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Short-term memory and working memory as indices of children's cognitive skills

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In the current literature, empirical and conceptual distinctions have been drawn between a more or less passive short-term memory (STM) system and a more dynamic working memory (WM) system. Distinct tasks have been developed to measure their capacity and research has generally shown that, for adults, WM, and not STM, is a reliable predictor of general cognitive ability. However, the locus of the differences between the tasks has received little attention. We present data from children concerning measures of matrices reasoning ability, reading, and numerical skill along with forward and backward order serial recall of WM, STM, and STM with articulatory suppression tasks. As indices of children's cognitive skills, STM and WM are shown to be rather similar in terms of memory *per se*. Neither the opportunity for rehearsal nor task complexity provides satisfactory explanations for differences between memory tests.

Memory researchers, it seems, like to exploit dichotomies in their field. One long-standing controversy relates to arguments between a unitary view of memory (Laming, 1999; Melton, 1963) and a duplex account that distinguishes short- and long-term stores (Baddeley & Scott, 1971; Shallice & Warrington, 1970). In recalling a sequence of items, a distinction is often made between the advantage for the initial (primacy) and final (recency) list items. Much has also been written of the difference between verbal and visuo-spatial based memories, particularly relevant in a developmental context where children's reliance on these codes appears to vary (e.g., Hitch, Halliday, Schaafstal, & Schraagen, 1988).

Another popular dichotomy distinguishes short-term memory (STM) and working memory (WM). The traditional concept of STM describes a more or less passive temporary memory store, the capacity of which is typically assessed via the immediate serial recall of lists of information (e.g., Atkinson & Shiffrin, 1968). The concept of WM, as well as being chronologically more recent, describes a more dynamic system, concerned with the temporary retention and transformation of information in support of cognitive activity (Baddeley & Hitch, 1974). Although STM and WM clearly share a close relationship, both referring to transient memory, it has been argued on both empirical and conceptual grounds that there are nonetheless important distinctions to be made. After reviewing these, we report a study that evaluates several pertinent issues in a developmental context and makes for a richer appreciation of the two concepts.

STM tasks commonly require just the preservation of sequential order information. For example, the digit span task requires subjects to read or listen to lists of temporally separated digits and then repeat the sequence. In the span format, the number of list items increases until errors exceed threshold. Measuring WM is less straightforward in that there are widely differing views as to what represents the core of WM (Miyake &

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Shah, 1999). Nonetheless, the most common way of measuring WM capacity involves *working memory span* tasks, which essentially contain both a memory and a processing element. For example, the reading span task (Daneman & Carpenter, 1980) involves reading and comprehending sentences and remembering the sentence-final words for subsequent recall. Counting span involves counting arrays and remembering the count totals for subsequent recall (Case, Kurland, & Goldberg, 1982). Operation span involves solving arithmetic problems and remembering sums or accompanying words (Turner & Engle, 1989). Therefore, an important commonality of working memory span tasks is that they involve completing an additional processing task before each to-be-remembered item becomes apparent.

There are several differences between data from STM and WM tests among children and adults. WM scores are often lower than their STM counterparts, sometimes half the value. More important, perhaps, WM tasks are often better predictors of complex cognitive skills. Research has consistently demonstrated significant relationships between WM and a range of abilities, including reading comprehension (Daneman & Carpenter, 1980, 1983), language comprehension (King & Just, 1991; MacDonald, Just, & Carpenter, 1992), reasoning (Kyllonen & Christal, 1990), mental arithmetic (Ashcraft, 1995; Logie, Gilhooly, & Wynn, 1994), and general intelligence (Daneman & Tardif, 1987). Among adults, STM is not consistently related to ability (e.g., Perfetti & Lesgold, 1977; but see Turner & Engle, 1989). Developmental studies have also reported STM to be a weaker predictor of cognitive performance than WM (Daneman & Blennerhassett, 1984; Leather & Henry, 1994).

It is therefore important to consider the psychological features responsible for STM and WM performance. According to one theoretical view, tasks like reading span and counting span involve a limited-capacity system in which resources are consumed by either the processing or memory components, leading to a trade-off in resource availability (Case et al., 1982; Daneman & Carpenter, 1980). As complex cognitive tasks likewise comprise elements of both retention and transformation, they too rely on a central limited-capacity system, and so correlate well with working memory span tasks. STM may be less successful at capturing variance in cognitive skills because it assesses only the memory component of the system.

However, this resource-sharing account of WM span performance has been questioned. Towse and Hitch (1995) argued that evidence for a trade-off, with for example impaired memory performance following an increase in processing demand, could be an artefact. High processing demand might not impair retention functions directly, but rather might slow processing down and therefore increase the amount of forgetting that takes place. Towse and Hitch (1995) reported that children's counting span was equivalent across conditions comparable in duration but differing in difficulty. This supports an alternative interpretation of WM, according to which forgetting over time is more important than resource-sharing. Subsequent research also favours this *task-switching* account (Hitch, Towse & Hutton, in press; Towse, Hitch & Hutton, 1998, 2000).

The task-switching model, then, suggests that WM phenomena may be an emergent property of the dynamics of memory degradation. By avoiding the need to invoke some explanatory mechanism such as resource-sharing within a central executive, WM is placed on a more similar footing to STM. For example, to *some* extent at least the processing component of WM tasks could be regarded as a recall delay, emphasising children's ability to engage in rapid processing in order to limit forgetting. Consistent with that view, processing time and working memory span correlate in children (Hitch et al., in press; Towse et al., 1998). In these terms, task configurations may differentiate WM and STM more than fundamentally different underlying memory mechanisms. A major aim of the present study is therefore to compare WM and STM tasks directly among children. By collecting relevant on-line data, it is possible to evaluate whether the superior predictive ability of WM disappears once statistically shorn of its processing time influence, as the task-switching model suggests.

Engle, Tuholski, Laughlin, and Conway (1999b) investigated the relationship between STM and WM in adults. They found that STM and WM latent variables were highly intercorrelated, but that when variance common to both tasks was removed WM was related to fluid intelligence whereas STM was not. Engle, Kane, and Tuholski (1999a) argue that WM and STM tasks are not "pure" measures of underlying abilities, but nonetheless propose that WM capacity can be equated to the capacity for controlled processing, which in turn reflects general fluid intelligence. According to this position, the extent to which

STM or WM tasks correlate with complex cognition will depend on the demand for controlled attention.

We evaluated this controlled attention hypothesis by comparing different forms of memory tasks, as varying their attentional demands should produce corresponding changes in the relationship with standardised ability measures. Achieving this goal is difficult because it requires manipulations of the relevant construct, yet the computations that are constitutive of controlled attention are not well defined. Here, two manipulations are considered. One involves children recalling the presented sequence in reverse order, because a number of authors argue that backward recall increases the task demands, making for a working memory or executive task (see Elliott, Smith & McCulloch, 1997; Gathercole, 1999; Gathercole & Pickering, 2000; Groeger, Field, & Hammond, 1999; Rosen & Engle, 1997). A second manipulation of STM is the inclusion of articulatory suppression requirements. This is likely to make retention more difficult, almost certainly less successful. Furthermore, Cantor, Engle, and Hamilton (1991) suggest that one reason STM may not correlate with cognitive abilities is that individual differences in rehearsal strategies are important for STM but not WM. If this is the case, then curtailing rehearsal in STM will lead to stronger relationships with cognitive abilities and align the task with WM.

The study sampled two groups, at 8 and 11 years of age. Previous studies have investigated the task-switching model in children of this age (e.g., Towse et al., 1998). By the age of 8 years, we can expect that many children will be using articulatory rehearsal to support at least some memory tasks (Henry & Millar, 1993), making it feasible to examine rehearsal in different situations. Furthermore, the ages represent an important period for the development of reading and number skills at the upper end of primary school, allowing us to examine the role of memory in this development.

In summary, the present study compares STM and WM across development in terms of absolute measures and intercorrelations between variables. "General" reasoning and more specific reading and maths performance provided target skills to be explained. Three primary issues were addressed. First, if WM differs from STM among children because the former incorporates a processing element, then controlling for WM processing differences should make the tasks comparable. In contrast, if WM is inherently different, then it should retain its predictive power. Second, if WM is a better predictor of ability because it represents a "purer" measure of temporary memory not confounded by individual differences in rehearsal strategies, then WM and STM performed with articulatory suppression should predict ability better than a standard STM task. Third, if controlled attention mediates the relationship between measures of temporary memory and ability, then backward recall tasks should correlate more highly with ability than forward recall tasks.

METHOD

Design and participants

A mixed design involved age (8 and 11 years) and testing order (using Latin square design) as between-subjects variables, with memory span (STM, WM, and STMAS—STM with articulatory suppression) and recall order (forward and backward) as within-subject variables. Parental consent was obtained for 58 children from two age groups, reflecting class assignment, while full datasets are available for 54. There were 29 "8 years-olds", mean age 7 years 7 months, ranging 7;1 to 8;1. There were 25 "11 year-olds" mean age 10 years 9 months, ranging 10;3 to 11;3.

Apparatus and materials

A single experimenter conducted all trials. A Macintosh Powerbook 5300c computer presented all the memory tasks, which commenced with two items to remember. There were three trials available at each list length and provided two of these were recalled correctly, sequence length increased by one item and testing continued to a maximum length of eight items. Testing stopped when children made errors on more than one trial at a sequence length. The experimenter entered children's recall responses via an external keyboard.

Short-term memory

Stimulus items were single digit numbers, generated by random selection without replacement. They appeared in black type, approximately 2 cm high, within red rectangles, behind which were drawn partially occluded rectangles representing subsequent stimuli. Digits remained on-screen for 1 second with 0.5 second inter-stimulus intervals.

Working memory

Stimulus problems appeared in black type (within red rectangles, behind which outline edges of subsequent problems could be partially seen) approximately 2 cm high in the format $a+b=c$, where c was the to-be-remembered number and a and b were numbers between 0 and 14. Problems were selected at random without replacement for each trial, from a pool of 100 sums with 10 problms for each numerical answer from 1–9 (with a total of 37 addition and 63 subtraction sums).

Recall conditions

The computer cued serial order recall with a screen comprising yellow rectangles (n = list-length for that trial) and a moving blue question mark, as shown in Figure 1. On forward recall trials, the question mark symbol moved successively downwards after each response was entered, whereas on backward recall trials the question mark symbol moved in the opposite direction.

Ability measures

There were three ability measures: Raven's Standard Progressive Matrices ("matrices") (Raven, Court, & Raven, 1990), BAS Single Word Reading Test ("reading"), and BAS Basic Number Skills Test ("number") (Elliott, 1983). Matrices and reading tests required verbal responses (written down by the experimenter) and number tests involved subjects' individually written responses.

Procedure

Each child was initially informed that they would be playing a variety of games over the forthcoming weeks, and then completed four sessions. Two sessions involved a memory task followed by an ability task, one session involved a memory task alone, and one session involved the number test alone. All sessions took place individually in a quiet room except for the number test which children completed in their class. Session order, recall instruction order, and the pairing of ability and memory tasks were counterbalanced as equally as possible.

The experimenter initially explained each game using laminated practice cards to illustrate the computer screens. The experimenter repeated this explanation if subject made any errors on a practice trial. Satisfied that the child understood the task, the experimenter initiated a "Get Ready" instruction in the centre of the screen. Following a manual key press by the experimenter, the first trial commenced.

STM trials required children to read the numbers silently as they appeared on the screen. Children repeated the phrase "la la" throughout the presentation phase of STMAS trials. The experimenter gave an example of the suppression speed required (i.e., normal speech pace) and informally monitored children's repetition speed. On WM tasks, children silently read through each sum as soon as it appeared, and gave their answer out loud so that the experimenter could type this into the computer. Children recalled the items in forward or backward order, with recall order tests blocked together. Children began recall as soon as

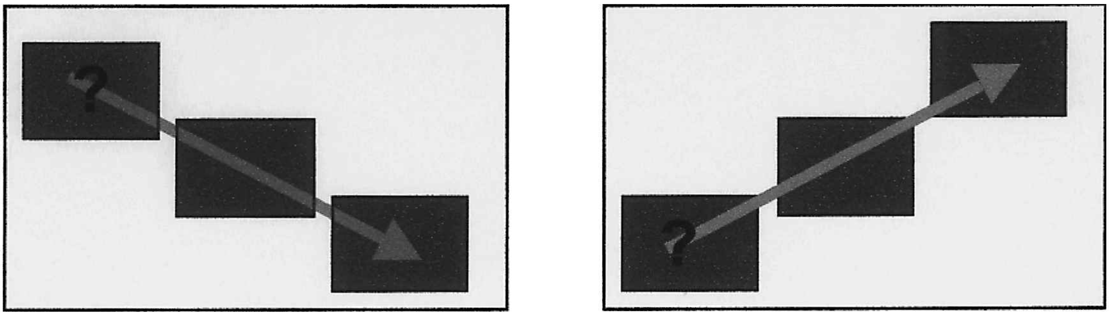

Figure 1. Recall cues for forward and backward order tasks in lists of three items. Arrows indicate direction of cue movement.

they saw the on-screen cue. It was emphasised that it would be easy to forget items and in these cases children should offer a "don't know" response. The experimenter typed children's verbal responses into the computer, which provided visual feedback following each trial. If a child gave more than two incorrect answers to the sums in the WM task, a reminder to solve the sums accurately appeared below the recall feedback.

RESULTS

Visual inspection of the standard deviations, skewness, and kurtosis values for the memory and ability measures indicated satisfactory distribution profiles for most variables. However, reading scores exhibited considerable skew: further inspection identified two extreme values (year 1 case, $z = 3.22$; year 2 case, $z = 3.67$) and as this appeared to be a specific reading problem for these participants, they were excluded from analyses. Re-examination of the descriptive statistics for the remaining participants indicated much improved skewness and kurtosis values. As reported in Table 1, older children obtained significantly higher ability scores than younger children; for matrices, $F(1,51) = 26.50$; $p < .001$, reading, $F(1,51) = 16.26$; $p < .001$, and number, $F(1,51) = 40.01$; $p < .001$.

TABLE 1
Mean ability scores for 8 and 11-year-olds

Age group	*Matrices (total score 60)*	*Reading (total score 90)*	*Number (total score 34)*
8-year-olds	25.4 (8.49)	67.9 (15.0)	16.1 (5.86)
11-year-olds	37.3 (8.08)	80.8 (4.8)	24.3 (2.59)

(n = 52) Standard deviations in parentheses.

Span was estimated following the procedure in Towse et al. (1998). Thus, each score represents the maximum sequence length where recall was correct on 2/3 trials, plus a fraction based on the quality of recall at the next, terminal, level. Overall, as shown in Table 2, older children reached significantly higher span scores, $F(1,46) = 26.08$; $p < .001$[1]. There were also significant differences between memory tasks, $F(2,92) = 50.21$; $p < .001$, and a significant task by year group interaction, $F(2,92) = 3.68$; $p < .05$—older children obtained significantly higher recall on all the memory tasks (all six ps < .05 or better[2]) and the age differences were particularly apparent in the WM tasks.

Forward recall yielded higher spans than backward recall, $F(1,46) = 59.79$; $p < .001$, and there was a significant memory task by recall instruction interaction, $F(2,92) = 12.57$; $p < .001$. While forward span was higher than backward span for STM, $t(51) = 7.18$; $p < .05$, and WM, $t(51) = 6.77$; $p < .05$, the difference was not significant for STMAS, $t(51) = 2.06$; ns. There was no significant recall by year interaction, $F(1,46) < 1$. The three-way interaction between recall, task, and year group was also non-significant, $F(2,92) < 1$. Between-task comparisons confirmed that WM scores were significantly lower than STM scores for forward and backward recall, $t(51) = 9.23$; $p < .05$ and $t(51) = 9.59$; $p < .05$ respectively. Articulatory suppression significantly reduced STM scores for forward, $t(51) = 6.37$; $p < .05$, but not backward recall, $t(51) = 2.55$, ns. WM scores were lower than STMAS, a non-significant difference for forward recall, $t(51) = 0.94$, but significant for backward recall, $t(51) = 6.47$; $p < .05$.

TABLE 2
Mean memory span scores for 8- and 11-year-olds

	STM		*STMAS*		*WM*	
Age group	*Forward*	*Backward*	*Forward*	*Backward*	*Forward*	*Backward*
8-year-olds	4.82 (0.88)	3.77 (0.60)	3.68 (0.83)	3.51 (0.77)	3.28 (1.3)	2.42 (0.81)
11-year-olds	5.37 (0.88)	4.60 (0.79)	4.52 (1.00)	4.24 (0.75)	4.6 (1.16)	3.58 (0.97)

(n = 52) Standard deviations in parentheses.

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[1] All probability statements incorporate Greenhouse-Geisser corrected values where the Mauchly sphericity test was significant.

[2] Bonferroni corrections were used throughout.

Although the main effect of test-administration order was non-significant, there was a significant interaction between order and task, $F(4, 92) = 3.48$; $p < .05$. WM performance appeared to vary little across test order, whereas STM was lower when it appeared as the first test. All other interactions involving order were non-significant (ps < .05).

Analyses of individual differences

Table 3 reports the correlation matrix of the relationship between all variables (three ability measures, six memory tasks, age, and processing time). The lower panel, in italics, displays the partial correlations between the measures when controlling for age[3], where it is apparent that controlling for this variable depressed the associations. STM and WM span measures correlated significantly with all three ability measures. Furthermore, WM scores showed stronger relationships with ability than STM scores, although statistical comparison of correlations (Clark-Carter, 1997) indicated that differences reached significance for number skills only, $t(49) = 1.89$; $p < .05$, 1-tailed test. Articulatory suppression improved the relationship between STM and ability although differences were not significant; for matrices, $t(49) = 0.88$; ns, reading, $t(49) = 0.45$, and number, $t(49) = 1.11$; ns.

The role of processing time

One question motivating the present study was the influence of processing time as a possible explanation for the commonly found predictive advantage of WM tests over STM tests. Thus, the partial correlations between WM and ability, having controlled for age and processing time, were calculated in order to assess the role of processing time as a mediator in the WM–ability relationship. Table 4 reports these statistics (central column). WM for forward recall order still correlated with reading but not with number or matrices. A similar pattern was observed with backward recall. Note than in each case, the relationships are left *weaker* than the corresponding value between STM and ability with age partialled out (right-hand column). The same conclusion is reached when processing time only (i.e., not age) is partialled out of the WM associations $r(49) = .43$, $p < .01$, $r(49) = .25$ respectively, for these values are in the direction of being smaller than those between STM and ability.

To consider the relationship between the various memory tasks and ability measures, a number of hierarchical multiple regressions were conducted. By controlling the entry of variables, it was possible to assess the extent to which memory tasks explain unique variance in an ability measure.

TABLE 3

Bivariate correlations between ability measures and memory tasks for all children

	Matrices	*Reading*	*Number*	*STMF*	*STMB*	*STMASF*	*STMASB*	*WMF*	*WMB*	*TIME*	*AGE*
Matrices		.52**	.62**	.43**	.53**	.55**	.52**	.53**	.55**	−.75**	.63**
Reading	_.30**_		.67**	.51**	.46**	.57**	.39**	.59**	.58**	−.56**	.50**
Number	_.33*_	_.52**_		.44**	.69**	.59**	.55**	.52**	.58**	−.71**	.68**
STMF	_.36*_	_.45**_	_.38**_		.42**	.29*	.34*	.76**	.47**	−.41**	.26*
STMB	_.32*_	_.28*_	_.55**_	_.35*_		.44**	.44**	.53**	.56**	−.45**	.50**
STMASF	_.38**_	_.44**_	_.43**_	_.20ns_	_.27*_		.65**	.37**	.30*	−.58**	.46**
STMASB	_.34*_	_.21ns_	_.38**_	_.25ns_	_.28*_	_.54**_		.43**	.48**	−.58**	.45**
WMF	_.35*_	_.48**_	_.33*_	_.74**_	_.40**_	_.21ns_	_.28*_		.71**	−.51**	.44**
WMB	_.31*_	_.43**_	_.34*_	_.41**_	_.40**_	_.07ns_	_.31*_	_.62**_		−.60**	.55**
TIME	_−.57**_	_−.36**_	_−.49**_	_−.33*_	_−.20ns_	_−.42**_	_−.43**_	_−.33*_	_−.38**_		_−.65**_

(n = 52)
** Correlation is significant at the .01 level (2-tailed).
* Correlation is significant at the .05 level (2-tailed).
Type in italics represents correlation coefficients with age partialled.

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[3] Statistical significance involves 2-tailed tests unless otherwise stated.

TABLE 4
The role of processing time in the memory–ability relationships

Ability task	*WM–ability relationships*		*STM–ability relationships*
	Age partialled	*Age and time partialled*	*Age partialled*
MATRICES	**0.35**	0.14	**0.36**
READING	**0.48**	**0.41**	**0.45**
NUMBER	**0.33**	0.20	**0.38**

Bold type indicates significant correlation coefficients.

TABLE 5
The role of rehearsal in the memory–ability relationship

	STM Forward	*STM Backward*
Matrices	**Change $\mathbf{R^2 = 0.06}$;** $\boldsymbol{F(1,48) = 6.27; p < .05}$	Change $R^2 = 0.04$; $F(1,48) = 4.06$; $p = .05$
Reading	**Change $\mathbf{R^2 = 0.10}$;** $\boldsymbol{F(1,48) = 9.11; p < .05}$	Change $R^2 = 0.02$; $F(1,48) = 1.06$; ns
Number	**Change $\mathbf{R^2 = 0.07}$;** $\boldsymbol{F(1,48) = 8.78; p < .01}$	**Change $\mathbf{R^2 = 0.03}$;** $\boldsymbol{F(1,48) = 4.22; p < .05}$

Summary of multiple regression statistics.

Bold type indicates STMAS contributed significant variance to ability measures.

For matrices, with age on the first step and the memory tasks blocked by recall order on steps 2 and 3, neither forward recall tasks together, Change $R^2 = 0.05$; $F(3,44) = 1.61$; ns, nor backward recall tasks together, Change $R^2 = 0.02$; $F(3,44) = 1.68$; ns, contributed any additional variance to matrices when entered last. With separate treatment of recall order conditions, only the STMASf measure contributed unique variance to matrices when entered after other variables, Change $R^2 = 0.06$; $F(1,47) = 5.78$; $p < .05$.

Analyses of reading showed significant effects of entering both forward recall tasks last, Change $R^2 = 0.14$; $F(3,44) = 4.82$; $p < .001$, and both backward recall tasks last, Change $R^2 = 0.08$; $F(3,44) = 2.91$; $p < .05$. With separate treatment of recall order tasks, STMASf, Change $R^2 = 0.09$; $F(1,47) = 8.40$; $p < .01$, and WMb, Change $R^2 = 0.08$; $F(1,47) = 6.03$; $p < .05$, added variance when entered last. Analysis of number indicated backward recall but not forward recall tasks contributed unique variance to number when entered last, Change $R^2 = 0.09$; $F(3,44) = 4.11$; $p < .05$, Change $R^2 = 0.04$; $F(3,44) = 1.88$; ns, respectively. Separate recall order analyses showed STMASf, Change $R^2 = 0.07$; $F(1,47) = 8.36$; $p < .01$, and STMb, Change $R^2 = 0.09$; $F(1,47) = 11.91$; $p < .005$, contributed unique variance to number skill.

The role of rehearsal

The contrast between the predictive success of STMS and STMAS illuminated the role of rehearsal in the memory–ability relationships. Table 5 displays the relevant statistical effects. After age on the first step and STM on the second step, STMAS on the third step did contribute significant variance in matrices scores under forward recall, whereas for backward recall the effect was marginal. In similar regression models, STMAS also explained unique variance in reading for the forward but not backward recall tasks, as well as unique variance in number skills for both recall orders.

The role of attention

The importance of recall order instructions on the predictive power of the memory tests is illustrated in Table 6. In the case of STM, with age entered on the first step and forward recall on the second

TABLE 6
The role of attentional demands in the memory–ability relationship

	STM	*STMAS*	*WM*
Matrices	Change $R^2 = 0.03$; $F(1,48) = 2.45$; ns	Change $R^2 = 0.01$; $F(1,48) = 1.37$; ns	Change $R^2 = 0.01$; $F(1,48) = 0.76$; ns
Reading	Change $R^2 = 0.01$; $F(1,48) = 1.00$; ns	Change $R^2 = 0.00$; $F(1,48) = 0.10$; ns	Change $R^2 = 0.02$; $F(1,48) = 1.73$; ns
Number	**Change $\mathbf{R^2 = 0.11}$;** $\boldsymbol{F(1,48) = 14.42; p < .001}$	Change $R^2 = 0.02$; $F(1,48) = 1.67$; ns	Change $R^2 = 0.02$; $F(1,48) = 1.76$; ns

Summary of multiple regression statistics.

Bold type indicates that backward recalled tasks contributed significant variance.

step, backward recall then contributed significant additional variance to number skills but not matrices or reading. In the case of WM and STMAS, backward recall did not contribute significant additional variance after forward recall on any of the three ability measures. Furthermore, entering instead forward recall after backward recall, there were significant effects with STM, STMAS, and WM in the prediction of reading, Change $R^2 = 0.11$; $F(1,48) = 8.72$; $p < .05$, Change $R^2 = 0.11$; $F(1,48) = 8.91$; $p < .05$, and Change $R^2 = 0.06$; $F(1,48) = 4.89$; $p < .05$ respectively. Forward recall STMAS also contributed significant variance over backward recall in predicting number, Change $R^2 = 0.04$; $F(1,48) = 4.27$; $p < .05$.

Developmental change and individual differences

Within the experimental design, it was possible to examine separately younger and older children's individual differences in the prediction of target skills, as well as assess the role of age as a mediating variable in the regression analyses. In most cases results were consistent in both age groups, although there were some age-related changes too, and intimations that STM tasks showed more developmental sensitivity than the WM tasks (which might reflect differing reliance on rehearsal across the age groups). At the same time, inconsistencies and lack of significance in some of the findings, attributable in part to the loss of experimental power, make strong interpretation problematic (a full set of age-specific analyses can be obtained from the first author).

Overview

The preceding analyses describe a data set in which many of the variables interrelate, and yet the measures are clearly not interchangeable. To provide an additional perspective on memory performance, principal components and factor analyses were conducted. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.734, suggesting that such analyses are appropriate (Field, 2000) even though based on a small dataset. Principal components analysis extracted two components on the basis of substantial eigenvalues, which together explained 74.1% of variance. This two-factor solution structure kept forward and backward tasks together, but distinguished STMAS (comprising one component) from STM and WM (both comprising another component); loadings afer varimax rotation are presented in the Appendix. It is worth noting that unweighted and generalised least squares, maximum likelihood, principal axis factoring, alpha factoring, and image factoring extraction techniques all produced essentially comparable two-factor patterns, emphasising the stability of the solution. In summary, the analyses converge with preceding results to indicate articulatory suppression makes short-term memory more, not less, distinct from WM.

DISCUSSION

To summarise, analysis showed substantial developmental improvement across a range of memory tasks. Standard STM tasks yielded the highest span while WM tasks yielded the lowest in both age groups. With conventional recall instructions articulatory suppression reduced STM performance to that of WM. Many of the variables intercorrelated. The zero-order correlations confirmed previous reports that WM tends to correlate more highly with ability measures than does STM. However, controlling for individual differences in the arithmetic processing task eliminated this advantage to WM tasks. Some analyses also showed that backward recall and articulatory suppression requirements made a difference to the characteristics of STM tasks.

It is important to acknowledge that the present analyses assume the various measures of memory have been estimated reliably, and to an equivalent extent. If one memory task measurement was less reliable than another, then clearly this could attenuate the relationship with ability scores. The present study, in common with many involving working memory span, did not collect test–retest reliability, so this issue cannot be addressed precisely (for exceptions with adults, see Klein & Fiss, 1999; Waters & Caplan, 1996. Hitch et al., in press, report data among children using multiple measures and a test–retest interval of 12 months). However, inspection of the correlations to identify the strongest association establishes a rough lower bound of reliability. Among forward order recall, WM and STM correlate .76 while STMAS in forward and backward recall order correlate .65. Clearly, therefore, all the tasks manifest the statistical potential for healthy correlations with ability.

The overlap between STM and WM and the mediating influence of processing time

WM correlated with all three ability measures. STM, in the form of a visually presented digit span task, also correlated with ability. Indeed, although the correlations involving STM were rather modest, they were robust and withstood partialling out of several other variables[4] (see also Towse & Houston-Price, in press, who report significant correlations between children's digit span and BAS achievement scores).

The present experiment allows a more detailed analysis of STM and WM, comparing these tasks after statistical control of individual differences in the processing component of working memory. Although it is often ignored, the present results confirm that among children, working memory processing time can act as an important mediator of ability (see also Hitch et al., in press). The results indirectly support the task-switching model of working memory span by showing how the temporal duration of the processing operation can influence span performance. The present analyses demonstrated that, having controlled for processing time and age, the relationships between STM and abilities were quantitatively *superior* to the WM scores (the direction of effect means this cannot be simply an issue of poor experimental power). Furthermore, WM measures no longer correlated with matrices or number after controlling for processing time.

Thus, the results illustrate the potential danger in ignoring the influence of processing time, as it may confound the relationships between children's memory *per se* and cognitive skill. At the same time, it is important to reiterate that these conclusions apply to children; among adults processing rate does not appear to account—at least directly—for span differences (Conway & Engle, 1996; Engle, Cantor, & Carullo, 1992; Towse et al., 2000). In the same vein, we note that the oft-reported superior predictive performance of WM tasks is most frequently based on a consideration of the adult, rather than developmental, literature and without controlling for differences in the processing task (e.g., Daneman & Carpenter, 1980; Daneman & Blennerhassett, 1984).

Articulatory rehearsal as a critical difference between STM and WM

One previous account of the differential relationships between WM and STM tasks and abilities proposes that conventional STM measures are confounded by a variety of strategies including rehearsal (Cantor et al., 1991; Cohen & Sandberg, 1980). It is possible that STM tasks afford greater opportunity for rehearsal during the inter-stimulus intervals and/or at the recall stage, as only one operation is required compared with two operations in WM tasks—processing *in addition* to retention. However, we believe it is also possible to argue the reverse case, the WM tasks may actually offer more opportunity for rehearsal. The scheduling of various aspects of the task is under the control of the subject and thus the opportunity exists to rehearse memoranda before beginning any subsequent processing operation.

Imposing articulatory suppression requirements during stimulus presentation largely blocked the opportunity for rehearsal on a STM task. If rehearsal normally masks the relationship between STM and ability, then not only would absolute span scores for STMAS be low, but also there would be a stronger relationship between STMAS and WM than between STM and WM. However, with age or with age and processing time partialled out, although there *were* significant correlations between the STM and WM tasks, there was no correlation between forward recall STMAS and either forward or backward recall WM tasks. Neither did STM correlate with forward or backward STMAS. Furthermore, of the forward recall tasks, only STMAS accounted for unique variance in all three ability measures. Thus, while they are related, preventing rehearsal on STM renders performance more different from rather than more similar to WM, a conclusion reinforced by the principal components analysis. That is, the STMAS tasks appear to be qualitatively different from both the WM and the STM tasks and also more predictive of children's ability.

One possible explanation for the pattern of findings is that articulatory suppression makes the STM task sensitive to how children manage the complex task requirements of interleaving encoding and maintenance operations with con-

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[4] Although some children received a variant of STM—with articulatory suppression—prior to their STM test, analysis of just those children who performed STM first also demonstrated strong correlations between STM and abilities. It is therefore unlikely that the administration of two STM tasks is responsible for the present findings.

current articulation. At any rate, as WM and STM are more similar than WM and STMAS, and as STMAS is predictive of ability measures in instances where WM is not, we conclude that STM and WM cannot be distinguished merely by the presence of rehearsal in the former task. Instead, we suggest it is more plausible to assume that both STM and WM tasks involve rehearsal, and thus account for why STM with suppression behaved differently from both STM and WM. In summary, while support is obtained for the conclusion that rehearsal strategies may negatively impact on the relationship between short-term memory span and ability (Cantor et al., 1991), this does not fully describe the differences between memory tasks.

The controlled attention hypothesis of working memory

Engle et al. (1999a) argue that WM tasks involve controlled attentional processing. The present study manipulated this factor by requiring children to recall to-be-remembered items in forward or backward order. Backward recall has been demonstrated to be a more effortful task, possibly involving controlled attention. Engle et al. (1999b) have suggested that, although backward recall may involve increased attentional demands, it is not a good measure of adults' working memory because the procedures would be highly automatised. However, this argument does not necessarily hold true for children because sequencing the order of items might well involve greater attentional demands, being less proceduralised. Backward recall tasks produced lower span scores than their forward recall analogues (although not significant for the more poorly recalled STMAS), confirming the additional task difficulty. Yet the backward recall tasks were *not* universally more highly correlated with abilities. Neither forward nor backward recalled tasks together uniquely contributed significant variance to the explanation of matrices. Backward and not forward recall tasks uniquely predicted number skills, but both backward and forward recall tasks contributed significantly to reading skill. Furthermore, only backward recall STM contributed unique variance to any ability measure—for number—when entered after the forward recall analogue, whereas forward recall STMAS predicted number over the backward recall version. Thus, in certain cases forward recall tasks, with lower attentional demands, were more strongly related to ability measures than backward recall tasks.

The preceding conclusions again emphasise differences between memory tasks as well as specificity to skill and achievement domains, and suggest further that increasing "attentional demands" need not enhance the relationship between memory task and ability for children. In general, the supposedly most attention-demanding tasks, those with the greatest subjectively rated difficulty, were less strongly correlated with abilities. As alluded to in the introduction, it is always possible to respond that controlled attention was not appropriately manipulated. However, this rather begs the question of the value of the controlled attention construct and certainly emphasises the necessity to define the concept in a precise and non-circular way.

Overall, the present study stresses a number of important points in the conceptualisation of STM and WM. It appears that what holds for WM in adults may not be equally true for children, and vice versa. The study highlights the value of taking account of children's on-line processing during WM tasks, and in doing so suggests that among children WM and STM may, at least in some circumstances, be rather equivalent. Data suggest the locus of differences between STM and WM does not lie just in differential opportunity for rehearsal, because curtailing rehearsal in STM makes the task more different from, not more similar to, WM. It seems that a more complete description of the range of retention strategies and task characteristics is required to understand the relationship between memory tasks. A straightforward dichotomy between STM and WM represents a considerable oversimplification.

REFERENCES

Ashcraft, M.H. (1995). Cognitive psychology and simple arithmetic: A review and summary of new directions. *Mathematical Cognition*, *1*(1), 3–34.

Atkinson, R.C., & Shiffrin, R.M. (1968). Human memory: A proposed system and its control processes. In K.W. Spence & J.T. Spence (Eds.), *The psychology of learning and motivation: Advances in research and theory* (Vol 2, pp. 89–195). London: Academic Press.

Baddeley, A.D., & Hitch, G.J. (1974). Working memory. In G.H. Bower (Ed.), the psychology of learning and motivation. *Advances in research and theory* (Vol 8, pp. 47–89). London: Academic Press.

Baddeley, A.D., & Scott, D. (1971). Short-term forgetting in the absence of proactive inhibition. *Quarterly Journal of Experimental Psychology*, *23*, 275–283.

Cantor, J., Engle, R.W., & Hamilton, G. (1991). Short-term memory, working memory and verbal abilities: How do they relate? *Intelligence*, *15*, 229–246.

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

Clark-Carter, D. (1997). *Doing quantitative psychological research: From design to report*. Hove, UK: Psychology Press.

Cohen, R.L., & Sandberg, T. (1980). Intelligence and short-term memory: A clandestine relationship. *Intelligence*, *4*, 319–331.

Conway, A.R.A., & Engle, R.W. (1996). Individual differences in working memory capacity: More evidence for a general capacity theory. *Memory*, *4*, 577–590.

Daneman, M., & Blennerhassett, A. (1984). How to assess the listening comprehension skills of prereaders. *Journal of Educational Psychology*, *76*(6), 1372–1381.

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

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

Daneman, M., & Tardif, T. (1987). Working memory and reading skill reexamined. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp 491–508). Hove, UK: Lawrence Erlbaum Associates Ltd.

Elliot, C.D. (1983). *British Abilities Scale, Technical manual*. Windsor, UK: NFER-Nelson.

Elliott, C.D., Smith, P., & McCulloch, K. (1997). *British Ability Scales II. Technical manual*. Windsor, UK: NFER-Nelson.

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

Engle, R.W., Kane, M.J., & Tuholski, S.W. (1999a). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and active control* (pp. 102–134). Cambridge: Cambridge University Press.

Engle, R.W., Tuholski, S.W., Laughlin, J.E., & Conway, A.R.A. (1999b). Working memory, short-term memory and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General*, *128*, 309–331.

Field, A. (2000). *Discovering statistics using SPSS for Windows*. London: Sage.

Gathercole, S. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Science*, *3*(11), 410–418.

Gathercole, S.E., & Pickering, S.J. (2000). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *British Journal of Educational Psychology*, *70*, 177–194.

Groeger, J.A., Field, D., & Hammond, S.M. (1999). Measuring memory span. *International Journal of Psychology*, *34*(5/6), 359–363.

Henry, L.A., & Millar, S. (1993). Why does memory span improve with age? A review of the evidence for two current hypotheses. *European Journal of Cognitive Psychology*, *5*(3), 241–287.

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

Hitch, G.J., Towse, J.N., & Hutton, U. (in press). What limits working memory span? Theoretical accounts and applications for scholastic development. *Journal of Experimental Psychology: General*.

King, J., & Just, M.A. (1991). Individual differences in syntactic processing: The role of working memory. *Journal of Memory and Language*, *30*, 580–602.

Klein, K., & Fiss, W.H. (1999). The reliability and stability of the Turner and Engle working memory task. *Behavior, Research Methods, Instruments, & Computers*, *31*(3), 429–432.

Kyllonen, P.C., & Christal, R.E. (1990). Reasoning ability is (little more than) working-memory capacity?! *Intelligence*, *14*, 389–433.

Laming, D. (1999). Testing the idea of distinct storage mechanisms in memory. *International Journal of Psychology*, *34*(5/6), 419–426.

Leather, C.V., & Henry, L.A. (1994). Working memory span and phonological awareness tasks as predictors of early reading ability. *Journal of Experimental Child Psychology*, *58*, (1), 88–111.

Logie, R.H., Gilhooly, K.J., & Wynn, V. (1994). Counting on working memory in mental arithmetic. *Memory and Cognition*, *22*, 395–410.

MacDonald, J.M.A., Just, M.A., & Carpenter, P.A. (1992). Working memory constraints on the processing of syntactic ambiguity. *Cognitive Psychology*, *24*, 56–98.

Melton, A.W. (1963). Implications of short-term memory for a general theory of memory. *Journal of Verbal Learning and Verbal Behavior*, *2*, 1–21.

Miyake, A., & Shah, P. (1999). Toward unified theories of working memory: Emerging general consensus, unresolved theoretical issues and future directions. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 442–481). Cambridge: Cambridge University Press.

Perfetti, C.A., & Lesgold, A.M. (1977). Discourse comprehension and sources of individual differences. In M.A. Just & P.A. Carpenter (Eds.), *Cognitive processes in comprehension*. Hillsdale, NJ: Lawrence Erlbaum Associates Inc.

Raven, J.C., Court, J.F., & Raven, J. (1990). *Standard progressive matrices*. Oxford: Oxford Psychologists Press.

Rosen, V.M., & Engle, R.W. (1997). The role of working memory capacity in retrieval. *Journal of Experimental Psychology: General*, *126*, 211–227.

Towse, J.N., & Hitch, G.J. (1995). Is there a relationship between task demand and storage space in tests of working memory? *Quarterly Journal of Experimental Psychology*, *48*A(1), 108–124.

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

Towse, J.N., Hitch, G.J., & Hutton, U. (2000). On the interpretation of working memory span in adults. *Memory and Cognition*, *28*, 341–348.

Towse, J.N., & Houston-Price, C.M.T. (in press). Combining representations in working memory: A brief report. *British Journal of Developmental Psychology*.

Turner, M.L., & Engle, R.W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*, 127–154.

Shallice, T., & Warrington, E.K. (1970). Independent functioning of verbal memory stores: A neuropsychological study. *Quarterly Journal of Experimental Psychology*, *22*, 261–273.

Waters, G.S., & Caplan, D. (1996). The measurement of verbal working memory capacity and its relation to reading comprehension. *Quarterly Journal of Experimental Psychology*, *49*A(1), 51–70.

APPENDIX

Component loadings from Principal Components Analysis of memory scores, with varimax rotation.

Component	*1*	*2*
STM (forward)	.844	.097
STM (backward)	.586	.471
WM (forward)	.905	.219
WM (backward)	.771	.296
STMAS (forward)	.144	.896
STMAS (backward)	.268	.846