample sizes (Bentler & Wu, 1995).

In order to provide a direct statistical evaluation of the consistency of the three-factor models across the four age groups, a multiple population analysis was conducted in which both factor loadings (the regressions of the variables onto their associated factors) and factor covariances were constrained to be equal in each group. In addition to computing the model statistics for the multiple group analysis, this method allows each constrained parameter to be evaluated for equality or invariance across populations, using the LaGrange multiplier (LM) test. In the resulting model, the chi-square value (with $df = 129$) was 207.71 ($p < .01$). This statistic indicates that there was a significant difference between the model and the data. The remaining goodness-of-fit statistics for the model were satisfactory: CFI = .934, RMSEA = .033. The factor correlations for the model were as follows: Factors 1 and 2 (central executive and phonological loop), .80; Factors 2 and 3 (phonological loop and visuospatial sketchpad), .36; Factors 1 and 3 (visuospatial sketchpad and central executive), .78.

The LM test identified three (of 33) groupwise constraints in the factor loadings that were significant on univariate test, indicating group inequalities. These were the factor loading of digit recall onto Factor 2 (phonological loop) between the 6- to 7-year-old and 8- to 9-year-old age groups, $\chi^2(1) = 4.20$, $p = .04$, and between the 6- to 7-year-old and 13- to 15-year-old age groups, $\chi^2(1) = 13.30$, $p < .01$, and the factor loading of the Visual Patterns Test onto Factor 3 for the 6- to 7-year-old and 10- to 11-year-old groups, $\chi^2(1) = 5.17$, $p = .02$. There therefore appear to be some

Table 5
Summary of Statistics From Model Solutions for Each Age Band

Age group	Model	Statistics χ^2	*df*	*p*	Model comparison statistics CFI	RMSEA	χ^2	*df*	*p*
6–7	2-factor	91.849	26	$< .001$	.871	.118			
	3-factor	37.327	24	.041	.974	.055	54.52	2	$< .001$
8–9	2-factor	59.726	26	$< .001$	.858	.092			
	3-factor	39.425	24	.024	.935	.065	20.30	2	$< .001$
10–12	2-factor	53.624	26	.001	.876	.090			
	3-factor	38.272	24	.033	.936	.067	15.35	2	$< .001$
13–15	2-factor	44.436	26	.014	.913	.083			
	3-factor	35.851	24	.057	.944	.069	8.59	2	.014

minor changes in the extent to which two of the test battery measures mapped onto their associated working memory constructs across age groups. More important, the equality constraints in factor covariances across groups were satisfactorily imposed, with no significant group differences in the univariate LM tests ($p > .05$ in each case). The relationships between the three factors therefore appear to be stable across age.

Discussion

Our aims in the study were to investigate changes across the childhood years in the capacity of the individual components of the Baddeley and Hitch (1974) model of working memory and to establish whether the structure of working memory remains consistent across this crucial developmental period or undergoes significant change. The developmental functions for measures associated with the phonological loop, the central executive, and the visuospatial sketchpad were found to be very similar, showing linear increases in performance from 4 years through to adolescence. Furthermore, the tripartite structure of the adult working memory model (consisting of the phonological loop, the visuospatial sketchpad, and the central executive) provided a good account of the interrelationships between measures of short-term memory from 6 years onward, with no evidence of consistent developmental changes in the relationships between the components.

This study is, to our knowledge, the first to compare developmental trajectories across the childhood years with multiple assessments of all three main subcomponents of working memory. In general, the developmental functions are markedly consistent both across individual tasks and across the three components of working memory. Other studies have reported different developmental trajectories for the visual and spatial aspects of short-term memory, with much steeper age-related increases in the recall of visual patterns than of block-tapping sequences (Logie & Pearson, 1997; Pickering et al., 2001). There is no evidence of this in the present study: In fact, performance on the Visual Patterns Test reached an earlier asymptote (at about 11 years) than did the two more spatially based tasks, block recall and mazes memory. It therefore seems likely that earlier reports of different developmental trajectories for visual and spatial short-term memory measures reflect differences in their measurement scales, because recall of visual patterns is associated with much higher test scores than is block recall. Such scaling differences are eliminated when standard scores are used to compute the developmental functions across tasks, as in the present case.

The consistency of the structure of working memory across this substantial childhood period and its close resemblance to the tripartite adult-based model provide substantial evidence that the short-term memory subsystems corresponding to the central executive, the phonological loop, and the visuospatial sketchpad are in place by 6 years of age at least. Detailed consideration of the tasks suggests that this consistency in structure does not reflect similarities and differences in the surface characteristics of the tasks; rather, it reflects more fundamental differences in the underlying cognitive systems they tap. The tasks associated with the visuospatial sketchpad and the central executive in particular varied substantially in their informational formats. The visuospatial tasks varied from studying a route drawn through a two-dimensional schematic maze and then attempting to draw the same route on a blank maze to recalling (by tapping) the temporal sequence of blocks touched by the experimenter in a three-dimensional array. These tasks shared very few surface features but consistently loaded on a common factor. The processing components of the three complex span tasks associated with the central executive were similarly contrasting, involving processing language for meaning (listening recall), resequencing spoken numbers (backward digit recall) and dot counting (counting recall). The three verbal storage-only measures included as assessments of the phonological loop were more similar in nature, each involving spoken presentation of a sequence of short verbal stimuli that varied in conceptual category and familiarity (digits, words, and nonwords). These measures were selected because serial recall of verbal stimuli is widely accepted as the classic (and only reliable) means of assessing the capacity of the phonological loop, and these different categories of stimulus are widely used in theoretical explorations of this short-term memory system loop (e.g., Burgess & Hitch, 1998; Page & Norris, 1998). Across the tests as a whole, however, the degree of integrity in each of the three factors and their relative distinctiveness from one another cannot simply be explained in terms of surface similarities in associated tasks.

The patterns of associations and dissociations observed in this study across all age groups are more adequately explained in terms of two independent slave systems (the phonological loop and the visuospatial sketchpad) linked to a coordinating central executive. The relative independence of the phonological loop and visuospatial memory factors in the present study fits well both with the absence of a direct link between the two slave systems in the Baddeley and Hitch (1974) model and with previous evidence that verbal and visuospatial short-term memory systems are separable at a range of different points in childhood (Jarvis & Gathercole, 2003; Pickering et al., 1998). It is also consistent with evidence for the neuroanatomical separation of the underlying brain systems (e.g., Smith & Jonides, 1997; Vallar & Papagno, 2002). The much closer links between the central executive factor and both the phonological and visuospatial components are consistent with claims that the central executive is responsible for coordinating the flow of information through working memory and for the transmission and retrieval of information from the slave systems (e.g., Baddeley, 2000; Baddeley & Hitch, 1974). The strengths of the relationship between the central executive and visuospatial factors in our model are particularly noteworthy given the lack of surface similarity between the tasks. The visuospatial tasks were devised to minimize opportunities for verbal recoding and involved neither verbal inputs nor verbal recall. In contrast, all three of the complex memory span tasks required verbal recall, and the inputs in two of the tasks required verbal processing (listening recall and backward digit recall) rather than visuospatial processing. Only counting recall involved visuospatial processing at input. The moderately high association between these two factors therefore provides substantial support for claims that visuospatial memory is significantly dependent on support from domain-independent resources associated with the central executive (see Phillips & Christie, 1977, and Wilson et al., 1987, for related evidence).

The close association between the factors associated with the phonological loop and the central executive also merits comment. Recent working memory accounts have proposed that the storage component of tasks such as listening or reading span that involve the retention of verbal material is mediated by the phonological loop, whereas the processing demands of the tasks are supported by central executive resources (Baddeley & Logie, 1999; Duff & Logie, 2001; see also, LaPointe & Engle, 1990; Lobley et al., 2003). On this basis, a stronger association would be expected between the central executive and the phonological loop than between the central executive and the visuospatial factor in the CFA, because the central executive's identification was based on tasks that are constrained by phonological loop capacity. If this interpretation is correct, the strength of association between the central executive and phonological factors may be overestimated in the present study.

An important finding of the study is the absence of major developmental changes in the strengths of relationships between the three components of working memory across this large childhood period. It is, however, notable that the statistical advantage of the three-factor model (Baddeley & Hitch, 1974) over a two-factor model in which the complex span and verbal storage-only measures tap a single common factor did diminish with increasing age (although not significantly so). Relatedly, the correlation between the factors associated with the phonological loop and the central executive increased from .73 for the 6- to 7-year-old group to .90 and greater for the two older age groups (10- to 12-year-olds and 13- to 15-year-olds). Correspondingly high associations between verbal storage-only and complex span tasks were obtained with 11- and 14-year-old children by Jarvis and Gathercole (2003). One may speculate that the closer links between these assessments of the phonological loop and the central executive factors in older age groups may arise from developmental increases in processing efficiency. The processing demands imposed by the various complex span tasks (resequencing the numbers in the case of backward digit recall, dot counting in counting recall, and sentence processing in listening span) may diminish in older children to such an extent that they are minimal; hence, the complex memory span and verbal storage-only measures would indeed be expected to be sensitive to phonological loop constraints to nearly equivalent extents. However, the correlational structure of the data even in the oldest age group does not favor eliminating the central executive as a separate factor. The reason for this is that despite the close associations between the central executive and phonological loop factors, the visuospatial factor remains much more highly associated with the central executive than it does with the phonological loop. This feature of the data strongly reinforces the tripartite structure of the working memory model.

One important issue that could not be addressed in the present study because of the lack of suitable tasks for young children at the time of its design is the relationship between the components of working memory assessed in the present study and complex memory span measures involving visuospatial rather than verbal storage and processing. However, a recent study of working memory in older children has established statistical independence of complex memory span scores for verbal and nonverbal tests (Jarvis & Gathercole, 2003). These findings indicate that the limited processing capacity associated with the central executive is domain specific, a conclusion also reached in some studies with adult participants (Jurden, 1995; Shah & Miyake, 1996). Whether this domain-specific fractionation of central executive resources extends back into the middle and early childhood years remains unknown at present.

In conclusion, the findings from this study indicate that the three main components of the Baddeley and Hitch (1974) model of working memory are in place by 6 years of age. The capacity of each component increases linearly from age 4 to early adolescence. Despite the general similarity of the developmental functions, the relationships between the components of working memory vary in strength: The central executive is linked closely with both the phonological loop and the visuospatial sketchpad, which are themselves relatively independent. This structural organization of working memory remains more or less constant over the childhood years.

References

Baddeley, A. D. (1986). *Working memory.* Oxford, England: Oxford University Press.

Baddeley, A. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 49A,* 5–28.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4,* 417–422.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47–90). New York: Academic Press.

Baddeley, A. D., & Lieberman, K. (1980). Spatial working memory. In R. S. Nickerson (Ed.), *Attention and performance VIII* (pp. 521–539). Hillsdale, NJ: Erlbaum.

Baddeley, A. D., & Logie, R. (1999). Working memory: The multiple component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 28–61). Cambridge, England: Cambridge University Press.

Bentler, P. M., & Wu, E. J. C. (1995). *EQS for Macintosh user's guide.* Encino, CA: Multivariate Software, Inc.

Bishop, D. V. M. (1997). Cognitive neuropsychology and developmental disorders: Uncomfortable bedfellows. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 50A,* 899–923.

Burgess, N., & Hitch, G. J. (1998). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review, 106,* 551–581.

Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology, 33,* 386–404.

Collette, F., & Van der Linden, M. (2002). Brain imaging of the central executive component of working memory. *Neuroscience and Biobehavioral Reviews, 26,* 105–125.

Cowan, N., Day, L., Saults, J. S., Keller, T. A., Johnson, T., & Flores, L. (1992). The role of verbal output time in the effects of word length on immediate memory. *Journal of Memory and Language, 31,* 1–17.

Cowan, N., Wood, N. L., Wood, P. K., Keller, T. A., Nugent, L. D., & Keller, C. V. (1998). Two separate verbal processing speeds contributing to verbal short-term memory span. *Journal of Experimental Psychology: General, 127,* 141–160.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading comprehension. *Journal of Verbal Learning and Verbal Behavior, 19,* 450–466.

Daneman, M., & Carpenter, P. A. (1983). Individual differences in integrating information within and between sentences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 561–584.

Della Sala, S., Gray, C., Baddeley, A. D., Allemano, N., & Wilson, L. (1999). Pattern span: A tool for unwielding visuo-spatial memory. *Neuropsychologia, 37,* 1189–1199.

Della Sala, S., Gray, C., Baddeley, A. D., & Wilson, L. (1997). *Visual Patterns Test.* Bury St Edmonds, England: Thames Valley Test Company.

Dempster, F. M. (1985). Short-term memory development in childhood and adolescence. In C. J. Brainerd & M. Pressley (Eds.), *Basic processes in memory development* (pp. 209–248). New York: Springer.

De Renzi, E. & Nichelli, P. (1975). Verbal and nonverbal short term memory impairment following hemispheric damage. *Cortex, 11,* 341–353.

D'Esposito, M., Detre, J. A., Alsop, D. C., Shin, R. K., Atlas, S., & Grossman, M. (1995). The neural basis of the central executive system of working memory. *Nature, 378,* 279–281.

Duff, S. C., & Logie, R. H. (2001). Processing and storage in working memory span. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 54A,* 31–48.

Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 972–992.

Gathercole, S. E. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences, 3,* 410–418.

Gathercole, S. E. (2002). Memory development during the childhood year. In A. D. Baddeley, M. D. Kopelman, & B. A. Wilson (Eds.), *Handbook of memory disorders* (2nd ed., pp. 475–500). Chichester, England: Wiley.

Gathercole, S. E., & Hitch, G. J. (1993). Developmental changes in short-term memory: A revised working memory perspective. In A. Collins, S. E. Gathercole, M. A. Conway, & P. E. Morris (Eds.), *Theories of memory* (pp. 189–210). Hove, England: Erlbaum.

Gathercole, S. E., & Pickering, S. J. (2000). Assessment of working memory in six- and seven-year old children. *Journal of Educational Psychology, 92,* 377–390.

Henson, R. (2001). Neural working memory. In J. Andrade (Ed.), *Working memory in perspective* (pp. 151–173). Hove, England: Psychology Press.

Henson, R., Burgess, N., & Frith, C. D. (2000). Recoding, storage, rehearsal and grouping in verbal short-term memory: An fMRI study. *Neuropsychologia, 38,* 426–440.

Hitch, G. J., & Halliday, M. S. (1983). Working memory in children. *Philosophical Transactions of the Royal Society of London, Series B, 302,* 324–340.

Hitch, G. J., Halliday, M. S., Schaafstal, A. M., & Schraagen, J. M. C. (1988). Visual working memory in young children. *Memory & Cognition, 16,* 120–132.

Hitch, G. J., Towse, J. N., & Hutton, U. (2001). What limits children's working memory span? Theoretical accounts and applications for scholastic development. *Journal of Experimental Psychology: General, 130,* 184–198.

Hulme, C., Thomson, N., Muir, C., & Lawrence, A. (1984). Speech rate and the development of short-term memory span. *Journal of Experimental Child Psychology, 38,* 241–253.

Isaacs, E. B., & Vargha-Khadem, F. (1989). Differential course of development of spatial and verbal memory span: A normative study. *British Journal of Developmental Psychology, 7,* 377–380.

Jarvis, H. L., & Gathercole, S. E. (2003). Verbal and non-verbal working memory and achievements on national curriculum tests at 11 and 14 years of age. *Educational and Child Psychology, 20,* 123–140.

Jurden, F. H. (1995). Individual differences in working memory and complex cognition. *Journal of Educational Psychology, 87,* 93- 102.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences, 2,* 389–398.

LaPointe, L. B., & Engle, R. W. (1990). Simple and complex word spans as measures of working memory capacity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 1118–1133.

Lobley, K. J., Gathercole, S. E., & Baddeley, A. D. (2003). *The phonological loop and complex memory span: A developmental analysis.* Unpublished manuscript.

Logie, R. H. (1986). Visuo-spatial processing in working memory. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 38A,* 229–247.

Logie, R. H. (1995). *Visuo-spatial working memory.* Hove, England: Erlbaum.

Logie, R. H., & Pearson, D. G. (1997). The inner ear and the inner scribe of visuo-spatial working memory: Evidence from developmental fractionation. *European Journal of Cognitive Psychology, 9,* 241–257.

Manoach, D. S., Schlaug, G., Siewert, B., Darby, D. G., Bly, B. M., Benfield, A., et al. (1997). Prefrontal cortex fMRI signal changes are correlated with working memory load. *NeuroReport, 8,* 545–549.

Mardia, K. V. (1970). Measures of multivariate skewness and kurtosis with applications. *Biometrika, 57,* 519–530.

McDonald, R. P., & Ho, M-H. R. (2002). Principles and practice in reporting structural equation analyses. *Psychological Research, 7,* 64–82.

Morra, S. (1994). Issues in working memory measurement: Testing for M capacity. *International Journal of Behavioural Development, 17,* 143–159.

Nelson, C. A. (1995). The ontogeny of human memory: A cognitive neuroscience perspective. *Developmental Psychology, 31,* 723–738.

Nelson, C. A. (2000). Neural plasticity and human development: The role of early experience in sculpting memory systems. *Developmental Science, 3,* 115–136.

Owen, A. M., Evans, A. C., & Petrides, M. (1996). Evidence for a two-stage model of spatial working memory processing within the lateral frontal cortex: A positron emission tomography study. *Cerebral Cortex, 6,* 31–38.

Page, M. P. A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review, 105,* 761–781.

Phillips, W. A., & Christie, D. F. M. (1977). Interference with visualization. *Quarterly Journal of Experimental Psychology, 29,* 637–650.

Pickering, S. J. (2001). The development of visuo-spatial working memory. *Memory, 9,* 423–432.

Pickering, S. J., & Gathercole, S. E. (2001). *Working Memory Test Battery for Children.* London: Psychological Corporation.

Pickering, S. J., Gathercole, S. E., Hall, M., & Lloyd, S. A. (2001). Development of memory for pattern and path: Further evidence for the fractionation of visual and spatial short-term memory. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 54A,* 397–420.

Pickering, S. J., Gathercole, S. E., & Peaker, M. (1998). Verbal and visuo-spatial short-term memory in children: Evidence for common and distinct mechanisms. *Memory & Cognition, 26,* 1117–1130.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General, 125,* 4–27.

Siegel, L. S. (1994). Working memory and reading: A life-span perspective. *International Journal of Behavioural Development, 17,* 109–124.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology, 33,* 5–42.

Smith, E. E., Jonides, J., & Koeppe, R. A. (1996). Dissociating verbal and spatial memory using PET. *Cerebral Cortex, 6,* 11–20.

Swanson, H. L. (1999). What develops in working memory? A life span perspective. *Developmental Psychology, 35,* 986–1000.

Towse, J. N., & Hitch, G. J. (1995). Is there a relationship between task demand and storage space in tests of working memory capacity? *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 48A,* 108–124.

Towse, J. N., Hitch, G. J., & Hutton, U. (1998). A reevaluation of working memory capacity in children. *Journal of Memory and Language, 39,* 195–217.

Towse, J. N., Hitch, G. J., & Hutton, U. (2002). On the nature of the relationship between processing activity and item retention in children. *Journal of Experimental Child Psychology, 82,* 156–184.

Vallar, G., & Papagno, C. (2002). Neuropsychological impairments of verbal short-term memory. In M. Kopelman, A. D. Baddeley, & B. Wilson (Eds.), *Handbook of neuropsychology* (2nd ed., pp. 249–270). Chichester, England: Wiley.

Willis, C. S., & Gathercole, S. E. (2001). Phonological short-term memory contributions to sentence processing in young children. *Memory, 9,* 349–364.

Wilson, J. T. L., Scott, J. H., & Power, K. G. (1987). Developmental differences in the span of visual memory for pattern. *British Journal of Developmental Psychology, 5,* 249–255.

Received December 17, 2001
Revision received October 10, 2003
Accepted October 27, 2003 ■