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Working memory in children with reading disabilities

Susan Elizabeth Gathercole [a,*], Tracy Packiam Alloway [a], Catherine Willis [b], Anne-Marie Adams [b]

[a] *Department of Psychology, University of Durham, Science Laboratories, Durham DH1 3LE, UK*
[b] *School of Psychology, Liverpool John Moores University, Liverpool L3 8PY, UK*

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Abstract

This study investigated associations between working memory (measured by complex memory tasks) and both reading and mathematics abilities, as well as the possible mediating factors of fluid intelligence, verbal abilities, short-term memory (STM), and phonological awareness, in a sample of 46 6- to 11-year-olds with reading disabilities. As a whole, the sample was characterized by deficits in complex memory and visuospatial STM and by low IQ scores; language, phonological STM, and phonological awareness abilities fell in the low average range. Severity of reading difficulties within the sample was significantly associated with complex memory, language, and phonological awareness abilities, whereas poor mathematics abilities were linked with complex memory, phonological STM, and phonological awareness scores. These findings suggest that working memory skills indexed by complex memory tasks represent an important constraint on the acquisition of skill and knowledge in reading and mathematics. Possible mechanisms for the contribution of working memory to learning, and the implications for educational practice, are considered.

Keywords: Reading disabilities; Working memory; Short-term memory; IQ; Mathematics

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[*] Corresponding author. Fax: +44 191 334 3241.
E-mail address: s.e.gathercole@durham.ac.uk (S.E. Gathercole).

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Introduction

The purpose of this study was to investigate the extent to which impairments of working memory contribute to the severity of the learning difficulties experienced by children with reading disabilities. Although close links between memory function and many aspects of learning and academic achievement in unselected samples of children are well established, the degree to which working memory function constrains learning progress in children with learning disabilities is less well understood. The study focused in particular on the extent to which impairments of working memory contribute to the problems in both reading and mathematics commonly experienced by children with learning disabilities and on whether any associations that are found could be mediated by other aspects of cognitive function.

Immediate memory involves several related subsystems of memory. The capacity to store material over short periods of time in situations that do not impose other competing cognitive demands is typically referred to as short-term memory (STM). Findings from experimental, developmental, and neuropsychological studies indicate that STM is fractionated into at least two domain-specific components that are specialized for the retention of phonological and visuospatial material (for reviews, see Gathercole, 1999; Vallar & Papagno, 2002). In the influential working memory model of Baddeley and Hitch (1974), developed subsequently by Baddeley (1986, 2000), these components correspond to different slave systems. The phonological loop retains material in a phonological code that is highly susceptible to time-based decay, and the visuospatial sketchpad has limited capacities to represent information in terms of its visual and spatial characteristics. The phonological loop is assessed using methods such as the recall of digit or word sequences, and visuospatial sketchpad functioning is typically measured by tasks involving the recall or recognition of visual patterns or sequences of movement.

Working memory is related to, but distinguishable from, STM. The term is widely used to refer to the capacity to store information while engaging in other cognitively demanding activities, and it is most commonly assessed using complex memory paradigms that impose demands for both temporary storage and significant processing activity with selected task components varied across domains. An example of a complex memory task is listening span, where participants are asked to make a meaning-based judgment about each of a series of spoken sentences and then to remember the last word of each sentence in sequence (e.g., Daneman & Carpenter, 1980). Another task is counting span, where participants are asked to count target items in successive arrays and then to recall in sequence the tallies of the arrays (Case, Kurland, & Goldberg, 1982). Despite disparate processing demands, scores on the two tasks are highly correlated (e.g., Gathercole, Pickering, Ambridge, & Wearing, 2004) and are also linked with performance on memory updating tasks that are believed to tap working memory (Jarvis & Gathercole, in press; Miyake et al., 2000).

Most theoretical accounts of immediate memory incorporate a distinction between the storage-only capacities of STM and the broader and more flexible nature of working memory. In addition to the domain-specific storage systems of the phonological loop and the visuospatial sketchpad, the Baddeley and Hitch (1974) model includes the central executive, responsible for a range of functions such as retrieval of information from long-term memory, regulation of information within working memory, attentional control of both encoding and retrieval strategies, and task shifting (Baddeley, 1986, 1996). Proponents of the working memory model have suggested that the storage demands of complex memory tasks depend on appropriate subsystems, with processing demands supported principally by the central executive (Baddeley & Logie, 1999; Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002). Thus, complex memory span, such as listening span and counting span, appears to tap both the central executive and the phonological loop (Lobley, Gathercole, & Baddeley, in press), whereas analogous visuospatial complex memory tasks (Jarvis & Gathercole, 2003; Shah & Miyake, 1996) may draw on the resources of the central executive and the visuospatial sketchpad. There is a substantial domain-general component to such working memory tasks (e.g., Bayliss, Jarrold, Gunn, & Baddeley, 2003; Kane et al., 2004; Swanson & Sachse-Lee, 2001) that has been interpreted as reflecting central executive function.

Another influential conceptualization of working memory is of a limited resource that can be flexibly allocated to support either processing or storage (e.g., Daneman & Carpenter, 1980; Just & Carpenter, 1992). According to one model in this theoretical tradition, developmental increases in complex memory performance reflect improvements in processing speed and efficiency that release additional resources to support storage (Case et al., 1982). Other theorists have proposed that working memory consists of activated long-term memory representations and that STM is the subset of working memory that falls within the focus of attention (Cowan, 2001; Engle, Kane, & Tuholski, 1999).

Because the current research is not concerned specifically with distinctions between models, the theoretically neutral terms phonological and visuospatial STM are used to refer to storage-only assessments of the respective informational domains, and complex memory tasks are interpreted as tapping working memory. The primary focus is on the extent to which complex memory performance is associated with the scholastic abilities of reading disabilities, characterized by marked difficulties in mastering skills such as word recognition, spelling, and reading comprehension. Links between complex memory scores and reading ability are well established, with scores predicting reading achievement independently of measures of phonological STM (e.g., Swanson, 2003; Swanson & Howell, 2001). Current evidence suggests that although phonological STM is significantly associated with reading achievement over the early years of reading instruction, its role is as part of a general phonological awareness construct related to reading development rather than representing a causal factor per se (Wagner & Muse, in press; Wagner et al., 1997). It is also well established that children with reading disabilities show significant and marked decrements on working memory tasks relative to typically developing individuals (Siegel & Ryan, 1989; Swanson, 1994, 1999; Swanson, Ashbaker, & Lee, 1996).

Mathematical difficulties commonly accompany reading disabilities (Swanson & Saez, 2003) and are also characterized by deficits in working memory. Associations between complex memory performance and mathematical abilities vary across age and level of expertise, probably due to the changes in procedures and strategies that characterize mathematical development. For example, addition commences with simple counting strategies, success at which contributes to the gradual acquisition of arithmetic facts. More complex addition computations require memory-based problem solving involving either direct retrieval of facts or problem decomposition, leading to eventual automatic retrieval of facts (Geary, 2004). Working memory appears to play an important role at the earliest stage of counting; children with low scores on complex memory tasks are more likely to use primitive finger-based counting strategies than are those with high scores, possibly due to the relatively low working memory demands of the activities (Geary, Hoard, Byrd-Craven, & DeSoto, 2004). In addition, low complex memory scores have been found to be strongly and specifically associated with both poor computational skills (Wilson & Swanson, 2001) and difficulties in solving mathematical problems expressed in everyday language (Swanson & Sachse-Lee, 2001).

A key issue is how deficits of working memory impair reading and mathematical abilities. One explanation is that poor working memory capacities compromise the crucial process, for both mathematics and reading, of maintaining recently retrieved knowledge and integrating this with recent inputs (Swanson & Beebe-Frankenberger, 2004). A related suggestion is that learning activities in which children must engage in literacy and mathematics classes often impose heavy demands on working memory, resulting in frequent task failures in children with poor working memory function. As a result, the normal incremental process of acquiring knowledge and skills in these domains is impaired (Gathercole, 2004). In a more specific account of the association between working memory and mathematical abilities, Geary and colleagues (2004) proposed that poor working memory capacity impairs the process of acquiring mathematical facts that arises from successful counting strategies.

The participants in the current study were children who were identified by their schools as having reading difficulties of sufficient severity to warrant remedial support and who scored at least 1 standard deviation below the mean on a standardized measure of reading ability administered as part of this study that included subtests of word recognition, spelling, and reading comprehension (Wechsler, 1993). These selection criteria were less restrictive than those in the majority of studies in this field, which typically exclude children with low performance IQ or low scores on other measures of nonverbal ability measures. Although working memory deficits in children with learning difficulties have been found to persist even after measures of performance IQ have been taken into account (Swanson & Sachse-Lee, 2001), the inclusion in such studies of only children with scores in the normal range limits sensitivity to this potentially confounding factor. Selecting children purely on the basis of their reading disabilities, as we did in the current study, provides a much stronger test of this hypothesis.

Three further factors that could potentially mediate the link between complex memory performance and scholastic attainments were also investigated. It has been argued that the key factor underlying individual differences on working memory tests is general verbal ability (Nation, Adams, Bowyer-Crane, & Snowling, 1999; Stothard & Hulme, 1992). There is already some evidence that, in fact, complex memory performance is dissociable from verbal ability more generally (Cain, Oakhill, & Bryant, 2004; Siegel, 1988). However, it was considered important to test whether the two factors could be distinguished in the current sample of children with learning disabilities. If complex memory performance taps general verbal abilities, potential associations between complex memory and abilities in mathematics and literacy should be eliminated when variation in language and verbal IQ scores is taken into account.

Another factor that could contribute to the association between working memory and learning achievements is phonological STM. Scores on standard measures of STM, such as digit span and complex memory measures, are moderately associated with one another (e.g., Gathercole & Pickering, 2000; Gathercole, Pickering, Knight, & Stegmann, 2004), possibly due to the role played by phonological STM in supporting the storage component of the complex memory measures (Baddeley & Logie, 1999; Lobley et al., in press). The extent to which STM and complex span measures are independently associated with learning achievements in this sample would establish whether possible associations are mediated by the contribution of STM abilities rather than working memory more generally.

The final mediating factor investigated in this study was phonological awareness. Phonological awareness skills, as tapped by tasks requiring the manipulation of phonological structure, are highly associated with both reading ability (e.g., Bradley & Bryant, 1985; Brady & Shankweiler, 1991; Catts, Gillispie, Leonard, Kail, & Miller, 2002; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987; Wolf & Bowers, 1999) and mathematical skills (e.g., Geary, Hoard, & Hamson, 1999; Rourke & Conway, 1997). It has been argued that both phonological awareness and STM measures reflect a common phonological processing substrate (Bowey, 1996; Metsala, 1999). On the basis of the significant verbal storage component of working memory tasks, this account could also be extended to encompass verbal working memory. To test whether possible associations between working memory and learning abilities are mediated by phonological processing skills more generally, standardized assessments of phonological awareness abilities (Frederickson, Frith, & Reason, 1997) were also included in the current study.

Finally, it was predicted in this study that working memory places general constraints, rather than specific constraints, on reading and mathematics abilities, so that associations between complex memory measures and reading should be abolished when differences in mathematical abilities are taken into account and vice versa. This prediction was made on the basis of our recent findings that children classified by their schools as having problems in both reading and mathematics had depressed performance on complex memory tasks, whereas individuals with difficulties restricted to reading did not (Pickering & Gathercole, 2004). Impairments of working memory deficits, therefore, appear to be associated with learning disabilities that extend beyond reading.

Method

Participants

Data are reported for 46 children (13 girls and 33 boys) with a mean age of 9 years 0 months (range = 6 years 6 months to 11 years 0 months, $SD = 12$ months) taken from a larger study of children identified by their schools as having special educational needs that require additional educational support. All children were attending state schools in the Durham area of North East England. None of the children had emotional or behavioral difficulties, and each child obtained a composite standard score of less than 86 on the Wechsler Objective Reading Dimension (WORD) (Wechsler, 1993). This score is derived from three subtests: reading (of letters and single words), spelling (of letters and single words), and reading comprehension (involving passage reading followed by orally presented questions). Test–retest reliability coefficients for 6- to 11-year-olds range from .94 to .96 for reading, from .90 to .96 for spelling, and from .90 to .94 for reading comprehension in the WORD.

All children were also tested on a measure of mathematical skills, the Wechsler Objective Numerical Dimensions (WOND) (Wechsler, 1996b). This measure consists of two subtests: mathematical reasoning and numerical operations. The mathematical reasoning subtest is designed to tap the ability to reason mathematically and incorporates a wide range of materials requiring skills such as identifying shapes, telling time, solving mathematical problems expressed in language, and interpreting graphs and charts. The numerical operations subtest measures abilities to solve computational problems involving mathematical operations such

Table 1
Descriptive statistics for literacy and mathematics measures (standard scores)

Measure	*M*	*SD*	Minimum	Maximum
Reading				
Reading	78.91	6.51	63	90
Spelling	82.07	7.51	64	93
Reading comprehension	80.83	9.98	58	99
Composite score	76.46	8.44	55	85
Mathematics				
Mathematical reasoning	89.59	10.27	62	111
Number operations	84.02	12.43	60	111
Composite score	84.39	12.13	58	108

as addition, subtraction, multiplication, division, and algebra. Test–retest reliability coefficients for 6- to 11-year-olds range from .85 to .92 for mathematical reasoning, from .82 to .91 for numerical operations, and from .90 to .95 for the composite score in the WOND.

Descriptive statistics for the reading and mathematics measures are shown in Table 1. Scores on the WORD were low across all three subtests (reading, spelling, and reading comprehension), with a sample mean composite score of 76.46. Scores on the WOND were higher overall (mean composite score = 84.39), with lower performance on the numerical operations subtest than on the mathematical reasoning subtest.

Procedure

Each child was tested individually in a quiet area of the school for six sessions lasting up to 30 min per session across 6 weeks. A member of the research team administered the following tests in a fixed sequence designed to vary task demands across the testing session.

Ability tests

All participants were administered the Wechsler Objective Language Dimensions (WOLD) (Wechsler, 1996a). This test battery assesses receptive and expressive aspects of oral language function in two subtests: listening comprehension and oral expression. The listening comprehension subtest taps understanding of orally presented words and passages, with performance measured either by picture pointing or oral responses. The oral expression subtest assesses abilities to express a target word that has been defined and to orally describe scenes, give directions, and explain steps. Test–retest reliability coefficients for 6- to 11-year-olds range from .83 to .88 for listening comprehension, from .90 to .92 for oral expression, and from .91 to .93 for the composite test score in the WOLD. Participants also completed the Wechsler Intelligence Scale for Children–Third Edition U.K. (WISC-III^{UK}) (Wechsler, 1992), yielding measures of verbal IQ and performance IQ. Test–retest reliability coefficients range from .92 to .96 for verbal IQ and from .90 to .91 for performance IQ in the WISC-III^{UK}.

Memory tests

Three complex memory measures from the Working Memory Test Battery for Children (WMTB-C) (Pickering & Gathercole, 2001) were administered: backward digit recall, counting recall, and listening recall. In backward digit recall, the child is asked to recall a sequence of spoken digits in the reverse order. The number of digits in each list increases across trials, and the number of lists correctly recalled is scored. Up to six trials are presented at each list length, with list length increasing when children respond correctly on four trials at a particular length, testing is discontinued when three errors are made at the same length. In counting recall, the child is asked to count the number of dots in an array and then to recall the tallies of dots in the arrays in the sequence in which they were presented. The number of dots in the array increases across trials, and the number of correct trials completed by the child is scored. In listening recall, the child listens to a series of short sentences, determines the veracity of the statements by responding "true" or "false," and then attempts to recall the final word of each sentence in sequence. The number of sentences in each block increases across trials, and the number of correct trials is scored. Split-half reliability for the current sample was .83 for backward digit recall, .71 for counting recall, and .73 for listening recall.[1]

Three measures of phonological STM from the WMTB-C (Pickering & Gathercole, 2001) were administered. Digit recall and word list recall both involve spoken recall of sequences of spoken items (either single digits or high-frequency monosyllabic words). In each case, the number of items in each sequences increases across trials, and the number of correct trials is scored. Word list matching involves the child detecting whether words in a second list are in the same order as in the first word list. The number of lists increases in each block, and the number of correct trials is scored. Split-half reliability for this sample was .87 for digit recall, .79 for word list recall, and .85 for word list matching.

Two measures of the visuospatial component were administered. In the block recall test of the WMTB-C (Pickering & Gathercole, 2001), the child views nine cubes randomly located on a board. The test administrator taps a sequence of blocks, and the child is asked to tap that sequence in the correct order. The number of correct trials is recorded. Test–retest reliability coefficients are .63 for 5- to 8-year-olds and .43 for 9.5- to 11.5-year-olds in the block recall test of the WMTB-C. Split-half reliability for this sample on this measure was .71. In the Visual Patterns Test (Della Sala, Gray, Baddeley, & Wilson, 1997), the child views a two-dimensional grid of black and white squares. After viewing the grid for 3 s, the child is asked to mark the black squares on an empty grid. The number of correctly marked grids is scored. This test is standardized for use with children as part of the WMTB-C. No estimates of reliability are available for this measure.

Phonological awareness tests

Three measures from the Phonological Assessment Battery (Frederickson et al., 1997) were administered. The rhyme task assesses the child's ability to identify rhyming words in sequences of three monosyllabic words such as *sand, hand, cup* and *bead, wheat, seat.* In the spoonerism task, the child is required to segment single-syllable words and then exchange initial phonemes to produce new word combinations, for example, by combining *cot* with a

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[1] Split-half reliability was estimated for all six of the WMTB-C measures by computing two subscores on each measure for each child. Subscore A was the number of Trials 1 and 4 that were correct at each length prior to that at which testing was discontinued, plus an extra point if Trial 1 was correct at the final length. Subscore B was the number of Trials 2 and 3 that were correct at each length prior to that at which testing was discontinued, plus an extra point if Trial 2 was correct at the final length.

/g/ to give *got* and by transforming *riding boot* to *biding root*. The alliteration task assesses the child's ability to identify which two of three monosyllabic words share the same initial phoneme, as in *bike, name, nose* and *cross, twig, truck.* Performance on all tasks was scored as the number of correct trials. Test–retest reliability coefficients for 6- to 8-year-olds are .92, .95, and .90 for the rhyme, spoonerism, and alliteration tasks, respectively. Test–retest reliability coefficients for 9- to 11-year-olds are .91, .93, and .84 for the rhyme, spoonerism, and alliteration tasks, respectively.

Results

Table 2 provides descriptive statistics for the principal measures. Consider first the memory assessments. Very low performance was found on both complex memory and visuospatial STM measures. Phonological STM scores, in contrast, fell within the low average range. Performance levels were generally consistent across the various subtests associated with each area of memory function. Phonological awareness performance was at a low average level overall, although it should be noted that performance on the alliteration subtest was lower than that on the rhyme and spoonerism subtests. Language ability also fell in the low average range for both the oral expression and language comprehension subtests. Both verbal and performance IQ scores were at a low level across the group as a whole.

To investigate the extent to which different children performed at low or average levels on these measures, the proportion of children obtaining standard scores below a series of cutoff scores for each measure was calculated, as shown in Table 3. The majority of children scored in the lowest band on the complex memory and visuospatial STM measures (61 and 70%, respectively), with very small proportions performing in the 85+ range that can be classified as average (9 and 4%, respectively). Roughly half of the sample also obtained performance IQ scores below 86. Comparably low scores were less common in the remaining measures of phonological STM, phonological awareness, language, and verbal IQ.

Subsequent analyses focused on interrelations between the cognitive measures and achievements in reading and mathematics. For the purpose of these analyses, mean *z* scores were computed from the multiple measures of each construct. Correlation coefficients between these composite scores were computed and are shown in Table 4. Complex memory performance was significantly associated with all of the other measures and was the strongest predictor of both reading and mathematics scores. Although visuospatial STM scores were generally very low within this sample, they did not correlate significantly with either reading or mathematics scores. Phonological STM scores were significantly correlated only with complex memory and mathematics scores. In the regression analysis, language and verbal IQ scores were highly associated with one another, and both were significantly correlated with reading and mathematics scores. Performance IQ was highly correlated with all measures except phonological STM. Phonological awareness scores were strongly associated with complex memory scores as well as with both IQ measures and both reading and mathematics scores.

Given the high degree of intercorrelation among these measures, it was important to establish which factors independently predicted scores on the reading and mathematics measures. Accordingly, a series of multiple regression analyses on the data were performed with either reading or mathematics scores as the dependent variable. Because of the relatively small size of

Table 2
Descriptive statistics for principal measures (standard scores except where stated otherwise)

Measure	*M*	*SD*
Phonological STM		
Digit recall	90.35	16.48
Word recall	89.09	11.32
Word list matching	91.11	17.11
Mean score	90.18	11.08
Complex memory		
Backward digit recall	79.48	10.18
Counting recall	73.72	13.84
Listening recall	79.98	13.53
Mean score	77.72	8.96
Visuospatial STM		
Block recall	71.65	13.73
Visual patterns	78.61	10.73
Mean score	75.13	9.56
Phonological awareness		
Rhyme	87.26	11.75
Spoonerisms	92.85	10.57
Alliteration	82.83	14.85
Mean score	88.78	8.40
Language		
Oral expression	93.30	8.10
Language comprehension	88.91	10.65
Composite score	87.78	10.69
Verbal IQ		
Information[a]	7.54	2.15
Similarity[a]	8.04	3.08
Mathematics[a]	6.28	2.67
Vocabulary[a]	7.37	2.40
Comprehension[a]	7.26	3.32
IQ score	83.39	11.86
Performance IQ		
Picture completion[a]	8.24	3.63
Coding[a]	7.13	3.02
Picture arrangement[a]	7.74	2.69
Block design[a]	6.45	3.10
Object assembly[a]	7.78	3.33
IQ score	82.35	13.84

[a] Scaled score ($M = 10$, $SD = 3$).

the sample and the large potential number of predictor variables, it was necessary to limit the number of variables entered into each regression equation. Accordingly, predictor variables were included only with correlations with the dependent variable at the .05 level, leading to the omission of visuospatial STM from regression equations and the omission of both this measure and phonological STM from the regression analyses of reading scores.

The outcomes of the multiple regression analyses with reading score as the dependent variable are summarized in Table 5. Model 1 included verbal IQ, performance IQ, language,

Table 3
Proportions of children scoring below cutoff scores on each measure

Cutoff score	Complex memory	Phonological STM	Visuospatial STM	Phonological processing	Language	Verbal IQ	Performance IQ
81	0.61	0.22	0.70	0.22	0.33	0.39	0.52
85	0.78	0.35	0.87	0.33	0.46	0.57	0.65
90	0.91	0.48	0.96	0.50	0.59	0.72	0.72
95	0.98	0.70	1.00	0.80	0.78	0.85	0.85

Table 4
Correlations between cognitive skills and achievement measures

	Measure	1	2	3	4	5	6	7	8
1	Phonological STM	—							
2	Complex memory	.320*	—						
3	Visuospatial STM	.174	.443*	—					
4	Phonological awareness	.244	.582*	.243*	—				
5	Language	.049	.324*	.213	.179	—			
6	Verbal IQ	.052	.393*	.141	.336*	.679*	—		
7	Performance IQ	.126	.546*	.411*	.415*	.365*	.556*	—	
8	Reading	.167	.557*	.162	.442*	.478*	.350*	.330*	—
9	Mathematics	.338*	.591*	.254	.496*	.414*	.537*	.427*	.582*

* $p < .05$.

Table 5
Hierarchical regression analysis for the criterion measure of reading scores

Independent variable	*B*	*SE*	*b*	*T*
Model 1				
Verbal IQ	−.092	.130	−.130	−.713
Performance IQ	−.026	.096	−.043	−.273
Language	.334	.129	.423	2.595*
Phonological awareness	.213	.149	.212	1.430
Complex memory	.349	.152	.371	2.295*
$R^2 = .443$, $F(5,40) = 6.375$, $p < .001$				
Model 2				
Mathematics	.230	.110	.330	2.098*
Verbal IQ	−.165	.129	−.232	−1.279
Performance IQ	−.017	.093	−.028	−.185
Language	.316	.124	.401	2.533*
Phonological awareness	.151	.146	.151	1.034
Complex memory	.236	.156	.251	1.518
$R^2 = .499$, $F(6,39) = 6.481$, $p < .001$				

* $p < .05$.

phonological awareness, and complex memory. Two measures were significant predictors of reading scores: language and complex memory, accounting for 9.4 and 7.4% of variance, respectively. A further regression analysis was conducted to test the prediction that common associations would be found between complex memory scores and both reading and mathematics abilities. In this model, the mathematics score was included to determine whether complex memory made a common contribution to reading and mathematics performance;

if so, its unique predictive value should be diminished when mathematics ability was taken into account. In Model 2, the independent predictors of reading ability in this second analysis were mathematics and language scores (accounting for 5.1 and 8.3% of variance, respectively) but not complex memory scores. This outcome is consistent with the hypothesis that working memory makes a common contribution, rather than a distinct contribution, to the development of both reading and mathematical abilities.

Further regression analyses were conducted with mathematics score as the dependent variable (Table 6). The first regression equation, Model 1, included all six cognitive measures that were significantly correlated with mathematics scores: verbal IQ, performance IQ, language, phonological awareness, complex memory, and phonological STM. None of the variables predicted significant independent proportions of variance in this analysis. To test whether complex memory span failed to emerge as a significant predictor of mathematics ability in this analysis because it shared a common phonological processing component with the phonological awareness and STM measures, a higher order phonological processing variable that was a composite of the two latter measures was entered in a second analysis. In this Model 2, both complex span and phonological processing measures were significant predictors of reading scores, accounting for 5.1 and 5.2% of variance, respectively. Thus, complex memory and phonological processing had distinguishable associations with mathematical abilities. Model 3 tested whether the association between complex span and mathematics was mediated by reading scores by adding the reading measure as a sixth variable in the regression equation. The two significant predictors in this

Table 6
Hierarchical regression analysis for the criterion measure of mathematics scores

Independent variable	*B*	*SE*	*b*	*t*
Model 1				
Verbal IQ	.332	.177	.325	1.880
Performance IQ	−.033	.131	−.038	−.251
Language	.078	.175	.069	.445
Phonological awareness	.242	.204	.168	1.185
Complex memory	.412	.213	.305	1.933
Phonological STM	.202	.130	.184	1.549
$R^2 = .512$, $F(6, 39) = 6.824$, $p < .001$				
Model 2				
Verbal IQ	.337	.173	.330	1.952
Performance IQ	−.031	.129	−.035	−.241
Language	.075	.172	.066	.436
Complex memory	.205	.205	.310	2.047*
Phonological STM and awareness	.428	2.98	.273	2.061*
$R^2 = .512$, $F(5, 40) = 8.388$, $p < .001$				
Model 3				
Verbal IQ	.367	.166	.359	2.217*
Performance IQ	−.024	.123	−.027	−.194
Language	−.064	.176	−.056	−.362
Complex memory	.247	.211	.182	1.168
Phonological STM and awareness	.376	.200	.240	1.884
Reading	.437	.200	.304	2.190*
$R^2 = .565$, $F(6, 39) = 8.453$, $p < .001$				

* $p < .05$.

analysis were verbal IQ and reading scores, accounting for 5.4 and 5.3% of variance, respectively. Thus, as in the corresponding regression analysis of the reading scores, the path between complex span and mathematics ability was indeed eliminated when reading scores were taken into account, suggesting a common contribution of working memory to achievements across the two scholastic domains.

Discussion

Working memory skills were significantly related to the severity of learning difficulties in both reading and mathematics in this sample of children with reading disabilities. As a group, the children had low IQ scores and performed poorly on measures of working memory (complex memory tasks) and visuospatial STM. Phonological STM, language, and phonological awareness abilities in this sample were in the low average range. A key finding was that working memory skill independently predicted the children's attainments in reading and to a lesser extent in mathematics and that the contribution of working memory was common to both ability domains (see also Pickering & Gathercole, 2004). Reading ability was also significantly linked with the children's language and phonological awareness abilities. The association between working memory and reading ability in this sample of children with learning disabilities was not mediated by performance IQ, verbal abilities, STM, or phonological awareness skills. Attainments in mathematics were independently related to both complex span and general phonological processing ability.

The specificity of associations between complex memory performance and scholastic attainment in this study is consistent with findings from other developmental samples. These associations have been found to persist after differences in performance IQ have been statistically controlled in samples of children with learning difficulties and normal range intelligence (e.g., Swanson & Sachse-Lee, 2001). Differences in complex memory scores also persist both in children with reading comprehension problems and in children with other learning disabilities after differences in verbal IQ have been eliminated (Cain et al., 2004; Siegel & Ryan, 1989), indicating that complex memory taps more than verbal ability alone. The finding that complex memory and phonological STM scores share dissociable links with learning abilities (e.g., Gathercole & Pickering, 2000; Swanson et al., 2004) also rules out the possibility that complex memory scores simply reflect the contribution of phonological STM abilities. This conclusion is reinforced by the finding that phonological STM performance was not markedly impaired in the current sample of children with reading disabilities and is also consistent with other recent evidence that deficits in phonological STM alone do not lead to substantial learning difficulties (Archibald & Gathercole, 2005a; Gathercole, Tiffany, Briscoe, Thorn, & ALSPAC Team, 2005).

One limitation of the assessment of working memory skill in the current study is the dependence of verbally based assessment methods only. The reason for this is that at the time of data collection, robust methods for measuring nonverbal aspects of working memory in children were not available. As a consequence, it is not possible to make claims about the degree of domain generality of the working memory skills under assessment here. More recently, nonverbal complex memory tasks that are appropriate for use with young children have been developed. In a large unselected sample of 4- to 11-year-olds, we found that performance on these nonverbal tests correlates very highly with verbal complex span tasks (Alloway, Gathercole, & Pickering, 2005). However, research with a sample of children with specific language impairment has established substantial decrements in the verbal complex memory measures but age-appropriate performance on the visuospatial complex memory tasks (Archibald & Gathercole, 2005b). The extent to which the working memory problems of the current sample are restricted to verbal working memory, therefore, must still remain an open issue.

The independence of the working memory association with severity of learning difficulties from phonological awareness skills is also consistent with other findings from studies of children with learning difficulties (e.g., Swanson & Beebe-Frankenberger, 2004). Although the phonological awareness skills of the reading-disabled children participating in the current study were relatively low, the deficits were neither as extreme nor as marked as the working memory deficits. In the light of substantial evidence that children with reading difficulties have poor phonological awareness, it is perhaps surprising that these skills fell within the average range for the majority of children in the sample. This finding may reflect the age range of the group, which included children as old as 11 years. In most typically developing children of this age, phonological awareness skills are complete by this point, so the measures may lack some sensitivity. Also, because phonological awareness is now widely recognized as providing the foundation for literacy acquisition in the field of U.K. education, it is likely that these children will have received specific interventions targeting phonological skills that may have remediated any deficits in this area. The presence of significant unique associations between phonological processing skills and mathematics abilities in this sample is, however, worthy of note, and it is consistent with other evidence that skills in manipulating the phonological structure of language play an important role in both arithmetic computation skills (Hecht, Torgesen, Wagner, & Rashotte, 2001) and mathematical problem solving (Swanson & Sachse-Lee, 2001).

Why does working memory skill predict the severity of impairments in reading and mathematics in this sample? Swanson has argued that working memory provides a resource that allows the learner to integrate information retrieved from long-term memory with current inputs, so that poor working memory capacities will compromise the child's attempts to carry out such important cognitive activities (Swanson & Beebe-Frankenberger, 2004; Swanson & Saez, 2003). A related view that we favor is that impairments of working memory result in pervasive learning difficulties because this system acts as a bottleneck for learning in many of the individual learning episodes required to increment the acquisition of knowledge (Gathercole, 2004). An observational study of 5- and 6-year-olds who performed very poorly on measures of verbal working memory provided support for this view (Gathercole, Lamont, & Alloway, in press). The children were working in the lowest ability groups in both literacy and mathematics within their classrooms, and they were observed to make frequent errors in activities that placed heavy demands on working memory. Particularly high rates of failure were found in following complex instructions (which the children often forgot), performing tasks that imposed significant storage and processing loads, and performing tasks with a complex hierarchical structure (where the children often lost their place and eventually abandoned the tasks prior to completion). Failures in these kinds of activities occurred frequently in both literacy and numeracy classes. On this basis, we have suggested that children with low working memory skills will have difficulties in meeting the routine working memory demands of many structured learning activities that are common in the classroom. This will lead to frequent task failures, which represent missed opportunities to learn and so to achieve normal incremental progress in complex skill domains.

This account of why impairments of working memory result in learning difficulties in both literacy and mathematics has important implications for the provision of effective learning support for such children. It predicts that promoting teacher awareness of working memory loads in classroom activities and effective management of these loads for children with impairments of working memory should boost their learning. Current cognitive theory can be used to identify a number of methods for reducing working memory loads that could readily be applied to classroom practice (Gathercole & Alloway, 2004). For example, task instructions should be short and syntactically simple and should be repeated as required. In activities such as holding a sentence in mind while writing it down, the heavy storage and processing could be reduced by keeping sentences short and redundant and by using a highly familiar vocabulary. External memory aids, such as useful spellings and number lines, should be provided for children's use where possible, and children should be encouraged to practice them under conditions of low working memory load. Tasks with complex structures could be simplified into component parts as a means of reducing the burden of monitoring children's current place within the task. In addition, children might benefit from receiving training in self-help strategies for situations in which working memory fails.

In conclusion, the severity of deficits in the areas of both reading and mathematics in a sample of children with reading disabilities was closely associated with working memory skill. We propose that this association arises because working memory acts as a bottleneck for learning in classroom activities, and we suggest that effective management of working memory loads in structured learning activities may ameliorate the problems of learning that are associated with impairments of working memory.

Uncited references

Alloway, Gathercole, Willis, and Adams (2004), Conway, Kane, and Engle (2003), Engle, Tuholski, Laughlin, and Conway (1999), Fry and Hale (2000), and Raven (1986).

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