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The differential relations between verbal, numerical and spatial working memory abilities and children's reading comprehension

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Abstract

Working memory predicts children's reading comprehension but it is not clear whether this relation is due to a modality-specific or general working memory. This study, which investigated the relations between children's reading skills and working memory (WM) abilities in 3 modalities, extends previous work by including measures of both reading comprehension and reading accuracy. Tests of word reading accuracy and reading comprehension, and working memory tests in three different modalities (verbal, numerical and spatial), were given to 197 6- to 11-year old children. The results support the view that working memory tasks that require the processing and recall of symbolic information (words and numbers) are better predictors of reading comprehension than tasks that require visuo-spatial storage and processing. The different measures of verbal and numerical working memory were not equally good predictors of reading comprehension, but their predictive power depended on neither the word vs. numerical contrast nor the complexity of the processing component. In general, performance on the verbal and numerical working memory tasks predicted reading comprehension, but not reading accuracy, and spatial WM did not predict either. The patterns of relations between the measures of working memory and reading comprehension ability were relatively constant across the age group tested.

Keywords: Reading comprehension, reading accuracy, working memory, information processing

Introduction

The concept of working memory has a role in most theories of text comprehension, and in attempts to explain individual differences in text comprehension (see, e.g. Just and Carpenter, 1992). Daneman and Carpenter (1980) suggested that the crucial difference

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between tests of working memory and those of short-term memory (such as digit span and word span) which are not, or are only weakly, related to comprehension skill, is that short-term memory tests only require the use of a passive storage buffer. Daneman and Carpenter went on to argue that both storage and processing of information in memory is important in comprehension, and suggested that the concept of working memory (e.g. Baddeley & Hitch, 1974) better accounts for the sharing of resources between the processing and storage demands of a particular task. In order to measure this functional capacity, Daneman and Carpenter developed the *Reading Span* task. In contrast to digit span and related tasks, performance on both reading and listening versions of Daneman and Carpenter's working memory span tasks predicted performance on comprehension tests.

Daneman and Carpenter's (1980; 1983) reading span test is now a frequently used measure of working memory in reading research. In this test, participants either read or listen to a set of unrelated sentences (processing requirement) and have to retain the final word of each sentence (storage requirement) for recall after all the sentences have been read. Participants also have to answer simple comprehension questions about the sentences to ensure that they have processed the text for meaning. Studies of college students have shown that scores on this test correlate highly with many measures of reading comprehension such as remembering facts, detecting and recovering from semantic inconsistencies, and resolving pronouns, especially those with distant antecedents (see, e.g., Cantor, Engle, & Hamilton, 1991; Dixon, LeFevre, & Twilley, 1988; Engle, Nations, & Cantor, 1990). The correlations of span with performance on various comprehension tests ranged from .7 to .9 in the original samples, and a meta-analysis by Daneman and Merikle (1996), shows an average correlation of .41 between reading span and global reading comprehension in adults.

The link between working memory and reading comprehension probably holds because a major component of skilled comprehension is the ability to compute the semantic and syntactic relations among successive words, phrases and sentences, in order to construct a coherent overall representation of the text. In all current models of text comprehension (e.g. Gernsbacher, 1990; Johnson-Laird, 1983; Kintsch, 1998) the processes of integration and inference are important in the construction of a coherent model of the text, both locally and globally. In such models, working memory acts as a buffer for the most recently read propositions in a text, so that they can be integrated with the model of the text so far, and also holds information activated from long term-memory to facilitate its integration with the currently active text (Cooke, Halleran & O'Brien, 1998; Graesser, Singer & Trabasso, 1994). It follows that individuals with limited working memory capacities should be less able to undertake these types of processing than those with greater storage and processing capacities. However, Daneman and Carpenter's original reading span test itself requires reading, so performance on the test may be partly, or even largely, dependent on general reading ability, which is known to be correlated with reading comprehension skill, but which involves many components other than working memory. Furthermore, people have to perform comprehension tasks, albeit simple ones, as an integral part of the reading span task. Such considerations raise the question of what underlies the relation between reading span and reading comprehension. Thus, given more general arguments for the role of working memory in comprehension, the question remains open as to whether the type of working memory implicated in text comprehension is a general one, one that is specific to language, or to the processing of symbolic information. On the one hand, several studies support the idea that it is the processing of symbolic information that is crucial. These studies show that verbal and numerical span tasks, but not spatial span tasks, predict performance on tests of reading comprehension and other measures of verbal ability (see, e.g. Daneman & Tardif, 1987; Shah & Miyake, 1996) whereas spatial span, but not reading span, is a good predictor of performance on standardised visuo-spatial tests.

On the other hand, domain-general accounts of working memory have been advanced by Engle and his colleagues (e.g. Engle, Tuholski, Laughlin & Conway, 1999). In such accounts, individual differences are interpreted in terms of the quantity of resources available. Turner and Engle's (1989) results led them to describe working memory as a general capacity resource, in which it is the capacity to keep active a certain number of elements that is crucial. However, and importantly from our perspective, they did not include a measure of spatial working memory in their study, so it is impossible to know whether their findings would generalise to the spatial domain. In any case, these two views are not incompatible. By "domain-general" Engle and colleagues mean that this capacity is not restricted to a certain type of task. Furthermore, in a later study, Kane, Hambrick, Tuholski, Wilhelm, Payne & Engle (2004) found that a two-factor model (in which verbal and visuo-spatial memory were separated) was a slightly better fit than a one-factor model in which working memory was regarded as a single construct, although the verbal and visuo-spatial working memory constructs were highly correlated. Thus, their data are consistent with a (weak) dissociation between verbal and visuo-spatial working memory capacity. In addition, Kane et al. provide some possible reasons to be sceptical of the data that purport to support strong domain specificity and we return to those reasons at the end of the introduction, since they are particularly pertinent to the design of our own study. In a meta-analysis of the relations between WM and comprehension, Carretti, Borella, Cornoldi and De Beni (2009) suggest both domain-general and specific factors play a role, with verbal working memory being more predictive. However, they compared verbal working memory only with visuo-spatial tasks (not numerical working memory) and only three of the studies they review included more than one type of working memory task.

Finally, there is still some ambiguity about the relation between numerical working memory tasks and comprehension in adults. For example, Waters and Caplan (1996) found that adults' comprehension was not significantly correlated with numerical working memory tasks, only with reading span tasks. In general, even if both sorts of task correlate with comprehension skill, it is the reading span tasks that show the stronger correlation.

In children, as opposed to adults, a number of studies have shown a strong relation between working memory and children's reading comprehension (e.g. Leather & Henry, 1994; Oakhill, Yuill & Parkin, 1986; Swanson & Berninger, 1995; Yuill, Oakhill & Parkin, 1989). This relation between working memory and reading comprehension has been found to hold with tasks that require the processing and storage of words (de Beni, Palladino, Pazzaglia & Cornoldi, 1998), sentences (Engle, Carullo & Collins, 1991; Seigneuric, Ehrlich, Oakhill & Yuill, 2000) and numbers (Yuill et al., 1989). Other studies have compared listening and counting span (Siegel & Ryan, 1989; Leather & Henry, 1994). Compared with the work on adults, however, there has been little research into domain-specificity of the relation between working memory and reading comprehension in children, and in particular the possible role of spatial working memory in children's comprehension.

Swanson (1992; 1996) argued for a general resources model, based on similar correlations between verbal and spatial working memory tasks and comprehension skill. However, this argument is not compelling and, indeed, other work by Swanson has produced less clear-cut results: Swanson and Berninger (1995) showed that, even with similar overall correlations between visuo-spatial working memory and comprehension skill, and verbal working memory and comprehension skill, verbal, but not visuo-spatial, working memory differentiated between groups of good and poor comprehenders. Thus, the issue of whether skilled reading comprehension in children is associated with general working memory remains equivocal, and will be taken up in the present study.

Bayliss and colleagues (Bayliss, Jarrold, Gunn & Baddeley, 2003; Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005) also explored the relation between working memory and reading comprehension in children, using a sentence comprehension test (the NFER-Nelson group reading test II, 1998). They found moderate correlations between reading and both verbal and visuo-spatial span tasks (though not with a purely visuo-spatial task in their 2003 study). However, the reading comprehension measure was almost certainly confounded with word reading skills, which were not independently measured or controlled for. Indeed, in both studies, digit span was also correlated with the assessment of reading. This fact strongly suggests that the reading comprehension test was also assessing word reading which, unlike comprehension, tends to be associated with digit span.

An important, and novel, issue addressed in the present study is whether any of the working memory tasks are related to reading accuracy, as opposed to reading comprehension. We know of only two previous studies that explored the relation between reading comprehension and working memory in which assessments of reading comprehension skill were distinct from those of single word reading or decoding skills.

Seigneuric, et al. (2000) developed a test of spatial working memory: a simplified version of the tic-tac-toe task used by Daneman and Tardif (1987). They found that measures of working memory capacity – both verbal and numerical-predicted reading comprehension over and above vocabulary and decoding skills, but the spatial working memory task was not significantly related to comprehension skill. The present study builds on that of Seigneuric et al. in two important ways. First, we explore these relations over a wider age range and with more participants and, second, we control for general ability in each of the domains of interest.

The second study was conducted by Nation, Adams, Bowyer-Crain and Snowling (1999). The findings from their first experiment support those from previous studies (Oakhill et al., 1986; Stothard & Hulme, 1992) in showing that good and poor comprehenders do not differ in digit span and verbatim recall. Also in keeping with previous studies, Nation et al. found that good and poor comprehenders differed in verbal, but not in spatial, working memory and they argue that the poor comprehenders have specific problems with verbal processing and not more general capacity limitations. However, although Nation et al. collected data on the children's word reading accuracy, they did not look at the relation between working memory and word reading. The present study differs from theirs in various ways. First, we consider a wider age range, and include tasks of three different types (verbal, numerical and spatial). Second, Nation et al. compared the performance of groups who differed in comprehension ability on their working memory tasks, whereas we look at the relative contributions of working memory tasks in different domains, once general ability is controlled for. In the present study, we compared the relations of the various working memory tests to both accuracy and comprehension. We predicted that working memory would be more closely related to comprehension than to accuracy, and that it would predict variance in comprehension even when accuracy was controlled for.

A further issue addressed by our study is whether working memory systems become more differentiated with age. Contrasting views have been expressed by Alloway, Gathercole and Pickering (2006) and Hale, Bronik and Fry (1997), based, on the one hand, on correlational data and, on the other hand, on cross-task interference. It is possible that the relation between working memory and reading comprehension differs between children and adults. In particular, Kennedy and Murray (see, e.g. Kennedy, 1987; Murray & Kennedy,

1988) have suggested that spatial working memory is important for place-keeping skills in text comprehension, which might develop, at least partially, separately from other aspects of comprehension. These place-keeping skills of fluent readers allow them to re-inspect text selectively, and children who are good readers are much better at re-inspecting text selectively than poor readers (see Cataldo & Oakhill, 2000). Although spatial working memory does not predict text comprehension in adults, it might predict comprehension in children when these skills that depend on spatial working memory are developing, since the demands on the relevant memory systems may be higher. In this study, we assess the role of spatial and other measures of working memory in the reading comprehension performance of 6- to 8- and 9- to 11-year-olds separately.

In addition to the problems that we mentioned above, there is a more general problem of interpreting the relation between tests of working memory and assessments of reading. Working memory tests in any modality inevitably require some basic abilities in that domain. For example, reading and listening span tasks require general vocabulary knowledge. We might expect tests of verbal working memory to correlate better with measures of reading than tests of numerical working memory because of this shared dependence on general verbal ability. Of the previous studies, Yuill et al. (1989) used contrasting groups matched on basic vocabulary skills, but only Seigneuric et al. (2000) and Swanson (1992) have directly assessed this possibility by controlling for vocabulary or other general skills. Of course, tests of general ability are also likely to require some degree of working memory skills, but it would be an important indicator of the importance of working memory in reading if correlations with reading skills remained significant after performance on tests of general ability had been partialled out. In the present study, we include assessments of general ability in the three areas of interest: verbal, numerical and spatial, so that the particular working memory tasks can be assessed against the contribution of general ability in the relevant domain.

Another approach to this confounding was adopted by Yuill, Oakhill and Parkin (1989) who developed a working memory test that required processing and storage of numbers rather than words and sentences. They found a significant correlation between performance on this test and reading comprehension in 7- to 9-year-old children, but they did not directly compare the predictive power of their numerical task with that of a listening or reading span task, which is one of the aims of the present study.

A subsidiary question is how the level of verbal complexity of a working memory task contributes to the relation between that task and reading comprehension. Reading span tasks are complex, in that they require the simultaneous use of several skills: not only the verbal encoding of information and switching between storage and processing, but also the syntactic and semantic processing of sentences and the processing of word meanings (although the complexity of the processing component does not seem to relate very directly to the predictive power of the task: see Lépine, Barrouillet & Camos, 2005). In the present study, we developed and validated a verbal measure for use with children that does not require sentence-level comprehension, and compared its predictive power with that of the listening span task. In addition, the inclusion of these two verbal tasks enabled us to explore how tasks with different processing components relate to comprehension skill. We also included two different numerical tasks for similar reasons, but also because the final digit task we have used previously (see Yuill, et al., 1989), is not so strongly related as to comprehension skills as are verbal tasks (Seigneuric et al., 2000). One possible explanation for this weaker relation is that the processing requirement of the final digit task is low (children simply have to read out a set of single-digit numbers). In the present study we therefore also included a second test of numerical working memory, with a more demanding processing requirement. We used only one spatial task, a version of that used successfully in the study by Seigneuric et al.

Kane et al. (2004) point out some major limitations in previous (adult) studies that purport to show domain-specificity in working memory tasks, and we have attempted to overcome these criticisms in the present study, as follows. First, many studies have used small and quite homogeneous samples. We have used a large sample of children, across a wide age range. Second, in some studies, the verbal and spatial working memory tasks differ markedly in difficulty. We have piloted and developed tasks that were similar in difficulty, and adapted the level of difficulty to give similar levels of average performance in the different age groups. Third, it is not clear in previous studies whether it is the domain-specificity of the working memory construct that is important, or the domain-specificity of resources in that domain that are not specific to working memory tasks: for example, if verbal working memory is related to reading comprehension, is that something to do with the working memory task, or with the verbal nature of the task? In contrast to most previous studies of the dissociation between verbal and spatial working memory, we also included general measures of verbal, mathematical and spatial ability, so that the contributions of domain-specific working memory, as opposed to competence in a domain more generally, could be taken into account.

In summary, the present study aimed to explore the relation between working memory skills in different domains (verbal, numerical and spatial) and reading comprehension in children. This work extends previous studies in two main ways. First, we include comparisons of all three areas. Second, we explore the relation between working memory and reading skill when general ability in the relevant domain has been taken into account. Third, we explore whether any links between working memory and reading ability are specific to reading comprehension, or apply to reading skill more generally. Finally, we explore the way in which the level of complexity of the verbal and numerical tasks contributes to the relation between that task and reading skill.

Methods

Participants

All available children (excluding those few identified by teachers as having language or behavioural problems) from 12 classes of 6 to 11-year-olds in 5 schools took part in the study. This produced a sample of 197 children, divided into two age groups: 97 6- to 8- year-olds and 100 9- to 11-year-olds.

Overview of Design and Procedure

Each child completed 3 types of test, described in detail in the Materials section:

(1) reading tests (RA: Accuracy and RC: Comprehension tests of the Neale Analysis of Reading Ability Revised (Neale, 1997), (2) working memory tests of three types: verbal (2 tests, odd word out, VWM1, and reading span, VWM2), numerical (2 tests, highest number, NWM1, and final number, NWM2) and spatial (1 test, SPWM) and (3) general ability tests selected from the Cognitive Abilities Test (CAT: Thorndike & Hagen, 1986) in three areas: verbal, numerical and spatial (nonverbal).

The reading test was presented individually in the first session, followed by the 5 working memory tests, in a separate random order for each subject, spread over 3 sessions, each in a separate room by a male experimenter familiar to the children. Finally the CATs were presented to children in separate random orders in groups of 36.

Materials

Reading test. The Neale Analysis requires children to read aloud a series of narrative passages of increasing difficulty, and then to answer from memory a mix of factual and inferential questions about each passage. Children are corrected on words that are misread or not read, so that they are not disadvantaged on comprehension questions, but testing is stopped when children make a pre-set number of reading errors on a particular passage. Separate norm-referenced scores are computed for accuracy (number of words read correctly) and comprehension (number of questions correct). This test, and its predecessor, have been shown to predict a range of differences in abilities between good and poor comprehenders (e.g. see Yuill & Oakhill, 1991). We used the raw scores for reading accuracy (RA) and reading comprehension (RC) in all analyses.

Working memory tests. All five of these tests had certain characteristics in common. All required the simultaneous storage and processing of information. For each of the tests, there were four levels of storage difficulty presented in order of increasing difficulty, each level containing three trials (except the pre-existing final number task devised by Yuill et al., which was the least demanding in terms of storage and processing, and had eight trials). The first storage level contained two recall items and for each of the next levels the number of recall items was increased by one, with the final storage level having a maximum of five recall items. Where appropriate (in tests V1, V2, N1 and SP) the position of correct responses was counterbalanced. Children practised at each storage level until it was clear they understood the processing requirements of the task. This never required more than three trials at any of the storage levels.

In all of the tests a strict scoring procedure was used: children were required to recall the correct items in the order of presentation. In all analyses, we used the proportion of items correct out of the possible maximum score as the independent variable.

We piloted the materials for the new or adapted tests (V1, V2, N1 and SP) with 40 6- to 11-year-olds, in order to ensure that children could provide the correct responses for the processing component, and only used items on which 90% of the youngest children were correct. (Recall of these correct responses was, naturally, considerably less than 90%.) The second aim of the pilot was to ensure that the tests produced similar mean scores and standard deviations both across the different modalities and across the age range. This aim was achieved, both in the pilot and in the main study, as shown in Table 1.

In all the working memory tests, the older children were presented with more trials in order to ensure that the tasks were at an appropriate level of difficulty. The younger age groups received three trials at each of three levels (two, three or four items to recall) and the older children received an additional set of trials with five items to recall. Thus, the younger children were given a total of nine trials (3 trials at each of 3 levels of difficulty) and the older children received a total of 12 trials (3 trials at each of 4 levels of difficulty). All children attempted all trials appropriate for their age group. Because different children received different numbers of trials, the scores entered into the analyses were proportions correct. The exception was the spatial working memory task, which proved to be sufficiently difficult for all children with a recall demand of four.

Aural word span: Odd word out (VWM1). This newly-devised test consists of series of single words of one or two syllables in groups of four. Three of the words are in the same category (e.g. names of fruits or colours) and the fourth is from a different category. The words within each group of four are presented in a fixed random order. Children listen to the four words and have to detect the 'odd word out'. They then have to recall the odd words in each series.

An example of a three-item series is:

Whale	Shark	Dolphin	Scarf
Cowboy	Curtain	Indian	Sheriff
Egg	Aunt	Cousin	Uncle

The correct response for this series is: “scarf, curtain, egg”.

Aural reading span (VWM2). This test is our UK English adaptation of the test used by Siegel and Ryan (1989). We adapted the test because we found that English children in some cases did not give the same completions as the original North American sample did. The child listens to a set of unrelated sentences and supplies the final word in each, then recalls these final words. The final words are highly constrained by the context. For example,

The sun shines during the day, the moon at _____.

At the library people read ______.

An apple is red, a banana is ______.

The correct response is: “night, books, yellow”.

Highest Number Task (NWM1). In this new test, children inspect sets of three numbers, shown on a card and read aloud by the experimenter. They have to pick the highest number and then recall the highest numbers from each set. All the numbers are between 1 and 19 and each set contains one number below 10, and two between 10 and 20. For example, a 3-item set is:

14	9	17
10	11	4
15	3	12

to which the answer is: “17, 11, 15”.

Final Number Test (NWM2). This task was the one developed by Yuill et al. (1989). Children are required to read sets of three-digit numbers and to recall the last numeral in each number. For example, a three-item set is:

528

434

489

to which the answer is: “8, 4, 9”.

It should be noted that, though we refer to the two above tests as tests of “numerical” working memory, they might better be described as tasks that require numerical processing, but verbal storage. We return to this point in the Discussion section.

Spatial Working Memory Test (SPWM). Daneman and Tardif (1987) described a spatial test using three-dimensional tic-tac-toe. We adapted this test to make it suitable for children. Children were shown a series of 3 by 3 matrices, one at a time, each containing two noughts, and had to point to the cell where a nought should be inserted to make a winning line. Each grid has noughts of a different colour, in order to facilitate children's recall of the positions in the correct order. After seeing all the matrices, children had to place strips of corresponding colours onto an adhesive grid, to indicate the positions of the winning lines. The colours of the lines could thus be linked to the order in which the grids had been presented: the sequence of colours was the same in each trial (e.g. the trials of 3 items showed orange, then blue, then green noughts, and the trials of 4 items added a set of pink noughts to this sequence). Although the probability of guessing the correct lines is 1 in 8 (as there are only 8 possible winning lines in a 3 by 3 grid), the probability of matching colours to positions is much lower.

Cognitive Abilities Tests (CATs). These are a series of standardised pencil-and-paper multiple-choice tests tapping general ability in different areas. The full CAT consists of four verbal subtests, three mathematical ('quantitative') subtests and three spatial ('nonverbal') subtests. We used one of each type of subtest: Verbal 2, Quantitative 1 and Nonverbal 2, all preceded by two to three practice items. These subtests were chosen on the basis that each correlated most highly with the other subtests in its battery and was most highly loaded on the relevant factor in a factor analysis (Thorndike, Hagen & France, 1986). There are two levels of each test: Level A consists of the first 25 questions in the test, which increase in difficulty through the test, and level B consists of the first 30 questions of the same test. All children took level B, except for the 7-year-old group, who were given Level A. An example from each of these tests is given below.

Verbal (CATV):

The fire is .... (possible choices: wet, green, hot, running, round)

Quantitative (CATN):

Which is greater: 1 1 + 1 1 OR 1 1 + 1 ?

Spatial (CATS):

Respondents have to make analogies between diagrams, for example: Large square is to small square as large circle is to ....?, with choices of a small circle, a large semicircle, a filled square and two triangles joined at the apices.

Results

Descriptive Statistics

Each child had a maximum of 10 test scores (though because of time constraints and absences, it was not always possible to collect the full set of data for every child; where data were missing, correlations and regression analyses were conducted using all available data: the actual numbers of children included in the correlation analyses is shown in the relevant tables): two reading scores, Neale Reading Accuracy (NRA) and Neale Reading Comprehension (NRC), five working memory scores, (Verbal, Odd Word; Verbal Reading Span; Numerical Highest Number; Numerical Final Digit and Spatial) which were calculated as proportion of total possible score, and three general ability scores (CAT Verbal, CAT Numerical and CAT Spatial). We also calculated chronological age at time of test in months (CA). The means and standard deviations of each score for the two age groups are shown in Table 1. The working memory tests, including the new ones, showed a reasonable spread of performance (all means within the range 35-59% correct) and similar levels of variability (alls s.d.s in the range .12 to .16). Importantly, the tests that turned out to be the strongest predictors of comprehension skill were not differentiated from the other tests by their particular ease or difficulty.

Table 1. *Summary of Means and Standard deviations of Overall Scores on the Assessments, and within each Age-group.*

		Age	Neale Accuracy	Neale compreh.	CAT: verbal	CAT: numerical	CAT: spatial	VWM: odd word	VWM: reading span	NWM: highest number	NWM: final digit	Spatial WM
Age group:												
6-8years	Mean	94.84	36.70	12.38	12.07	11.18	12.73	.35	.52	.44	.48	.44
	N	83	84	84	82	82	81	78	81	77	80	75
	s.d.	6.98	17.64	5.32	5.72	5.71	8.29	.13	.14	.14	.14	.14
9-11 years	Mean	121.10	62.36	20.95	21.20	21.05	20.84	.46	.59	.53	.55	.53
	N	95	95	95	95	94	95	66	81	65	77	83
	s.d.	7.53	21.59	7.73	5.68	5.44	8.92	.12	.12	.16	.14	.15
Overall	Mean	108.85	50.32	16.93	16.97	16.45	17.11	.40	.55	.48	.51	.49
	N	178	179	179	177	176	176	144	162	142	157	158
	s.d.	14.73	23.45	8.19	7.03	7.36	8.54	.12	.14	.16	.14	.15

Note: Chronological age is in months; Neale and CAT scores are raw scores; Working Memory Tasks are proportion correct.

The reliability of the different working memory measures was calculated using Cronbach's Alpha. It will be recalled that older children were required to complete more trials to ensure that the tasks were sufficiently difficult for them., so the total number of trials was 12 for the older children and 9 for the younger ones. However, estimates of reliability could be obtained only over the items that were completed by all the participants (*n* = 9 items) and, given the small number of items, were acceptable. The levels of Cronbach's Alpha ranged between .66 and .73 for the verbal and numerical tasks, but were slightly lower for the spatial working memory task (.61). It was not appropriate or necessary to calculate reliability in the case of the Neale Analysis scores or the CATs scores, since these are standardised tests with published reliability statistics.

Correlational analyses

The bi-variate correlations between the measures are shown overall, and separately for each age group, in Table 2. Because of the large number of correlations, we adopted a conservative (.01) level of significance. All five working memory measures were significantly correlated with both reading comprehension (correlations between .34 and .46) and reading accuracy (correlations between .36 and .47), and all the working memory measures were significantly correlated with each other (correlations between .34 and .59). Some of these correlations held up in both age groups separately, but it was only the Verbal Reading Span and Numerical Final Digit Task that were strong and consistently related to reading comprehension in both age groups. We return to this point in the regression analyses, presented below. In addition, the general ability measures (CATs) were significantly correlated with both the working memory measures and the reading measures in the data overall, and the CATs scores were correlated with the two reading ability measures in both age groups, with the exception of the CAT Spatial which did not correlate with RC in the younger group. The relation between the CATs scores and the working memory assessments in the two age groups considered separately were less consistent.

Table 2. *Intercorrelations among Age and Ability Variables*

		Age	Neale Accuracy	Neale Comprehension	VWM: odd word	VWM: reading span	NWM: highest number	NWM: final digit	Spatial WM:	CAT: verbal	CAT: Numerical	CAT: Spatial
Age		1	.602**	.581**	.427**	.250**	.334**	.211**	.413**	.716**	.734**	.483**
	N		178	178	143	162	141	157	158	176	175	175
Neale RA			1	.713**	.470**	.374**	.421**	.400**	.359**	.813**	.711**	.578**
	N			179	144	162	142	157	158	177	176	176
Neale RC				1	.464**	.464**	.345**	.440**	.344**	.715**	.612**	.520**
	N				144	162	142	157	158	177	176	176
VWM1					1	.590**	.515**	.506**	.470**	.492**	.464**	.488**
	N					133	139	131	129	142	141	141
VWM2						1	.472**	.542**	.339**	.377**	.369**	.344**
	N						131	157	146	160	159	159
NWM1							1	.559**	.483**	.394**	.511**	.389**
	N							127	126	140	140	139
NWM2								1	.359**	.361**	.463**	.344**
	N								141	155	154	154
SPWM									1	.384**	.454**	.439**
	N									156	155	155
CAT-V										1	.772**	.666**
	N										176	176
CAT-N											1	.592**
	N											175

** $p < 0.001$

* $p < 0.01$

Table 2a. *Intercorrelations among Variables within the Younger Age Group*

		Age	Neale Accuracy	Neale Compreh.	VWM: odd word	VWM: reading span	NWM: highest number	NWM: final digit	Spatial WM	CAT: verbal	CAT: numerical	CAT: spatial
Age		1	.300*	.215	.271	.267	.210	.056	.328*	.580**	.408**	.216
	N		83	83	77	81	76	80	75	81	81	80
Neale RA			1	.652**	.385**	.458**	.228	.456**	.273	.739**	.523**	.299*
	N			84	78	81	77	80	75	82	82	81
Neale RC				1	.428**	.466**	.280	.406**	.184	.580**	.348*	.244
	N				78	81	77	80	75	82	82	81
VWM 1					1	.613**	.503**	.451**	.500**	.433**	.315*	.491**
	N					75	77	74	71	76	76	75
VWM 2						1	.501**	.427**	.391**	.403**	.344*	.308*
	N						74	80	74	79	79	78
NWM 1							1	.372**	.398**	.241	.369**	.290
	N							73	70	75	75	74
NWM 2							1	.372**	.398**	.241	.369**	.290
	N							73	70	75	75	74
SPWM									1	.249	.291	.285
	N									73	73	72
CAT-V										1	.585**	.466**
	N										82	81
CAT-N											1	.355**
	N											81

** p< 0.001
* p < 0.01

Table 2b. *Intercorrelations among Variables within the Older Age Group*

		Age	Neale Accuracy	Neale Compreh.	VWM: odd word	VWM: reading span	NWM: highest number	NWM: final digit	Spatial WM	CAT: verbal	CAT: numerical	CAT: spatial
Age		1	.314*	.312*	-.030	-.176	.119	-.065	.337*	.339**	.441**	.268*
	N		95	95	66	81	65	77	83	95	94	95
Neale RA			1	.567**	.295	.132	.410**	.224	.233	.715**	.586**	.560**
	N			95	66	81	65	77	83	95	94	95
Neale RC				1	.242	.369**	.200	.368**	.262	.587**	.453**	.464**
	N				66	81	65	77	83	95	94	95
VWM 1					1	.446**	.399**	.413**	.304	.216	.261	.284
	N					58	62	57	58	66	65	66
VWM 2						1	.353*	.615**	.181	.159	.200	.235
	N						57	77	72	81	80	81
NWM 1							1	.688**	.481**	.331*	.505**	.329*
	N							54	56	65	65	65
NWM 2								1	.332*	.273	.427**	.212
	N								68	77	76	77
SPWM									1	.289*	.430**	.419**
	N									83	82	83
CAT-V										1	.637**	.647**
	N										94	95
CAT-N											1	.537**
	N											95

** $p< 0.001$
* $p < 0.01$

Since our prediction in relation to age differences was not upheld (that there may be a different relation between comprehension skill and visuo-spatial working memory in the two age groups) we conducted all further analyses on the entire data set.

Regression analyses

The regression analyses enabled us to assess the relative importance and specificity of the various predictors in relation to the measures of reading ability. We were particularly interested in comparing the predictive power of the numerical, verbal and spatial tasks.

The first goal was to determine whether working memory was a predictor of reading comprehension when age and general ability in the relevant domain were controlled. A first set of stepwise hierarchical multiple regression analyses were conducted with comprehension as the independent variable, in which the different working memory measures were entered at the final step. In each analysis, three variables were entered: age, performance on the relevant Cognitive Abilities Test (Verbal, Numerical or Spatial, depending on which working memory task was entered) and one of the working memory tasks. Thus, five different models were tested – each with a different working memory measure.

In all of these analyses, age and the relevant CAT were highly significant predictors of comprehension skill. However, the results showed that three of the four verbal and numerical working memory tests (but not the spatial test) accounted for variance in comprehension skill over and above that accounted for by age and the relevant CAT score. The Reading span task and the Final Digit task were the strongest predictors of comprehension skill, and the other verbal task (Odd Word Out) was only marginally predictive. The results of these regression analyses are shown in Table 3.

Table 3: *Stepwise Multiple regression Analyses Predicting Reading Comprehension.*

Table 3a: *VWM1 (odd word) Entered in Final Position*

Independent Variable	*R Square*	*R Square Change*	*F Change*	*d.f.*	*Sig. F Change*
1. Age	.306	.306	61.222	1,139	.001
2. CAT-V	.534	.228	67.589	1,138	.001
3. VWM 1	.546	.012	3.684	1,137	.057

Table 3b: VWM2 (reading span) Entered in Final Position

Independent Variable	*R Square*	*R Square Change*	*F Change*	*d.f.*	*Sig. F Change*
1. Age	.327	.327	76.710	1,158	.001
2. CAT-V	.506	.180	57.128	1,157	.001
3. VWM 2	.553	.047	16.371	1,156	.001

Table 3c: *NWM1 (highest number) Entered in Final Position*

Independent Variable	*R Square*	*R Square Change*	*F Change*	*d.f.*	*Sig. F Change*
1. Age	.316	.316	63.342	1,137	.001
2. CAT-N	.397	.081	18.277	1,136	.001
3. NWM 1	.399	.002	.486	1,135	.487

Table 3d: *NWM2 (final digit) Entered in Final Position*

Independent Variable	*R Square*	*R Square Change*	*F Change*	*d.f.*	*Sig. F Change*
1. Age	.320	.320	71.644	1,152	.001
2. CAT-N	.389	.068	16.854	1,151	.001
3. NWM 2	.444	.056	15.007	1,150	.001

Table 3e: *Spatial Working Memory Span Entered in Final Position*

Independent Variable	*R Square*	*R Square Change*	*F Change*	*d.f.*	*Sig. F Change*
1. Age	.332	.332	76.172	1,153	.001
2. CAT-Sp	.421	.089	23.375	1,152	.001
3. SpWM	.422	.001	.250	1,151	.618

Thus far, the results closely parallel those of Seigneuric et al. but also go beyond them in important ways, in that we control for measures of general ability in the relevant domain, whereas they did not. That is, even after performance on the relevant assessment of general ability measure had been entered, both verbal working memory measures, and the numerical final digit measure accounted for significant variance in comprehension skill. It is particularly impressive that the tests of verbal working memory accounted for variance in comprehension skill over and above the contribution of general verbal ability, since that variable alone accounted for around 20% of unique variance in comprehension skill.

Since the reading scores were highly correlated in this sample (r = .71) and each of the working memory tasks was correlated with accuracy in the sample overall (all $rs \geq .36$) it is important to establish whether working memory is a predictor of comprehension skill specifically, or reading more generally. In order to do this, we conducted a parallel set of regression analyses to those above, with reading accuracy as the dependent variable. After controlling for chronological age and the relevant measure of general ability, only one of the working memory measures predicted significant variance in word reading. That was the final digit task, which accounted for 1.6% of variance in accuracy (compared with 5.6% in comprehension). Because at least one of the working memory tasks was related to reading accuracy, over and above the effects of age and the general ability measure, we re-ran the regression analyses in which comprehension was the dependent variable, but controlled for reading accuracy as well as chronological age and the relevant general ability measure. Despite this very strong test of the predictive power of the measures of working memory, the verbal (Reading span) and numerical (Final Digit) working memory measures continued to predict variance in comprehension skill.

This first set of analyses enables us to provide a clear answer to the first question, which is whether working memory predicts comprehension skill in children over and above measures of general ability. The answer is that three of the four verbal and numerical working memory measures account for significant (or marginally significant) variance in comprehension skill, over and above the effects of age and a relevant general ability measure. It replicates and extends Seigneuric et al.'s (2000) finding that spatial working memory was not related to comprehension skill.

The second question concerns the nature of the working memory resources involved in reading comprehension. We wanted to determine whether the working memory system that is related to reading comprehension in children is a general system, or a symbolic system specialised for language processes. The results of the previous analyses provide some indications. As we saw above, only the verbal working memory tasks and one of the numerical tasks were significantly related to comprehension skill in both age groups once age and general ability had been partialled out, whereas the spatial working memory task was not related to comprehension skill over and above age and general ability. Thus, these analyses seem to support the "symbolic resource model" that we describe in the Introduction. In order to test this hypothesis more directly, we need to assess whether the verbal and numerical tasks draw on the same pool of symbolic resources to predict reading comprehension. Therefore we carried out a further set of analyses.

In these analyses, performance on the stronger verbal working memory task (Reading span) and the stronger numerical working memory task (Final Digit) was compared. The variables were again entered in a fixed order, and the order of entry of the verbal and the numerical working memory measures was reversed in order to assess the shared and the unique variance explained by each measure. Support for the symbolic system hypothesis would come from results showing the contribution of a verbal or numerical task to be substantially reduced when the effect of the other (numerical or verbal) task was previously entered into the regression equation. In these analyses, the spatial task was not considered further since it did not account for significant variance in reading comprehension, over and above age and a general measure of spatial ability. Because of the wide age range, and the general improvement with age on the working memory tasks, age was entered first in the regression analyses. It was not obvious which of the general ability measures (verbal or numerical) to enter in these analyses, but in fact the results showed an identical pattern whichever was used. The results including the Verbal CAT data are presented.

The results of these regression analyses are shown in Table 4. These analyses indicate that the verbal and numerical measures contributed independently to variance in comprehension skill, even after controlling for domain-relevant ability. We note here that this result is contrary to that obtained by Seigneuric et al., who found that neither of their numerical tasks explained variance over and above that contributed by one of the verbal measures. However, our data are probably more reliable since the sample was much larger (in these particular analyses 153 participants were entered as opposed to only 48 in Seigneuric et al.'s study). Despite the apparent difference in conclusion, however, we found that whichever working memory assessment was entered last contributed a very small percentage of additional variance (between 1.5 and 1.7%, see Table 4) though, of course, the preceding variables had already taken up about 55% of the variance. Thus, although the contribution of whichever task is entered at the final step is significant, there is also a very substantial amount of shared variance between the verbal and numerical working memory tasks.

Table 4: *Fixed Order Regressions with the Verbal (Reading Span) and a Numerical (Final digit) Working Memory Measure as Predictors; Reading Comprehension as the Dependent Variable*

Independent Variable	*R Square*	*R Square Change*	*F Change*	*d.f.*	*Sig. F Change*
1. Age	.321	.321	72.355	1,153	.001
2. CAT-V	.505	.184	56.505	1,152	.001
3. VWM 2	.550	.045	15.148	1,151	.001
4. NWM 2	.565	.015	5.109	1,150	.025
3. NWM 2	.548	.043	14.309	1,151	.001
4. VWM 2	.565	.017	5.896	1,150	.016

A subsidiary question, which we addressed in a further analysis, was the way in which the level of verbal complexity of a working memory task contributes to the relation between that task and reading comprehension. Reading span requires not only switching between storage and processing, verbal encoding of information and phonological storage, but also requires the syntactic and semantic processing of sentences and the processing of word meanings. The odd-word-out task was designed to tap the same processes, except that it did not require sentence processing. Thus, if it is the shared verbal component of the tasks that is important in predicting comprehension, then we might expect that the reading span task would not predict additional variance over and above that predicted by the odd-word-out task. However, if the sentence-level processing is an important additional aspect of the predictive power of the reading span task, over and above the more general verbal component, then we might expect that it would account for additional variance even after performance on the odd-word-out task is controlled for. In the analyses in which we compared the predictive power of the two verbal tasks, we found the latter pattern of results (see Table 5). As can be seen, the reading span task accounted for an additional, highly significant, 3% of variance even when entered last, whereas the word span task, when entered last, did not account for significant additional variance

Table 5: *Fixed Order Regression Analyses to Compare the Predictive Power of the Two Verbal Working Memory Tests (Reading Span and Odd Word Out)*

Independent Variable	*R Square*	*R Square Change*	*F Change*	*d.f.*	*Sig. F Change*
1. Age	.312	.312	58.592	1,129	.001
2. CAT-V	.535	.223	61.372	1,128	.001
3. VWM 1	.552	.017	4.740	1,127	.031
4. VWM 2	.580	.028	8.420	1,126	.004
3. VWM 2	.579	.044	14.309	1,127	.001
4. VWM 1	.580	.001	5.896	1,126	.608

Overall, these results provide support for the idea that working memory capacity is a strong predictor of reading comprehension in children. Both verbal and numerical (but not spatial) working memory tasks contributed substantially to the prediction of reading comprehension even when age and relevant general ability had been taken into account, but there was some indication that they are making independent contributions to this prediction. The results also provide some support for the idea of a symbolic capacity model since the verbal and numerical tasks were far more strongly related to comprehension skill than was performance on the spatial task.

Discussion

For the purposes of this study, we produced working memory tests for children across a wide age range. The tests were calibrated in such a way that they produced similar means and standard deviations from 6 through to 11-year olds. The new tests we have developed (the odd-word out task, the largest number task and the spatial task) and the comparison of these with tests of working memory we have used previously (the reading span and final-number tests) provide useful comparative data, and also provide new evidence on the relation of working memory to children’s reading skills: both comprehension and reading accuracy.

An important theoretical aspect of this study is that we have explored the predictive power of the various measures of working memory (verbal, numerical and spatial) once performance on the relevant general ability has been controlled. We found that, even after discounting age and relevant general ability, two of the tests (the reading span and final digit tasks) strongly predicted, and one (the odd-word-out task) marginally predicted, performance on the comprehension assessment. Of course, although we refer to two of the tests as “numerical tests”, they do require verbal storage (it is only the processing component that is numerical), so it is not surprising they are related to verbal tests. Indeed, the numerical tasks were significantly correlated with the verbal tasks, and more highly than they were with the spatial tasks. The spatial working memory test was moderately correlated with both accuracy and comprehension overall, but not predictive of comprehension once age and spatial ability had been partialled out.

These findings are consistent with those of Leather and Henry, who found a reading span task to be a significant predictor of comprehension in 7-year-olds, while Yuill et al. (1989)

found a high correlation between comprehension skill in 7- to 8-year-olds and the same digit working memory test that we used in the present study. Our results suggest that, overall, the verbal tasks are better predictors than numerical ones, but that the difference is not striking. Indeed, there was little difference in the predictive power of the two stronger numerical and verbal working memory tests: both accounted for about 5% of unique variance in comprehension skill, over and above the contributions of age and the relevant measure of ability in that domain. This pattern of findings suggests that verbal tasks, even ones that require sentence comprehension, are not particularly privileged in their relation to reading comprehension. Importantly, it argues against the idea that reading span measures relate to comprehension skill only because they have a comprehension component (see also, Lépine, et al, 2005).

These conclusions are consistent with the suggestion from previous (adult) studies (e.g. Daneman & Tardif, 1987) that the working memory system that is implicated in language comprehension is a system specialized for the processing of symbolic (particularly verbal) information, and that spatial working memory does not have a role in text processing.

In the present study, we were able to compare the relative predictive power of two verbal working memory tests, which we designed to have different characteristics, crucially their level of verbal complexity. The reading span task requires not only switching between storage and processing, the verbal encoding of information and phonological short-term storage, but also the syntactic and semantic processing of sentences, including word meanings. The odd-word-out task, in contrast, does not require any sentence processing (though it does require knowledge of word meanings and categories since the child has to select and remember the word in each set that comes from a different semantic category). Thus, if the sentence-level processing is an important additional aspect of the predictive power of the reading span task, then we might expect that it would account for additional variance even after performance on the other verbal task (the odd-word-out task) was controlled for, and this is what we found. However, as we have argued above, any explanation of the role of WM in comprehension that focuses entirely on the comprehension requirement of the reading span task does not hold up, given that the final digit task was as strong a predictor of reading comprehension. Furthermore, a comparison of the two numerical tests showed that the final digit test was a considerably stronger predictor than the highest number task, even though the final digit task had a low processing requirement (reading out digits) and did not make demands on sentence comprehension processes. Thus, our more general prediction about the relation between working memory and reading comprehension being dependent on the level of processing difficulty was not supported by the data (see also Lépine et al., 2005).

The ability of one of the verbal and one of the numerical working memory tests to predict comprehension skill remained strong after tests of general ability had been partialed out. This method of analysis represents a very conservative test of the hypothesised relation between working memory and comprehension, since ability in a particular modality will inevitably influence children's performance on working memory tests in that modality. As we noted previously, tests of general ability, including the CAT, can in turn be expected to tap working memory capacity to a limited degree.

Importantly, the pattern of relations reported above was specific to comprehension and did not apply to reading accuracy. Although working memory in each of the different tasks was correlated with reading accuracy, both overall and in each age group separately, most of the predictive power was lost when age and the relevant ability score were first entered into the regression equation. Only one of the working memory tasks (the final digit task) predicted a very small proportion of variance in word reading accuracy over and above age and the relevant CAT. Our finding that performance on particular working memory tasks was related specifically to reading comprehension, and not word reading accuracy, is consistent with some previous results (e.g. Swanson & Jerman, 2007; Oakhill, Cain & Bryant, 2003; Yuill et al., 1989). Swanson and colleagues have demonstrated that reading comprehension and growth in reading comprehension are best predicted by executive function tasks (i.e. working memory tasks), rather than short-term memory tasks involving phonological coding, which are more likely to be related to word recognition skills.

Although spatial working memory and reading comprehension were correlated, spatial working memory was not predictive of reading comprehension once age and spatial ability had been partialled out. Consistent with the results of Nation et al., (1999) and Seigneuric et al. (2000), there is no evidence, even within this wide age group, that the spatial working memory system plays a role in comprehension processes, and neither is it related more strongly to comprehension skill in younger than in older children, as we hypothesized it might be. Although we used the same visuo-spatial task as Seigneuric et al., this was different to the task used by Nation et al., thus demonstrating that the pattern of results in children generalizes over more than one task. We have suggested that the different predictive power of the spatial vs. the numerical and verbal working memory tests might be explained in terms of the verbal and numerical tests requiring processing of symbolic information (letters and numbers). However, an alternative explanation of the difference, which might be considered in further work, is that the verbal and numerical tasks, unlike the spatial task, depend on retrieval of information from long-term memory (which is, of course, also a characteristic of skilled reading comprehension. We also suggested, following Kennedy and Murray, that spatial working memory skills might be specifically related to the skill of place keeping in comprehension. However, it could be that the comprehension assessment is not sufficiently demanding of these skills. In any case, the time course of typical uses of place holding skills in reading is perhaps beyond the bounds of what is traditionally thought of as working memory processes. Thus, such skills might be more closely linked to spatial ability, rather than working memory *per se,* which is consistent with our finding that general spatial ability was a better predictor of reading comprehension in our sample than was the measure of spatial working memory.

As outlined in the Introduction, working memory skills are likely to be important in reading (and listening) comprehension (in both children and adults). The processes of integration and inference are important to the construction of an integrated and coherent model of a text (i.e. a *Mental Model* or a *Situation Model:* Gernsbacher, 1990; Johnson-Laird, 1983; Kintsch, 1998), and these processes require that the relevant information, either from the text or world knowledge, is both available and accessible. Working memory is proposed to serve as a buffer for the most recently read propositions in a text, enabling their integration to establish coherence, and for information retrieved from long-term memory to enable its integration with the currently active text (see e.g. Cooke, et al., 1998; Graesser, et al., 1994).

This study, along with several previous studies, demonstrates a strong relation between memory and children's reading comprehension. The majority of this work suggests that the relation between memory and reading comprehension is specific to working memory tasks that require the simultaneous storage and processing of symbolic information (both verbal and numerical), rather than memory tasks that simply assess the passive storage of such information (e.g. Leather & Henry, 1994; Oakhill et al., 1986; Swanson & Berninger, 1995; Yuill et al., 1989). Furthermore, and consistent with the present findings, the working memory resources that are related to reading comprehension appear to be specialised for language processing: tasks that require the manipulation of shapes and patterns do not explain variance in reading comprehension skill (Nation et al., 1999; Seigneuric et al., 2000).

This work does not establish directly whether it is the controlled attention aspect of working memory, or the storage function (or STM) that is important in reading comprehension. Both STM and working memory deficits have been shown to make contributions to reading problems (e.g. de Jong, 1998; Swanson & Ashbaker, 2000). However, STM tasks do not discriminate between good and poor comprehenders who are matched for word recognition (e.g. Yuill & Oakhill, 1991), and Swanson & Jerman (2007) found that it was working memory and not STM that predicted growth in reading comprehension. Of course, working memory tasks have an STM requirement, but there must be something over and above this storage component that is important to comprehension skill and its development.

In addition, although working memory capacity assessed by symbolic processing tasks explains individual differences in children's text comprehension over and above other well established predictors of reading comprehension, such as word recognition skill and vocabulary knowledge (e.g., Swanson & Berninger, 1995; Yuill et al., 1989), some researchers have suggested that the reported relation between children's working memory and text comprehension is the result of underlying levels of verbal and semantic skills. For example, Nation et al. (1999) argue that poor comprehenders have a specific semantic weakness that restricts their ability to store verbal information in short-term memory and that this weakness, in turn, impairs their performance on verbally mediated working memory tasks. A similar position was adopted by Stothard and Hulme (1992), who proposed that working memory differences between good and poor comprehenders would disappear if differences in verbal IQ were controlled. The present results argue against this position, since at least two of the working memory tasks were strongly predictive of comprehension skill over and above the contribution of general verbal (or numerical) ability, and demonstrate that working memory tasks that require symbolic processing are important predictors of comprehension skill in young children, over and above the cognitive skills that contribute to the tasks.

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