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How Common are WM Deficits in Children with Difficulties in Reading and Mathematics?☆

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The extent to which deficits in working memory (WM) are characteristic of children with reading and mathematics difficulties was investigated in a large sample aged 5–15 years reported to have problems in attention, learning and memory. WM performance was highly correlated with reading and mathematics scores. Although deficits in individual tests of short-term memory (STM) and WM occurred in less than half of the children with detected learning difficulties, three-quarters of the children with low reading and mathematics scores obtained one or more WM scores in the deficit range. These findings are consistent with proposals that WM or the broader cognitive dimensions it taps impede school-based learning, and point to the importance of managing WM loads in the classroom.

Keywords: Working memory, Reading, Language, Mathematics, Learning

Working memory (WM) is the cognitive system that supports the temporary maintenance and manipulation of information necessary for many demanding cognitive activities. Alternative models differ among many dimensions including the extent to which the system is domain-specific or domain-general (e.g., Baddeley & Hitch, 1974; Hambrick, Engle, & Kane, 2004), the roles played by attention and inhibitory processes (Cowan, 1999; Engle & Kane, 2004; Kane, Conway, Hambrick, & Engle, 2007; Wilhelm, Hildebrandt, & Oberauer, 2013), and linkage with longer-term memory systems (e.g., Baddeley, 2000; Unsworth & Engle, 2007). There is however a common assumption that WM is subject to stable capacity limitations that vary widely between individuals across the lifespan. Indeed, the study of individual differences within WM has proved to be one of the most powerful tools for exploring and understanding its structure e.g. (Alloway, Gathercole, & Pickering, 2006; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Daneman & Carpenter, 1980; Kane et al., 2004; Miyake et al., 2000).

Variations in children's WM capacities are highly related to progress across many areas of the curriculum including reading, mathematics and science (Gathercole, Pickering, Knight, & Stegmann, 2004; Jarvis & Gathercole, 2003). Low levels of WM performance are also widely reported in groups of children with difficulties in these areas of academic learning (e.g., Archibald & Gathercole, 2006a; Siegel & Ryan, 1989; Swanson, 1994). These findings have led to speculation that poor WM skills may contribute directly to problems in reading and mathematics. In the present study we investigate the consistency with which WM deficits are present in individual children in a large sample of students receiving support from education and health services for problems related to educational progress. The data are critical both for characterizing the symptom profiles in learning-disabled populations and understanding how low WM capacities may disrupt learning.

In children with reading difficulties and those with a more specific diagnosis of dyslexia, problems are most marked on verbal tasks that tap simple storage capacity (short-term memory or STM tasks) and more complex (WM) tasks with significant verbal processing demands in addition to storage (Kudo, Lussier, & Swanson, 2015; Swanson, Xinhua, & Jerman, 2009). A similar profile of verbal memory deficits is evident in children with Specific Language Impairment (SLI, e.g., Archibald & Gathercole, 2006b; Archibald & Gathercole, 2007; Hesketh & Conti-Ramsden, 2013; Montgomery & Evans,

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2009; Montgomery, 2000; Newbury, Bishop, & Monaco, 2005; Ramus, Marshall, Rosen, & van der Lely, 2013; Schuchardt, Bockmann, Bornemann, & Maehler, 2013). This is a disorder characterized by poor language development in the absence of other sensory or intellectual deficits. For individuals with mathematical difficulties, broader deficits are often reported that extend across verbal and visuo-spatial aspects of both STM and WM (Swanson & Sachse-Lee, 2001; Van den Bos, van der Ven, Kroesbergen, & van Luit, 2013). Some recent studies of children with selective maths problems suggest that their WM difficulties are primarily restricted to the visuo-spatial domain (Swanson et al., 2009; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013). The mixed profile reported in many other studies may therefore reflect the high levels of comorbidity between problems in reading and mathematics.

This evidence has led to speculation that poor WM skills may contribute directly to the difficulties experienced by some children in academic learning. WM failures may lead to the loss of task-critical information across multiple learning episodes, thereby impairing the rate of educational progress (Gathercole, Lamont, & Alloway, 2006). Weak storage in verbal STM also impair the learning of novel phonological representations of new words (Baddeley, Gathercole, & Papagno, 1998; Gathercole, 2006a, 2006b) and compromise complex aspects of language comprehension such as inference and anaphoric reference that rely on the storage of multiple segments for off-line syntactic analysis (Cain, Oakhill, & Bryant, 2004; Pimperton & Nation, 2012). In mathematical abilities and development, WM has been proposed to provide support for simple strategies such as verbal counting (Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Krajewski & Schneider, 2009), the direct retrieval of mathematical facts (Barrouillet & Lépine, 2005), selecting and switching between appropriate solution strategies (Bull & Scerif, 2001; DeStefano & LeFevre, 2004), the co-ordination of multiple steps of complex mathematical problems (Imbo, Vandierendonck, & De Rammelaere, 2007a; Imbo, Vandierendonck, & Vergauwe, 2007b), the maintenance of interim calculations during mental arithmetic (Adams & Hitch, 1997) and other aspects of verbal problem-solving (Swanson & Beebe-Frankenberger, 2004).

Causal explanations such as these are by no means universally accepted. In the field of research on reading and language development, it has been argued that close associations between deficits in WM and in learning are simply common consequences of impairments in broader representational dimensions. Poor verbal STM and WM in children with language-related difficulties has been suggested to be a consequence of core impairments in either phonological processing or phonological representations that also impede mastery of the orthographic system (Hulme & Snowling, 2009; McDougall, Hulme, Ellis, & Monk, 1994; Metsala, 1999; Ramus et al., 2013).

The present study provided the opportunity to investigate the consistency with which deficits in WM are present in children experiencing academic learning difficulties. Data were collected from a sample of over 200 children referred to a research clinic by professionals in the fields of education and health on the basis of problems in attention, learning and/or memory. Tests of verbal and visuo-spatial WM, vocabulary, nonverbal reasoning, reading, and mathematics were administered to each child. Although most of the children scored below age-typical levels on assessments of reading and mathematics at the clinic visit, a substantial minority did not. This degree of variability in the learning scores made it possible to examine the frequency of low WM test scores in children with learning scores in the age-typical range as well as in the struggling learners.

The co-occurrence of deficits in WM and learning was investigated in two ways. First, associations between WM and learning scores were examined across the sample as a whole. In line with previous research, significant associations were predicted for both reading and mathematics, with closer links expected between reading abilities and verbal than visuo-spatial aspects of WM. As a consequence of the high levels of co-morbidity between reading and mathematical difficulties (Vukovic, Lesaux, & Siegel, 2010) both verbal and visuo-spatial WM scores were expected to correlate with mathematics scores.

Second, we examined whether low scores on tests of WM could identify children with poor reading and mathematics performance and distinguish them from children with age-typical levels of attainment. To the best of our knowledge, use of individual WM scores to classify children according to learning abilities has been restricted to date to children with Specific Language Impairment (SLI). Two measures of verbal STM, sentence repetition and nonword repetition, are reliable discriminators of children who do and do not have a clinical diagnosis of SLI or a cognitive profile consistent with the diagnosis (Archibald & Joanisse, 2009; Dollaghan & Campbell, 1998; Hesketh & Conti-Ramsden, 2013). Bishop et al. have suggested that nonword repetition deficits are a phenotypic marker of SLI with a strong hereditary component (Bishop & Snowling, 2004; Bishop, North, & Donlan, 1996). The association may extend beyond verbal STM to verbal WM: in a sample of 14 children with SLI, every child had very low verbal WM scores (Archibald & Gathercole, 2006a).

The consistency of WM deficits in struggling learners is a critical test of theories ascribing a direct causal role to WM in learning to read and becoming mathematically competent. WM deficits that are highly consistent in children with reading and mathematics impairments but not in those without these problems would be entirely consistent with theories attributing a causal role to WM limitations e.g., (Gathercole et al., 2006; Swanson, 1993; Swanson et al., 2009). Conversely, findings that WM scores in the deficit range are not highly characteristic of children with learning difficulties would challenge claims that WM problems are either a necessary or sufficient cause of these problems. Finally, comparable numbers of children with WM deficits with and without detectable learning problems would rule out any simple explanation that WM capacity limitations directly and inevitably impair learning.

Method

Participants

Children aged 5–15 years were recruited via recommendations to parents/carers from health or educational professionals supporting the learning needs of the children. Families interested in the study returned a form to the Cambridge Centre for Attention, Learning and Memory (CALM) indicating their willingness to participate. Centre staff contacted the referrer to discuss the nature of the difficulties for which the child was receiving support and information regarding formal diagnoses of any medical, psychological or psychiatric conditions. If the verbal report met the inclusionary criteria of probable problems of attention, learning, and/or memory, the child and accompanying carer (typically, parent or other family member) were invited to a 2.5-hour assessment session at the CALM clinic. Children were tested individually on a wide set of standardized cognitive tests, and at the time of the visit carers were asked to complete questionnaires relating to the child's behaviour and their developmental and medical history. A report of the outcomes of the principal assessments was provided to the referrer to inform their continuing support for the child. The study was approved by the Local NHS Research Ethics Committee reference 13/EE/0157.

The participants for this study were the first 230 children (154 boys, 76 girls, mean age 9y 4m, range 5y 5m to 15y 11m) to attend the CALM clinic between October 2014 and November 2015. The majority of children lived within a 25-mile radius of Cambridge, England. Recruitment to the clinic was achieved through local partners in education (specialist needs coordinators, specialist teachers and educational psychologists) and children's health services (speech and language therapy services, Child and Adolescent Mental Health services, and community paediatrics).

Measures

Working Memory. Four subtests of the Automated Working Memory Assessment (Alloway, 2007) were administered. Standard scores (population mean 100, $SD = 15$) were calculated for each subtest.

Digit Span. This test of verbal STM involves immediate serial spoken recall of sequences of spoken digits. Test–retest reliability is .89.

Backward Digit Span. This verbal WM test involved the serial recall the digits in reverse sequence. Test–retest reliability is .86.

Dot Matrix. This test of visuo-spatial STM involves serial recall of the locations of successive dots that appeared in an otherwise empty grid a single dot appeared in sequence in an otherwise empty blank matrix. Test–retest reliability is .85.

Mr X. In this test of visuo-spatial WM, sequences of pairs of cartoon characters holding a ball in each hand were presented. The task was to judge whether the two characters were holding the ball in the same hand or not. The character on the right was presented in one of six possible positions in each display, where the ball is held at one of six possible compass locations. At the end of the sequence the task was to recall the locations corresponding to the position of the ball held by the character on the right in each successive display. Test–retest reliability is .84.

Learning.

Reading. The Single Word Reading subtest of the Wechsler Individual Achievement Test II (Wechsler, 2005) was administered. Children read aloud single words that increased in length and complexity as quickly and as accurately as possible. This test was completed by all but one child. Test–retest reliability ranges from .85 to.98 for this age range.

Mathematics. The first 66 children tested in the sample completed the Maths Fluency subtest of the Woodcock Johnson II (Woodcock, McGrew, & Mather, 2001). This involved completion of as many written calculations as possible in 3 min. Test–retest mean is $r = .96$. Subsequent participants completed the Number Operations subtest of the Wechsler Individual Achievement Test II (Wechsler, 1999, 2005), an untimed test that involved completion of written mathematical problems that become progressively more complex and varied drawing on knowledge of fractions, decimals and algebra. Test–retest is greater than .90 for this age range.

General Abilities.

Vocabulary. The Peabody Picture Vocabulary Test (Dunn & Dunn, 2009) is a measure of receptive vocabulary. It involves the child matching the word spoken by the tester to one of four pictures. Two children did not complete this test. Test–retest reliability is .91 for this age range.

Nonverbal Reasoning. The Matrix Reasoning subtest of the Wechsler Abbreviated Scales of Intelligence (Wechsler, 1999) is a test of nonverbal reasoning corresponding to fluid intelligence. Raw scores were converted into *T*-scores (population mean = 50, $SD = 10$). All children completed this assessment. The average test–retest reliability for this age range is .85.

Results

Descriptive Statistics

Standard scores and *T*-scores were used for the purpose of analysis due to the wide age range of the sample. Mahalanobis distance values were computed with the aim of identifying outlier for the following variable set: the 4 WM tests, the reading test, a single mathematics measure derived from the particular test (WIAT or WJ) completed by each child, the 2 measures of general abilities, and for scores on the inattentivity and hyperactivity/impulsivity subscales of the short version of the *Conners Parent Rating Scale* 3rd Edition (Conners, 2008), data from which are not reported here. Twenty children with Mahalanobis scores exceeding 16.919 (χ^2 value for $p = .05$) were excluded, yielding a sample size for analysis of 210. Finally, the multiple imputation option of SPSS v22, which uses the MCMC fully conditional implementation algorithm, was applied to impute missing data. Data were imputed for 2 vocabulary scores, 1 reading score and 1 Mr X score. Missing data could not be imputed for the two different mathematics tests for which there were three missing data values, due to the lower numbers of children completing each test (61 for the Woodcock–Johnson test and 146 for the WIAT).

Table 1 summarizes the information provided for participants at the time of recruitment. In total, 75% of the children were referred via professionals in education services, and the

Table 1
Referral Sources and Diagnoses

Category	*M*	*F*	Total
Referrer			
SENCo	92	48	140
Specialist teacher	8	4	12
Educational psychologist	3	1	4
Speech and language therapist	12	9	21
Clinical psychologist	9	6	15
Paediatrician	13	3	16
Diagnosis			
None	95	51	146
ADD	2	2	4
ADHD	10	2	12
DAMP	1	1	2
Dyslexia	6	4	10
Dyslexia, dysgraphia	1	0	1
Dyspraxia	2	3	5
Dyspraxia and dyslexia	2	0	2
FASD	1	2	3
Generalized developmental delay	1	1	2
Global delay and dyspraxia	1	0	1
Social anxiety disorder and depression	0	1	1
Autism/aspergers	6	0	6
Autism/aspergers and dyslexia	1	0	1
ADHD and tourettes	1	0	1
Autism/aspergers and DAMP	1	0	1
ASD & ADHD	1	1	2
Primary reason for referral	37	17	54
Attention	26	11	37
Memory	16	7	23
Literacy	28	7	35
Maths	6	2	8
Language	14	7	21
Poor general academic progress	42	34	76

remaining 25% through health service professionals. At least one diagnosed developmental disorders prior to the clinic referral was recorded for 27% of the children, most commonly for ADHD ($n = 15$) and dyslexia ($n = 14$). Referring agents were asked to identify the primary reason for recommending that the child should attend the CALM clinic. As shown in Table 1, poor academic performance including problems in either literacy or mathematics or both was the reason given for 66% of the children.

Descriptive statistics for the sample on the principal measures from the study are provided in Table 2. Reading and mathematics standard scores were, on average, low (84 for reading, 82 for WIAT Number Operations and 77 for WJ Maths Fluency). For both the reading and WIAT mathematics tests the range of scores was very wide, extending to the above-average range. Nonverbal reasoning abilities were in the low average range (T-score = 43), as were all measures of WM except the Mr X test of visuo-spatial WM which was within the age-typical range (97). Vocabulary scores were close to the population mean (97). Skewness and kurtosis values for all measures fell within acceptable ranges for statistical analyses assuming normality of distributions. Density plots smoothed with a Gaussian smoothing kernel created using ggplot (Wickham, 2009) in R (2015) with a bandwidth adjustment parameter of 3 are shown for the learning and general ability measures in Figure 1, and for the WM measures in Figure 2.

Individual Differences Analyses

To reduce the four WM measures to more stable dimensions of individual differences, an exploratory factor analysis was performed on the four WM tests. A Varimax extraction identified the following two factors. The first factor, accounting for 49.7% of the variance, had the following component loadings: digit span (.892), backward digit span (.743), dot matrix (.135), and Mr X (.207). The second factor accounted for further 20.2% of variance and had the following loadings: digit span (−.571), backward digit span (−.28), dot matrix (.488), and Mr X (.408). The first factor is accordingly labelled verbal WM and the second factor visuo-spatial WM.

The matrix of correlation coefficients for the principal measures and the two factor scores is shown in Table 3. All WM measures were significantly correlated with reading and mathematics scores with the exception of the dot matrix test of visuo-spatial STM and WJ maths fluency. Vocabulary and nonverbal reasoning scores were also significantly correlated with the WM test scores. Reading was more strongly correlated with the verbal than the visuo-spatial WM factor, $p = .001$. No significant differences in the strengths of the simple correlations across the two WM factors were found for mathematics scores ($p > .05$, both cases). The upper triangle of Table 3 shows the partial correlation coefficients with the matrix reasoning measure

Table 2
Sample Descriptive Statistics

Measure	*N*	Min.	Max.	Mean	SD	Skewness	Kurtosis
Age in months	210	65	182	112.857	25.658	0.508	−0.283
Matrix reasoning	210	20	67	43.481	9.341	0.039	−0.482
Vocabulary	210	66	130	97.010	14.034	0.089	−0.548
Reading	210	44	130	83.998	16.467	0.080	−0.426
WIAT maths	146	42	118	81.890	13.774	0.135	0.081
WJ maths	61	56	102	77.213	10.758	0.313	−0.313
Digit span	210	61	139	92.324	14.434	0.081	−0.293
Backward digit span	210	58	135	91.452	11.557	0.445	1.345
Dot matrix	210	62	135	93.919	14.162	0.162	−0.366
Mr X	210	62	137	96.502	13.667	0.333	0.143

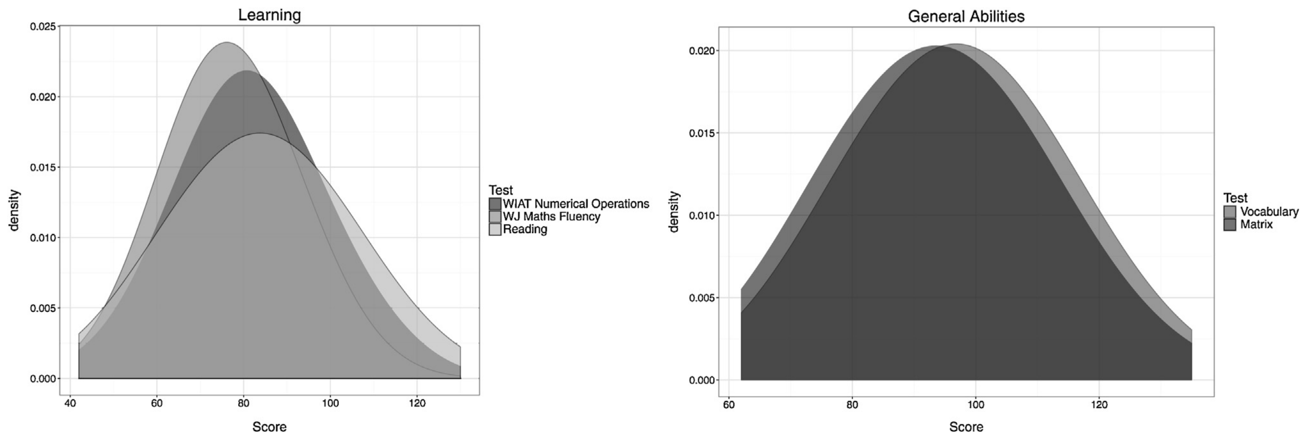

Figure 1. Density plots of the learning and general ability measures.

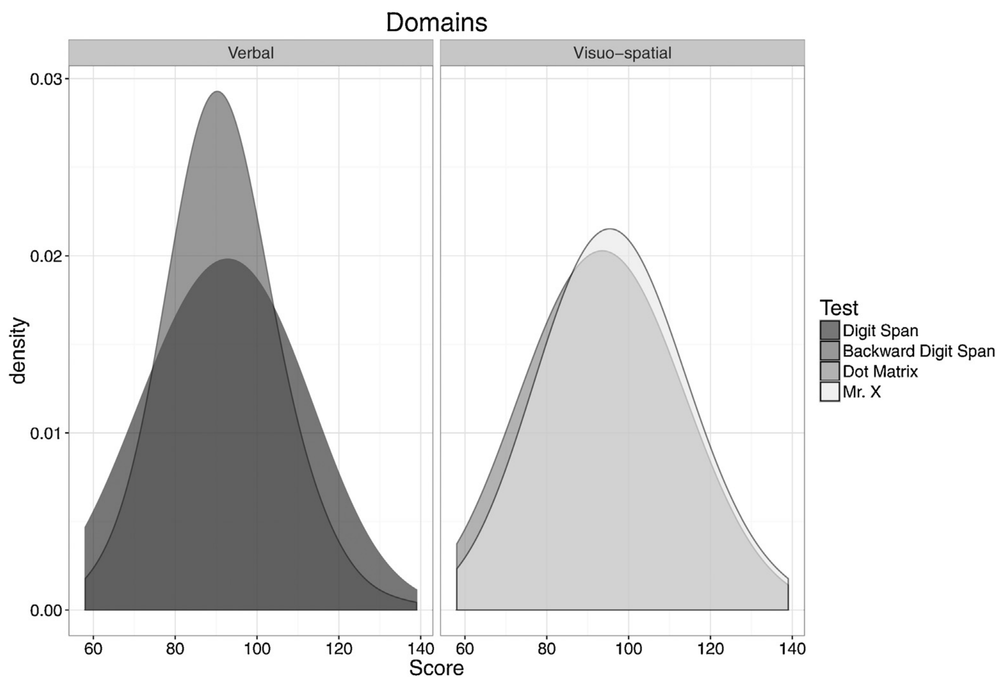

Figure 2. Density plots of the WM measures, by domain.

taken into account in order to control for general fluid cognitive abilities. The correlations between the two WM factors and reading remained significant, with a significantly higher correlation for verbal than visuo-spatial WM, $p = .005$. The WIAT Numerical operations test correlated significantly with both factor scores, but the WJ fluency measure correlated significantly only with verbal WM. No significant differences in the strengths of the correlations with the two WM factors were found for either mathematics test ($p > .05$, both cases).

We examined whether the particularly close association between verbal WM and reading could be mediated by vocabulary knowledge, which is also known to have strong links with verbal aspects of STM (Baddeley et al., 1998; Gathercole, 2006a, 2006b). Further partial correlations were performed controlling for differences in vocabulary scores. The correlation between reading and verbal WM remained highly significant, $r(207) = .321$, $p < .001$.

Diagnostic Analyses

The extent to which scores on individual WM tests distinguished those children with either low reading or low mathematics scores from children with age-typical scores was investigated. Each child was classified according to whether each learning and WM score were in the deficit range. Two cut-off values were used to define deficits: 80 (1.33 *SD*s below the population mean, corresponding to the lowest 9.2% in a normally distributed population) and 85 (1 *SD* below the population mean, corresponding to the lowest 15.9%). The patterns of overlap in the frequency distributions for each pairwise combination of a learning measure and a WM test scores were examined.

The resulting frequency distributions and summary statistics are shown in Table 4. The two principal measures were the probabilities that a child with and without learning performance in a deficit range had a WM score in the deficit range. The presence

Table 3
Correlation Coefficients for Principal Measures and WM Factor Scores: Simple Correlations in Lower Triangle, Partial Correlations Controlling for Matrix Reasoning in Upper Triangle

	Digit span	Backward digit span	Dot matrix	Mr X	Verbal WM	Visuo-spatial WM	Vocabulary	Reading	WIAT maths	WJ maths
Digit span	1	0.391**	0.200**	0.219**	0.885**	0.205**	0.314**	0.359**	0.164*	0.293*
Backward digit span	.433**	1	0.234**	0.295**	0.773**	0.414**	0.292**	0.338**	0.267**	0.355**
Dot matrix	.254**	.320**	1	0.293**	0.226**	0.805**	0.127	0.189**	0.272**	0.100
Mr X	.260**	.354**	.349**	1	0.313**	0.789**	0.169*	0.048	0.259**	0.205
Verbal WM	.892**	.743**	0.135	.207**	1	0.339**	0.363**	0.412**	0.247**	0.383**
Visuo-spatial WM	0.076	.338**	.817**	.776**	-	1	0.186**	0.155*	0.342**	0.200
Vocabulary	.374**	.416**	.270**	.268**	.415**	.254**	1	0.396**	0.195*	0.425**
Reading	.402**	.414**	.274**	0.125	.449**	.163*	.490**	1	0.340**	0.396**
WIAT maths	.247**	.394**	.385**	.342**	.275**	.404**	.408**	.444**	1	-
WJ maths	.356**	.464**	0.245	.297*	.443**	.261*	.576**	.489**	-	1
Matrix reasoning	.215**	.350**	.321**	.247**	.256**	.315**	.519**	.329**	.509**	.507**

* $p < .05$.
** $p < .01$.

Table 4
Frequency Data and Statistics by Learning and WM Cut-Off Values

	Working memory															
	Digit recall				Backward digit				Dot matrix				Mr X			
Cutoff value:	80		85		80		85		80		85		80		85	
Group	=<	>	=<	>	=<	>	=<	>	=<	>	=<	>	=<	>	=<	>
Reading																
80−	27	56	40	43	17	66	40	43	24	59	33	50	15	68	24	59
81+	21	106	30	97	12	115	26	101	14	113	27	100	13	114	27	100
p (reading deficit|WM deficit)	0.33		0.48		0.20		0.48		0.29		0.40		0.18		0.29	
p (no reading deficit|WM deficit)	0.17		0.24		0.09		0.20		0.11		0.21		0.10		0.21	
85−	33	77	49	61	23	87	50	60	28	82	41	69	19	91	32	78
86+	15	85	21	79	6	94	16	84	10	90	19	81	9	91	19	81
p (reading deficit|WM deficit)	0.30		0.45		0.21		0.45		0.25		0.37		0.17		0.29	
p (no reading deficit|WM deficit)	0.15		0.21		0.06		0.16		0.10		0.19		0.09		0.19	
Maths WIAT																
80−	20	45	30	35	14	51	29	36	19	46	29	36	17	48	27	38
81+	11	70	19	62	7	74	16	65	7	74	13	68	6	75	12	69
p (reading deficit|WM deficit)	0.31		0.46		0.22		0.45		0.29		0.45		0.26		0.42	
p (no reading deficit|WM deficit)	0.14		0.23		0.09		0.20		0.09		0.16		0.07		0.15	
85−	26	68	39	55	17	77	37	57	23	71	34	60	20	74	33	61
86+	5	47	10	42	4	48	8	44	3	49	8	44	3	49	6	46
p (reading deficit|WM deficit)	0.28		0.41		0.18		0.39		0.24		0.36		0.21		0.35	
p (no reading deficit|WM deficit)	0.10		0.19		0.08		0.15		0.06		0.15		0.06		0.12	
Maths WJ																
80−	12	27	14	25	7	32	18	21	10	29	13	26	5	34	10	29
81+	4	18	5	17	1	21	2	20	2	20	5	17	1	21	2	20
p (reading deficit|WM deficit)	0.31		0.36		0.18		0.46		0.26		0.33		0.13		0.26	
p (no reading deficit|WM deficit)	0.18		0.23		0.05		0.09		0.09		0.23		0.05		0.09	
85−	15	32	18	29	8	39	20	27	11	36	16	31	6	41	11	36
86+	1	13	1	13	0	14	0	14	1	13	2	12	0	14	1	13
p (reading deficit|WM deficit)	0.32		0.38		0.17		0.43		0.23		0.34		0.13		0.23	
p (no reading deficit|WM deficit)	0.07		0.07		0.00		0.00		0.07		0.14		0.00		0.07	
Mean values across all measures																
p (reading deficit|WM deficit)	0.31		0.42		0.19		0.44		0.26		0.38		0.18		0.31	
p (no reading deficit|WM deficit)	0.13		0.20		0.06		0.13		0.09		0.18		0.06		0.14	

Table 5
Frequency Data and Statistics for Learning Cut-Off Values by Total WM Deficits

	Reading				Maths WIAT				Maths WJ			
WM cut-off	80		85		80		85		80		85	
Total WM deficits	0	1+	0	1+	0	1+	0	1+	0	1+	0	1+
Learning cut-off												
80−	34	49	15	68	27	38	10	55	19	20	12	27
81+	91	36	58	69	59	22	36	45	18	4	13	9
p (reading deficit|WM deficit)	0.59		0.82		0.58		0.85		0.51		0.69	
p (no reading deficit|WM deficit)	0.28		0.54		0.27		0.56		0.18		0.41	
80−	49	61	23	87	45	49	21	73	24	23	14	33
86+	76	24	50	50	41	11	25	27	13	1	11	3
p (reading deficit|WM deficit)	0.55		0.79		0.52		0.78		0.49		0.70	
p (no reading deficit|WM deficit)	0.24		0.50		0.21		0.52		0.07		0.21	

of a WM deficit in a child with age-typical learning in the present sample must be interpreted cautiously, as all of the children had been recruited on the basis of reports of learning-related difficulties even if there were not detectable in the learning assessments at the time of the clinic visit. Sub-threshold WM problems could therefore be present in these children.

The frequency distributions and statistics for each combination of learning and WM cut-off scores are shown in Table 4. The proportions of children with learning scores in the deficit range with deficits on an individual test of WM was higher than would be expected by chance alone (.24 compared with .09 for the cut-off point of 80, and .39 compared with .16 the 85 cut-off point). The prevalence was nonetheless relatively low, present in only a minority of struggling learners. The strength of associations between the four tests of WM and the three learning measures did not vary systematically. The incidence of WM deficits in the children with reading scores in the age-typical range was lower (between .13 and .18), close to chance levels.

Next we investigated whether deficits aggregated across the multiple WM tests would improve discrimination of learning scores. There are two reasons why this might be the case. First, although test reliabilities for all measures included in this study are reasonably high (in excess of .80 in each case), the error component of any individual score will inevitably limit the differentiation between the children with and without detectable academic learning difficulties. The error can be reduced by combining data from multiple assessments. Second, the greatest challenge to learning abilities may arise when more than one aspect of WM is impaired in an individual, and this cannot be identified by examining test statistics in isolation. The number of WM scores in the deficit range was calculated for each child. For cut-off values of 80, the frequencies of each number of deficits were as follows: 0 (125), 1 (40), 2 (26), 3 (15), 4 (4). For 85, the frequencies were: 0 (73), 1 (68), 2 (35), 3 (27), 4 (7). Given the relatively low frequency of occurrence of 2, 3 and 4 deficits, each child was classified according to whether he or she had either (i) no WM deficit scores or (ii) 1 or more deficits at each criterion level. The resulting frequency distributions are shown in Table 5.

A much stronger association between WM and learning was evident than for the data from single tests reported above. Across the whole sample, 40% of the children had WM deficit scores at the 80 criterion (chance level 32%), and 64% (chance level 50%). Averaged across the three learning measures, 54% of the children with poor learning scores had one or more WM test scores at or below 80, and 77% for a criterion of 85. The corresponding values for children with learning scores above the deficit range were much lower, at 21% and 46%. Similar levels of deficits were observed across the reading test and both mathematics measures.

Discussion

This study investigated the extent to which WM problems are present in individuals within a large and heterogeneous sample of children struggling academically in mainstream schooling. The children were referred to the research clinic on the basis of attention, learning, and memory problems by practitioners within education and community health services. At the clinic visit, the majority of the children scored poorly on measures of literacy and mathematics. However, their mean vocabulary performance was age-appropriate and nonverbal reasoning abilities were in the low average range.

Learning abilities within the sample were closely associated with two distinct but correlated aspects of WM: a verbal dimension incorporating both STM and more complex WM test scores, and a visuo-spatial second dimension also extending across both STM and WM tasks (Jarvis & Gathercole, 2003). Both WM dimensions were correlated with achievements in reading and mathematics abilities. For reading, the association was stronger for verbal than visuo-spatial WM. This is entirely consistent with reports of poor verbal STM and WM skills in children with reading difficulties and dyslexia (e.g., Kudo et al., 2015). The special association between reading and verbal WM persisted even when fluid nonverbal abilities and vocabulary knowledge were taken into account. This suggests that the association does not simply reflect the broader dimensional constructs of either language or domain-general higher-level cognitive abilities.

There is much still to be understood regarding the links between verbal WM and reading. The potential role of more specific phonological processing skills in mediating these links is inconsistent across individual studies (e.g., McDougall et al., 1994; Swanson & Jerman, 2007) and has been strongly debated (Hulme & Snowling, 2009; Kudo et al., 2015). Whether the deficits in verbal STM and verbal WM have common or distinct origins is also unclear (Swanson et al., 2009). These uncertainties are a challenge for confident interpretation of the link between verbal aspects of WM and reading. It leaves open the contrasting possibilities that verbal WM may either contribute to the phonologically-based processing and learning of orthography required for literacy acquisition, or more simply arise from the common contribution of phonological processing skills (Hulme & Snowling, 2009; Ramus et al., 2013).

Mathematical abilities were strongly linked with both verbal and visuo-spatial aspects of WM. This is broadly consistent with reports that when the commonly comorbid reading impairments in children with mathematical difficulties characterized by strong verbal WM deficits are excluded, a specific impairment in visuo-spatial WM remains (Swanson et al., 2009; Szucs et al., 2013). Many elements of mathematical learning such as processing and transforming spatial relations such as symmetry, 3D geometry, and use of graphs require the learner to use spatially-based representations. It may therefore be unsurprising that the ability to do so is closely associated with an individual's visuo-spatial WM capacity (Holmes & Adams, 2006; Jarvis & Gathercole, 2003; St Clair-Thompson & Gathercole, 2006; Toll, Kroesbergen, & Van Luit, 2016)

The current study also investigated the degree to which problems in learning for the majority of individuals within this sample could plausibly be attributed to WM. Performance on single WM test scores was only weakly related to learning achievements. Only about a third of the children with difficulties in reading or mathematics scored at the deficit level for any single test, and even fewer individuals with age-typical learning scores. The test scores also failed to show the same sensitivity to individual differences in the domain-specific dimensions of WM such as the stronger links between reading and verbal than visuo-spatial WM that was evident in correlational analyses across the sample. Individual WM test scores are therefore not reliable indicators of significant current problems in reading and mathematics.

More compelling evidence that WM problems accompany learning difficulties for the majority of children was provided when deficits across multiple WM tests were considered. Approximately three-quarters of the children performing poorly on the reading and mathematics tests scored at least one standard deviation below the population mean on one or more WM test. Of the remaining children with learning performance in the age-typical range, 54% obtained deficit scores on 1 or more test, close to the chance level of 50%. Scoring poorly on one of the four WM tests employed in this study therefore increases the risk of a child within the current sample by 50% of having poor reading or mathematics performance. This high level of co-occurrence in WM and learning deficits even within a sample at high risk of learning difficulties reinforces other evidence for the value of WM as a screening tool prior to or at school entry to identify prospectively children at risk of poor academic attainment (Gathercole, Brown, & Pickering, 2003; Gersten, Jordan, & Flojo, 2005).

The present findings are entirely consistent with proposals that WM is critical for key classroom activities including remembering instructions (Gathercole & Alloway, 2008; Gathercole et al., 2006), the use of mathematical strategies and mental arithmetic (e.g., Adams & Hitch, 1997; Geary et al., 2004; Imbo et al., 2007a,b; Swanson & Beebe-Frankenberger, 2004). On this basis low WM capacities would indeed be expected to impair learning. It should, however, be acknowledged that WM impairments rarely occur in isolation during childhood and need to be considered in their broader developmental context. Verbal measures of WM are closely associated with other risk factors for learning including information processing speed e.g., (Moll, Göbel, Gooch, Landerl, & Snowling, 2016), weak phonological processing (e.g., Hulme & Snowling, 2009; Ramus et al., 2013; Ramus & Szenkovits, 2008) and fluid cognitive abilities including problem-solving (e.g., Engle & Kane, 2004; Kudo et al., 2015; Swanson et al., 2009). Rather than operating as a stand-alone system, WM may therefore be better conceived as closely integrated with the broader dimensions of cognitive abilities that include language and executive systems. By this account, WM deficits are symptoms of constellations of developmental problems that adversely affect learning but are also correlated with other cognitive abilities imposing other constraints. This perspective is in step with the emerging consensus within the field of cognitive developmental science that neurodevelopmental disorders of attention and learning are most appropriately characterized by impairments in multiple broad dimensions that can exist either singly or in combination in individual children (Coghill & Sonuga-Barke, 2012; Hulme & Snowling, 2009; Ramus et al., 2013; Willcutt et al., 2013).

For these reasons, it is unlikely that the kinds of learning difficulties encountered by many children in the current sample can be wholly explained in terms of their WM problems or, indeed, that addressing these problems in isolation will be sufficient to overcome their educational problems. Understanding the nature of the WM limitations of individual children may nonetheless be extremely valuable informing their educational support. Poor WM undoubtedly compromises cognitive performance in mental activities central to the classroom. Experimental evidence from adults and neuropsychological patients that cannot be readily explained in terms of other developmentally correlated skills has established that reducing WM capacities impairs three key abilities: understanding and following instructions (Caramazza, Basili, Koller, & Berndt, 1981; Jaroslawska, Gathercole, Logie, & Holmes, 2016; Vallar & Baddeley, 1987; Yang, Gathercole, & Allen, 2013), learning the phonological structures of new words (Baddeley, Papagno, & Vallar, 1988; Papagno & Vallar, 1992; Papagno, Valentine, & Baddeley, 1991) and engaging in mental arithmetic (Adams & Hitch, 1997). The implications are clear. Classrooms and teaching methods designed to help compensate or avoid WM-related learning failures, such as providing access to and training with effective mnemonic devices and employing methods for information delivery that minimize WM loads, should be one key element of programmes of educational support for struggling learners (Elliott, Gathercole, Alloway, Holmes, & Kirkwood, 2010; Gathercole & Alloway, 2008).

Conflict of Interest Statement

The authors declare that there are no conflicts of interest.

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