Children’s working memory: Investigating performance limitations in complex span tasks

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Abstract

Three experiments investigated the roles of resource-sharing and intrinsic memory demands in complex working memory span performance in 7- and 9-year-olds. In Experiment 1, the processing complexity of arithmetic operations was varied under conditions in which processing times were equivalent. Memory span did not differ as a function of processing complexity. In Experiment 2, complex memory span was assessed under three conditions designed to vary both processing and intrinsic storage demands: mental arithmetic (significant attentional demands–requires storage), odd/even judgments (significant attentional demands–no storage required), and articulatory suppression (minimal attentional demands–no storage required). The highest memory spans were found in the articulatory suppression task. Span was at an intermediate level with arithmetic processing and was lowest for processing involving odd/even judgments. This difference in memory span for processing tasks involving arithmetic processing and odd/even judgments was eliminated in Experiment 3 when the pacing requirements of the arithmetic and odd/even processing tasks were equated. The results are consistent with the view that complex memory span performance is disrupted by processing activities that divert attentional resources from storage.

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Introduction

The term “working memory” refers to the ability to store and manipulate information simultaneously (e.g., Baddeley, 1986; Baddeley & Hitch, 1974; Just & Carpenter, 1992). Working memory performance has been widely assessed using complex span tasks such as reading span, in which participants are required both to read sentences and to later recall a series of sentence final words (e.g., Daneman & Carpenter, 1980). Working memory constraints tapped by such tasks are closely linked with complex cognitive abilities, such as language comprehension, problem solving, mental arithmetic in adults (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002), and with attainments in learning domains, such as literacy and mathematics in children (e.g., Gathercole, Pickering, Knight, & Stegmann, 2004; Hitch, Towse, & Hutton, 2001).

One influential account developed by Case, Kurland, and Goldberg (1982) to explain developmental increases in working memory performance across the childhood years is that working memory is a single flexible system fueled by a limited capacity resource that can be flexibly allocated to support processing and storage. By this view, the total working memory resource remains constant, but the efficiency of processing speed increases with age. This leads to additional resources being released to support short-term storage. Consistent with this view, Case and colleagues found in a study of 6- to 12-year-olds that counting spans were highly predictable from individual counting speeds. Furthermore, counting spans were reduced to the level typical of 6-year-olds when adults’ counting efficiency was reduced by requiring the use of nonsense words rather than digits to count sequences. The authors concluded that the decreased memory spans resulted from the greater processing demands imposed by the unfamiliar counting task, leading to a processing/storage trade-off that diminished storage capacity.

Towse and Hitch (1995) argued that these findings may have resulted from uncontrolled differences in the temporal duration of the complex memory span tasks rather than from trade-offs between processing and storage. They proposed that children do not simultaneously process and store material in the course of complex span tasks but instead switch between the processing elements of the tasks and item retention. By this account, poorer span performance under more complex processing conditions results from the greater opportunity for time-based forgetting due to the lengthier retention intervals. Evidence consistent with this task-switching model was provided in a series of studies that either varied counting complexity while holding retention interval constant (Towse & Hitch, 1995) or manipulated retention requirements in counting, operation, and reading span tasks while holding the overall processing difficulty constant (Towse, Hitch, & Hutton, 1998). The results from these experiments suggested that working memory span, rather than being a measure of capacity for resource sharing, is constrained by a time-based loss of activation of memory items (Hitch et al., 2001).

Importantly, there is now a general consensus that no single factor constrains complex memory span (e.g., Halford, Maybery, O’Hare, & Grant, 1994; Miyake &
Shah, 1999; Ransdell & Hecht, 2003; Towse & Houston-Price, 2001). In a recent study, Barrouillet and Camos (2001) found that both time and limitation of attentional resources constrain performance in working memory tasks. In addition, Bayliss, Jarrold, Gunn, and Baddeley (2003) provided evidence to suggest that children’s performance on working memory span tasks is underpinned by domain-general processing and domain-specific storage resources.

The three experiments reported in this article were designed to investigate further the extent to which the nature of processing influences children’s performance on complex memory span tasks. The experiments also investigated whether the impact of processing activities on memory span is subject to developmental change, with the aim of casting light on the processes underlying the development of working memory. The first experiment extended the approach adopted by Towse and Hitch (1995) to investigate the influence of processing complexity on performance in a complex memory span paradigm involving mental arithmetic. Participants were 7- and 9-year-olds, who were required on each trial to add sequences of numbers and recall each total for later serial-ordered recall. The calculation varied in difficulty across two conditions involving the addition of either single-digit numbers or two-digit numbers that required a carrying operation. The time taken to complete the calculations in the two tasks was equated by presenting longer sequences of numbers for addition in the single-digit condition than in the double-digit condition.

Resource-sharing and temporal decay accounts of working memory make contrasting predictions concerning the outcomes of this experiment. According to a resource-sharing account, memory span should be lowest for the calculations involving carry operations because the resources available to support item retention will be diminished in this condition as a consequence of the greater processing load. In contrast, by a temporal decay account, memory spans should be equivalent for conditions involving carry and simple sum operations because their temporal durations are equivalent. The two age groups were included to test the generality of the experimental findings across age, in line with other studies that have examined working memory performance in children (e.g., Barrouillet & Camos, 2001; Halford et al., 1994; Towse & Hitch, 1995). Findings of age-related changes in the factors influencing complex memory span would provide new insights into the nature of developmental changes in working memory function, the nature of which currently is not fully understood.

**Experiment 1**

**Method**

**Participants**

A total of 64 children from Year 3 ($n = 33$, mean age 7 years 9 months, range 7 years 4 months to 8 years 3 months) and Year 5 ($n = 31$, mean age 9 years 9 months, range 9 years 3 months to 10 years 3 months) of a local primary school in Stockton-on-Tees, United Kingdom, participated in the experiment. Participants were taken
from a sample of children who were identified by their teachers as having normal arithmetic skills.

**Design**

The experiment employed a two-way mixed design with age as a between-subjects factor (7 or 9 years) and type of operation as a within-subjects factor (simple or carry sums). Dependent variables were the number of operation totals recalled accurately (operation span), the time taken to calculate operations (operation speed), and calculation errors. The order of testing the two conditions was counterbalanced.

**Materials**

In the carry condition, problems consisted of the addition of two two-digit numbers that involved a carry operation of the units (e.g., 35 + 17). The simple condition involved the addition of a series of five single-digit numbers (e.g., 1 + 2 + 1 + 2 + 3). Pretests with both age groups (a sample of five children from each age group) allowed these simple problems to be matched for time with the carry problems.

**Procedure**

All children were tested individually in a quiet area of their school. A laptop computer with a 12-inch color monitor was programmed to control the display of individual operations and to record the response times. Totals recalled subsequently were recorded on score sheets. The children were told that they would be shown a sum on the computer screen that had to be worked out and that as soon as they reported the answer out loud, they would be shown another sum that would also need to be calculated and reported. They would then be requested to recall, in order, the totals previously calculated. It was emphasized that although they were being timed, it was important that they try to work out the answer as accurately as possible. A practice trial at the beginning of each task established that all of the children grasped the concept immediately.

Each condition began with a sum displayed at the center of the computer screen as black numbers on a white background in 72-point Arial font. As soon as the child reported the answer, the next operation appeared (initiated by a key press by the experimenter). After each calculation, the answer was recorded manually and the response time was recorded electronically on the laptop (following a key press by the experimenter). The child was then asked to recall, in order, the successive totals. These were also recorded. Correct responses were scored in terms of the total that had been calculated, not the actual total. So, if a child erroneously gave the answer “50” to the operation “35 + 17” and then subsequently recalled “50,” a correct response was recorded. If a child was successful in recalling totals from two of three trials, the number of operations to be calculated—and, therefore, of the totals to recall—was increased by one. However, if the child did not recall the totals correctly on more than one of three trials, the span testing was discontinued for that condition. After a short break, testing resumed in the other condition. Operation span (in this...
and subsequent experiments) was calculated as the maximum level at which recall was correct, with 0.5 points being added if a single trial at the next level was also correct. In addition, the number of correct answers (correct item in the correct serial position) in each remaining trial was calculated as a proportion of the number of items to be recalled. This value was multiplied by 0.5, and the product was added to the total score obtained from the procedure above.

Results

The data for 3 children from the younger age group who were unable to calculate the carry operations were excluded from the analysis, leaving scores for 30 participants in the 7-year-old age group. Mean memory spans for the two types of operation, as well as reaction times and error rates, are shown in Table 1. Memory spans were higher for the 9-year-olds than for the 7-year-olds, but they did not vary markedly as a function of processing operation. A two-way analysis of variance (ANOVA) as a function of age and operation type was performed on the span scores. The analysis yielded a significant main effect of age, $F(1,59) = 22.48$, $MSE = 8.16$, $p < .001$, partial $\eta^2 = .276$, with mean operation span higher in the 9-year-olds (2.18) than in the 7-year-olds (1.66), but no significant effect of span, $F(1,59) = 0.37$, $MSE = 0.09$, $p > .05$, partial $\eta^2 = .006$, and no interaction, $F(1,59) < 1$, partial $\eta^2 = .001$.

A corresponding ANOVA was performed on the calculation speed scored for each child as a function of duration and age. There was no significant difference in speed as a function of type of operation, $F(1,59) = 0.002$, $MSE = 0.06$, $p > .05$, partial $\eta^2 = .001$. The older children were significantly faster than the younger children on this measure, $F(1,59) = 929.62$, $MSE = 15,287.73$, $p < .001$, partial $\eta^2 = .94$. The interaction between operation type and age was nonsignificant, $F < 1$, partial $\eta^2 = .001$.

The error rate was higher in the carry condition (20.67%) than in the simple condition (6.03%). Because of the non-normal distribution of error rates, these data were tested statistically using the Wilcoxon test. The increased rates of error in the carry condition compared with the simple condition were statistically significant for both the 7-year-olds, $z = 4.38$, $p < .001$, $r = .56$, and the 9-year-olds, $z = 4.10$, $p < .001$, $r = .52$. Finally, the correlation between processing speed and mean span for both types of task was significant, $r = -.43$, $p < .001$. This finding replicates previous findings (e.g., Hitch et al., 2001; Towe et al., 1998) that processing times were related to storage, and it is consistent with both trade-off and time-based forgetting accounts.

Table 1
Mean span performance, reaction times, and calculation errors of the 7- and 9-year-olds for simple and carry sums in Experiment 1

<table>
<thead>
<tr>
<th>Simple sums</th>
<th>Carry sums</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 years</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Span</td>
<td>1.69</td>
</tr>
<tr>
<td>Reaction time (seconds)</td>
<td>14.57</td>
</tr>
<tr>
<td>Errors (per 100 items)</td>
<td>7.89</td>
</tr>
</tbody>
</table>
Discussion

More errors were made for the calculations involving carrying sums than simple sums, indicating that the computations were more difficult. However, span did not differ across the two conditions, and calculation speeds were equivalent between the two conditions. These findings are not consistent with a simple resource-sharing account of working memory, according to which operation span should decrease in the carry condition as a consequence of the increased processing demands of the task. The results from this experiment instead favor the task-switching account advanced by Towse and colleagues (e.g., Hitch et al., 2001; Towse & Hitch, 1995). According to this account, in the course of complex memory span tasks, individuals alternate between processing (in this case, making an arithmetic calculation) and storage. An important factor in memory performance is the time taken to carry out the processing activity, during which the memory representations are lost (either through decay or through some other forgetting mechanism). Because processing times were equivalent for both types of operation in the current experiment, comparable levels of performance in the two conditions would indeed be expected.

Findings by Barrouillet and Camos (2001, Experiment 3) do, however, suggest that processing demands play a role in operation span performance. These authors made an important modification to the complex span paradigm. Rather than using two temporally matched conditions in which processing difficulty is varied, operation span performance was compared with a condition in which participants merely suppressed articulation for a corresponding period of time. Complex span for consonants was significantly poorer when the intervening activity involved arithmetic calculations than when it involved articulatory suppression. On this basis, Barrouillet and Camos suggested that a critical factor constraining performance on complex span tasks is the extent to which the processing task is demanding of attention over a set duration (see also Barrouillet, Bernadin, & Camos, 2004). Specifically, they argued that mental arithmetic demands sustained attention due to multiple memory retrievals, whereas articulatory suppression does not; therefore, the latter has a far more disruptive effect on the concurrent maintenance of items in memory due to greater temporal decay.

Towse, Hitch, and Hutton (2002) advanced an alternative account of the Barrouillet and Camos (2001) findings. They pointed out that mental arithmetic and articulatory suppression differ not only in the extent to which they demand effortful processing, and hence limited attentional resources, but also in the extent to which they impose substantial storage demands. Whereas storage of interim products of calculations is a key feature of arithmetic calculations involving carrying operations, articulatory suppression has no obvious storage requirement. Perhaps, then, the lower complex memory spans associated with mental arithmetic compared with suppression arise from storage-related interference processes.

Experiment 2 was designed to distinguish between the influences of processing and intrinsic storage demands of interpolated tasks on complex memory span performance in children. Memory span was compared for three processing tasks that varied in their processing and intrinsic storage demands. Mental arithmetic involving carry
operations imposes significant demands on both attention and storage. Articulatory suppression involving the repeated production of a single verbal item requires minimal processing and no intrinsic storage. A third processing activity imposed significant demands on attention but not on storage. This task involved judging whether each of a series of two-digit numbers is odd or even and required access to stored knowledge of the numerical status of each digit but no short-term storage of successive numbers or of their odd/even status.

According to resource-sharing accounts such as that provided by Case (1985), memory span is inversely related to processing difficulty and, therefore, should be lowest in the mental arithmetic condition, higher in the odd/even condition, and highest in the articulatory suppression condition. In contrast, the attentional resources account (Barrouillet & Camos, 2001) would predict equivalent performance in the odd/even and operation span conditions because the attentional demands of these two tasks both are significant. The suppression condition, however, should yield the highest span because there are few processing requirements, if any, in this condition. In contrast, a finding that performance was greater in the odd/even condition than in the mental arithmetic condition would be entirely consistent with the proposal by Towse and colleagues (2002) that memory span is impaired under conditions in which the processing task has its own competing memory demands. To investigate whether differences in processing requirements, rather than differences in the time taken to execute the task, lead to differences in span, the periods during which children were engaged in the processing activities were equivalent across all three conditions. Once again, age groups of children were tested (7- and 9-year-olds) to establish the generality of findings across age.

**Experiment 2**

**Method**

**Participants**

A total of 63 children from Year 3 ($n = 32$, mean age 7 years 7 months, range 7 years 5 months to 8 years 4 months) and Year 5 ($n = 31$, mean age 9 years 7 months, range 9 years 3 months to 10 years 1 month) of a local primary school in Stockton-on-Tees, participated in the experiment. The children had not taken part in Experiment 1.

**Design**

A two-way mixed design was employed, with age (7 or 9 years) as a between-subjects factor and type of interpolated task (arithmetic, odd/even judgment, or articulatory suppression) as a within-subjects variable. Span scores were calculated as in Experiment 1. The numbers of errors in the mental arithmetic and odd/even conditions were also scored.
Tasks and procedure

Following the task design in Barrouillet and Camos’s (2001) study, tasks were administered in two sessions to match exactly the durations of the individual processing tasks. Therefore, the task administered in Session 1 was always the operation span task, the odd/even task and articulatory suppression task were conducted in Session 2, and the design was counterbalanced by task order for these two tasks. The sessions were 3 weeks apart. Each session lasted a maximum of 20 min and began with a practice task. Fig. 1 illustrates the task design with the interpolated task requirements.

**Mental arithmetic span task**

For this task, the stimuli were taken from the carry sums in Experiment 1. That is, problems consisted of the addition of two two-digit numbers that involved a carry operation of the units (e.g., $28 + 16$). The children were required to work out and answer a problem that was displayed on a computer screen. As soon as the answer was given aloud, a new sum appeared on the screen (initiated by a key press by the experimenter). The reaction time for each operation was recorded electronically. At the end of a series, the children were requested to recall, in order, the answers calculated.

**Odd/Even span task**

For the odd/even task, a series of two-digit numbers (randomly generated by the computer) were presented on the computer screen for a period of 1 s each (black num-

![Fig. 1. Schematic representation of the task design in Experiment 2. The rectangles represent the interpolated task. Session 1 required the calculation of addition operations. Session 2a required the participants to decide whether the number presented was odd or even. Session 2b required the participants to suppress articulation by repeating the word “the.” The circles show the items to be remembered and recalled. The interpolated tasks in Session 2 were temporally equivalent to the task in Session 1.](image-url)
bers on a white background). The children were required to state aloud whether each number was odd or even. The duration of the series was determined by the amount of time each child had taken in the corresponding arithmetic task. For example, if it had taken a child 10 s to calculate the sum 28 + 16 in the arithmetic span task in Session 1, a series of numbers (judged by the child to be odd or even) would be displayed on the computer for 1 s per number for a total of 10 s. At the end of this time period, a black number was displayed prominently on a red background for 1.5 s. This was the item to be remembered and subsequently recalled. Another series of random numbers to be judged odd or even was then displayed for as long as it had taken that child to calculate the corresponding arithmetic operation before the second memory item was displayed. The child was then requested to recall the memory items in the correct order.

Articulatory suppression span task

This task differed from the odd/even task only in that where random numbers had been presented in the odd/even task, this condition required the children to suppress articulation by repeating the word “the” (at approximately one “the” per second) while looking at a blank screen. Again, the suppression duration was matched in time with each child’s corresponding arithmetic calculation duration. At the end of this time period, a two-digit number was presented on the screen for 1.5 s before the screen went blank again and the child was again required to suppress articulation. Thus, for each child in each series, the retention period was identical in all three tasks.

Results

Table 2 shows mean span performance (and error rates for the odd/even and operation span conditions) of the 7- and 9-year-olds for the different types of interpolated task. Memory span scores were highest for the articulatory suppression condition, at an intermediate level for the mental arithmetic condition, and lowest for the odd/even condition for both age groups. A two-way mixed ANOVA as a function of age and interpolated task was performed on the span scores. The results show a significant improvement in span with age, $F(1, 61) = 2812.03, MSE = 744.27, p < .001$, partial $\eta^2 = .98$, and a significant main effect of task, $F(2, 122) = 84.51, MSE = 16.30, p < .001$, partial $\eta^2 = .58$, but no interaction, $p > .05$, partial $\eta^2 = .006$.

Table 2
Memory span performance of the 7- and 9-year-olds for the different types of interpolated tasks, as well as processing errors for the odd/even and mental arithmetic conditions, in Experiment 2

<table>
<thead>
<tr>
<th>Interpolated task</th>
<th>7 years</th>
<th>9 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Memory span</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mental arithmetic</td>
<td>1.64</td>
<td>0.39</td>
</tr>
<tr>
<td>Articulatory suppression</td>
<td>2.30</td>
<td>0.44</td>
</tr>
<tr>
<td>Odd/Even judgment</td>
<td>1.32</td>
<td>0.25</td>
</tr>
<tr>
<td>Processing errors (per 100 items)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mental arithmetic</td>
<td>22.27</td>
<td>21.69</td>
</tr>
<tr>
<td>Odd/Even judgment</td>
<td>3.94</td>
<td>6.05</td>
</tr>
</tbody>
</table>
Simple effects of task were explored in a series of one-way within-subjects ANOVAs for each age group. The effect of task was significant for both the younger children, $F(2, 62) = 65.28$, $MSE = 7.73$, $p < .001$, partial $\eta^2 = .68$, and the older children, $F(2, 60) = 31.98$, $MSE = 8.63$, $p < .001$, partial $\eta^2 = .52$. Planned contrasts showed that for each of the age groups, performance on the odd/even span task was significantly poorer than performance on both the arithmetic span task and the articulatory suppression task ($ps < .01$) and that performance on the articulatory suppression task was also significantly better than performance on the arithmetic span task ($ps < .01$).

Errors for the odd/even and operation conditions were analyzed using the Wilcoxon test due to the non-normal distribution of the data. There were significantly more processing errors in the arithmetic condition (16.71%) than in the odd/even condition (3.50%), $z = 5.00$, $p < .001$, $r = .63$. This difference was significant for both the 7-year-olds, $z = 3.93$, $p < .001$, $r = .69$, and the 9-year-olds, $z = 3.03$, $p < .01$, $r = .54$.

**Discussion**

In both age groups, span performance varied significantly according to the nature of activity performed during the interval between memory items despite the temporal equivalence of conditions. The articulatory suppression condition yielded higher spans than did both the mental arithmetic and odd/even conditions, and the lowest levels of performance were found in the odd/even condition.

The span advantage when the interpolated task involved articulatory suppression, as compared with mental arithmetic, replicates Barrouillet and Camos’s (2001) findings and is consistent with their view that attentionally demanding processing activities divert limited attentional resources from storage and, hence, lead to accelerated temporal decay (Barrouillet et al., 2004). However, the lower levels of span performance observed in both age groups in the odd/even condition than in the mental arithmetic condition do not readily fit with any existing theoretical account. First, because both processing activities are attention demanding, with mental arithmetic demanding attention to an extent that is at least equivalent to—and probably more demanding than—the odd/even judgments, either comparable levels of performance or an advantage to the odd/even task would be expected according to Barrouillet and colleagues (2004). Second, and relatedly, the decrement in odd/even span cannot be explained in terms of greater processing demands leading to reduced availability of storage according to a trade-off account (Case, 1985). Third, the span advantage to mental arithmetic over odd/even cannot be explained in terms of differences in intrinsic storage demands (Towse et al., 2002) because these are greater in the former task than in the latter task. Finally, the temporal equivalence of all three processing conditions rules out any account in terms of differences in temporal decay (Towse & Hitch, 1995).

One possibility is that the unexpected finding of lower span scores in the odd/even processing condition than in the mental arithmetic condition may have reflected differences in task structure rather than processing or storage demands. Whereas the mental arithmetic condition was self-paced, participants in the odd/even condition were required to make parity judgments at an externally determined rate of one num-
ber per second. There is recent evidence that external pacing does have a more disruptive effect on complex span than does self-pacing, probably due to its disturbance of optimal switching strategies (Barrouillet et al., 2004).

Therefore, Experiment 3 was conducted to determine whether the differences in memory span across the mental arithmetic and odd/even conditions would persist if the pacing requirements of the two processing activities were equated. In Experiment 2, only the mental arithmetic condition was self-paced. In Experiment 3, both the mental arithmetic and odd/even tasks were self-paced, with presentation of successive items for processing being initiated by the children’s response to the previous item. A finding that the performance cost to odd/even judgments over mental arithmetic persists in this experiment would rule out the possibility that differences between these two conditions in Experiment 2 reflected the varying pacing requirements of the tasks.

Experiment 3

Method

Participants and design

A group of 9-year-olds (N = 42, mean age 9 years 8 months, range 9 years 1 month to 10 years 2 months) was recruited from a local school to participate in the experiment. Given the absence of any age-related interactions in the previous experiments, the sample was composed of children of a single age group. Type of interpolated processing task (mental arithmetic or odd/even judgment) was the independent variable. Span scores were calculated in each condition, and additional measures were taken of numbers of items processed and processing accuracy.

Materials and procedure

The experiment was conducted using a laptop computer programmed to control presentation durations. The tasks were presented on a 13-inch color monitor, with the processing items being colored black and the storage/memory items being colored red. All items were presented in black 72-point Arial font against a white background. The interpolated processing task took place within an 8-s window under a response-based presentation format. Specifically, in the mental arithmetic condition, the children were presented with a simple operation (e.g., 12 + 3 = ?) and required to calculate the answer, with an additional problem being presented each time the total was spoken aloud (initiated by a key press by the experimenter). This allowed for continuous processing throughout the 8-s window. At the end of the processing phase, a two-digit number (randomly generated by the computer) was displayed prominently in red on the screen for 2 s. This was the item for retention and subsequent recall. Another processing phase then commenced for a duration of 8 s, followed by the presentation of an additional memory item. As before, trials were
increased by one if two of three items were recalled correctly. Similarly, during the processing phase of the odd/even condition, numbers were presented in reaction to the children’s spoken responses for an overall maximum of 8 s.

**Results and discussion**

Mean span in the mental arithmetic condition was 2.07 ($SD = 0.68$), and mean span in the odd/even condition was 2.19 ($SD = 0.72$). No significant differences in memory span were found across the two conditions, $t(41) = 1.33, p > .05, d = .17$. In addition, there were no differences in the number of items processed in either of the conditions, $t(41) = 1.71, p > .05, d = .17$ [mean number of additions: 5.62 ($SD = 1.55$); mean number of digits assessed: 6 ($SD = 1.38$)], indicating that the tasks captured attention in a comparable manner.

Across these two conditions, the same number of items was processed during the same period of time under conditions of self-pacing. In the odd/even task, such retrievals took the form of accessing stored knowledge of the numerical status of each digit, whereas in the operation span task, each sum involved a sequence of simple additions. The elimination in the current experiment of memory span differences across these two conditions found in Experiment 2 indicates that such differences arose from variations in task pacing.

It should be noted that the mental arithmetic task involving carrying operations in Experiment 2 was changed to that of successive addition of simple sums in Experiment 3, corresponding to the procedure adopted by Barrouillet and colleagues (2004). In line with these authors’ findings that the complexity of arithmetic computations per se has no effect on complex span, span levels were very similar for the 9-year-old groups in Experiment 2 (2.07) and Experiment 3 (2.17).

Finally, a correlational analysis of the association between span scores and number of items processed was conducted to examine whether the length of time taken to process individual items was linked to span performance. The two measures were highly correlated with one another, $r(40) = .70, p < .01$, indicating that children who processed most items typically had higher memory spans.

**General discussion**

The experiments reported here were designed to investigate the cognitive processes involved in children’s complex working memory span by manipulating the nature of the processing activity. In all three experiments, the time spent on the processing activity prior to recall was held constant, and the complexity and intrinsic memory demands of the processing activities were manipulated. In Experiment 1, span scores were found to be independent of the difficulty of mental arithmetic operations, with carry and simple sums yielding comparable spans despite differences in task difficulty as indexed by performance accuracy. In Experiment 2, three different processing activities were compared: mental arithmetic, odd/even judgments, and articulatory suppression. Span scores were highest for the articulatory suppression condition,
intermediate for mental arithmetic, and lowest for the odd/even task. However, in Experiment 3, when both the mental arithmetic and odd/even processing conditions employed self-paced rather than externally imposed presentation, differences between the two conditions were eliminated.

Overall, the results indicate that under conditions in which task duration is held constant, processing difficulty and intrinsic memory requirements have no effect on memory performance, in conflict with a basic resource-sharing account of working memory. The notion that working memory comprises a single flexible capacity that deals with both storage and processing demands (e.g., Case, 1985) cannot accommodate the absence of a task difficulty effect in Experiment 1, thereby challenging the notion that a more difficult task will result in a greater consumption of limited cognitive resource and, hence, a reduction in capacity for storage. These data do not, however, rule out the possibility that resource sharing plays a role in other working memory tasks, for example, when the processing portion of the task does not prevent the use of mnemonic strategies such as grouping of items and elaborate rehearsal (e.g., Cowan et al., 1998).

In Experiments 1 and 3, memory span performance was equivalent across different processing conditions conducted over matched time periods. Although this aspect of the results fits well with claims that storage period, and hence opportunity for time-based decay, is important (e.g., Towse & Hitch, 1995), it is clear that span is constrained by other factors as well. Performance was greater in the articulatory suppression condition than in either the mental arithmetic or the odd/even processing condition of Experiment 2, replicating earlier findings of Barrouillet and Camos (2001) and Barrouillet and colleagues (2004). The nature of the processing activity, therefore, clearly has significant consequences for complex span in children, as it does in adults.

The current findings cast new light on why different processing tasks are associated with different levels of span performance. The equivalence of memory span in the mental arithmetic and odd/even judgment tasks in Experiment 3 runs counter to the suggestion that lower spans associated with arithmetic processing than with articulatory suppression reflect the intrinsic storage demands of the former task (Towse et al., 2002) because there is no storage burden in the odd/even task. More direct experimental manipulations of memory demands of processing activities are needed, however, to provide stronger tests of the hypothesis that item storage in complex span paradigms is influenced by the storage demands of processing activities, particularly given that previous work suggests that intrinsic memory demands in some types of mental arithmetic can affect children’s working memory (Adams & Hitch, 1997).

Finally, the absence of significant age-related interactions in Experiments 1 and 2 provides no support for the notion of qualitative developmental change in the mechanisms underpinning complex span performance at these ages. At both 7 and 9 years of age, processing activities that impose significant processing demands resulted in lower span scores than did an undemanding processing task, articulatory suppression, despite temporal equivalence of the processing conditions.

In summary, the findings illustrate that complex span performance in children is mediated by a constellation of factors. Both the way in which complex span tasks
are combined and specific task requirements, such as processing duration, are important in shaping performance. Complex span in our experiments was impaired by processing activities that were attentionally demanding (mental arithmetic and odd/even judgments), but it was independent of the detailed nature of the processing involved within these activities. This pattern of findings fits well with Barrouillet and colleagues’ (2004) view that a critical determinant of complex span is the proportion of time available to refresh item representations and, therefore, that memory performance will be most impaired in tasks where limited attentional resources have to be frequently diverted to support processing activity. It is also clear that external pacing of processing tasks is particularly disruptive, presumably due to its disturbance of optimal strategies for switching between the processing and storage components of complex memory tasks or because it prevents the implementation of idiosyncratic strategies such as rehearsal (e.g., Friedman & Miyake, 2004; Towse et al., 2002).

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