On the nature of the relationship between processing activity and item retention in children

Running title: Forgetting with an interpolated task

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Abstract

The concept of working memory emphasises the interrelationship between the transient retention of information and concurrent processing activity. Three experiments address this relationship in children between 8 and 17 years of age, by examining forgetting when a processing task is interpolated between presentation and recall of the memory items. Unlike previous studies, delivery of interpolated stimuli was under computer control and responses to these stimuli were timed. There were consistent effects of the duration of the interpolated task, but no effects of either its difficulty or similarity to memory material, and no qualitative developmental differences in task performance. The absence of an effect of difficulty provides no support for models of working memory in which limited capacity is shared between the dual functions of processing and storage, but is compatible with an alternative 'task-switching' account. However, task-switching did not explain developmental differences in recall. Other aspects of the results suggest that there can be interactions between processing and storage but it is argued that these cannot be straightforwardly explained in terms of either task-switching or resource-sharing.

Key Words: working-memory, children, resource-switching, forgetting.

On the nature of the relationship between processing activity and item retention in children

The success of the concept of working memory (Baddeley, 1986; 1996) lies partly in its simplicity, and partly in its multi-faceted nature. As a framework, it encourages a focus on the relevance of retention for cognition. Thus, working memory serves important functions, and is more than a simple, transient, repository of episodes. Yet the term working memory also refers to a rather daunting panoply of different theoretical ideas. It has been deployed variously as synonymous with short-term memory, a historical successor to short-term memory, a general framework, an architectural constraint of artificial processing systems or a component of long-term memory (see Miyake & Shah, 1999 for additional examples). Furthermore, although Baddeley (1986) views working memory as a multi-component system, other models regard it as a unitary system (Just & Carpenter, 1992). This paper focuses on a theme common to many of these approaches, namely, working memory as a limited capacity system supporting activities that combine memory for current information with ongoing processing (e.g., Daneman & Carpenter, 1980). Three experiments assess the idea that working memory capacity corresponds to the size of an arena within which processing and memory functions compete, by examining evidence for a trade-off between resources for processing and retention in working memory. The idea of such a trade-off is central to some influential accounts of cognitive development. For example, according to Case (1995), as children develop they require a smaller amount of a central workspace to support processing operations. As a result of trade-off, more of the workspace becomes available for temporary storage, and this in turn allows successful performance of increasingly complex cognitive tasks. Accordingly, the present experiments investigated the relationship between processing activity and item retention in children.

Daneman and Carpenter (1980) were the first to emphasise a distinction between short-term memory tasks, for example word span, and working memory tasks, such as reading span.

In a word span task, individuals encode a sequence of items, normally presented at a regular pace, which they subsequently attempt to repeat. In a reading span task, individuals process a series of sentences for meaning - for example, by completing each sentence with a semantically acceptable word - and then attempt recall of these sentence completions. Thus, in a working memory span task, memory requirements are combined with – indeed, in one sense, emerge out of – ongoing mentation, whereas in a short-term memory task there is no concurrent processing. Differences between the tasks have been taken to suggest that they access different underlying processes. Tasks like word span are thought to depend heavily on phonological STM (Baddeley, 1986; Gathercole, 1999), whereas tasks like reading span have been assumed to reflect ‘central resources’ for combining processing and memory (Daneman, 1995; Engle, Kane & Tuholski, 1999; Just & Carpenter, 1992).

A demarcation of this type offers one explanation for why working memory tests often correlate with high-level cognition to a significantly greater extent than short-term memory tasks (Daneman & Merikle, 1996). However, there are a number of potential complications (e.g., Hutton & Towse, 2001; Kail & Hall, 2001; Oberauer & Kliegl, 2001). One particular concern is over-dependence on the widely-used working memory span paradigm, which is typically assumed to measure a capacity for resource sharing (Case, Kurland & Goldberg, 1982; Daneman & Carpenter, 1980; Just & Carpenter, 1992). Yet, when this assumption has been carefully scrutinised, it has been seriously challenged (Duff & Logie, 2001; Towse & Hitch, 1995; Towse, Hitch & Hutton, 1998). For example, in a study of 6 to 11-year-old children, Towse and Hitch (1995) found no significant differences on working memory spans with tasks that differed in difficulty once they were matched for processing duration, for any age group. As an alternative, Towse and colleagues advocated a simplistic 'task-switching' model of working memory. According to this model, processing demand does not influence memory via the trading-off of memory and processing resources. Rather, memory deteriorates over intervals spent ‘switched out’ of memory functions, when occupied by the processing requirements of the task. The important question then arises whether other paradigms, that have been argued to reflect an interaction between processing load and immediate retention, offer convincing evidence for a resource trade-off.

Seminal research by Posner and Rossman (1965) employed an interpolated task paradigm to explore the impact of processing difficulty on the retention of information. Posner and Rossman presented adults with pairs of digits. The first pair was to be remembered, while others required transformations to be performed on them. Different transformations provided interpolated tasks designed to differ in processing demand, as measured by information reduction. For example, in their first experiment, the interpolated tasks ranged from easy (writing each pair of digits in reverse order) to hard (classifying each pair as type “A” if it is high (>50) and odd or low (<50) and even, and type “B” otherwise). Overall, Posner and Rossman’s data showed that retention declined as a function of processing demand for any given retention interval. This effect of processing load was taken to signal the interdependence of memory and processing through competition for a shared limited capacity.

There is a substantial literature based on the Posner and Rossman paradigm, sometimes involving intricate experimental manipulations. However, data relating to children’s performance are much more sparse. Halford, Maybery, O'Hare and Grant (1994) provide an important exception. They studied 8- and 9-year-olds in situations that approximated to the interpolated task format, but concluded that there was little evidence of a trade-off between processing load and memory (i.e., variation in processing load had little effect on recall of a short-term memory preload). Whilst the Halford et al. findings are inconsistent with those of Posner and Rossman, they are compatible with the task-switching model which predicts that recall of a preload will not be a function of the difficulty of interpolated processing. The present experiments on children are conceptually similar to those of Posner and Rossman (1965), and Halford et al. (1994), and amongst other issues consider whether the results from these papers differ because of developmental differences. Thus they re-address the relationship between memory and interpolated processing but include a number of potentially important procedural differences.

First, we consider more extensively the developmental trajectory of the relationship between the difficulty of interpolated processing and recall. Towse et al. (1998) suggested that there might be a developmental transition away from task-switching and towards resource-sharing. This is plausible given marked developmental changes in strategies such as rehearsal (Gathercole, 1999; Hitch & Halliday, 1988). However, because Halford et al. (1994) and Posner and Rossman (1965) used different tasks it is not safe to conclude that their results reflect a developmental change towards resource-sharing. The present research explores the extent of developmental change between the ages of 8 and 17 using the same tasks and materials for all participants. Although recent data from the working memory span paradigm discourage the view that resource-sharing emerges during development (e.g. Hitch et al., 2001; Towse, Hitch & Hutton, 2000), the interpolated task paradigm may provide a more sensitive test. By design, span only measures the point at which memory falls below some pre-set threshold; it is less suitable for the investigation of performance lying somewhere between ceiling and floor. Moreover, using the interpolated task paradigm, Halford et al. (1994) reported that processing operations were slowed down by a short-term memory load, with this effect greater for older children. This might be interpreted as evidence for the development of resource-sharing.

An added advantage of the interpolated task procedure is that item presentation can be controlled to a greater extent than in working memory span tasks, where the memory items are the products of sequential processing activities that are essentially under the participant's command. The present experiments involved computerised presentation so that a participant's response to one interpolated stimulus immediately cued presentation of the next. Continuous presentation for the interpolated task is potentially important because gaps between stimuli provide the opportunity for consolidation strategies including rehearsal (see Dillon & Reid, 1969, where rehearsal between interpolated stimuli was explicitly encouraged). However, we do not claim that computerised presentation guarantees rehearsal-free performance (indeed, we will present evidence for rehearsal in the final study). An equally important feature of computerised presentation is that it facilitates the monitoring of interpolated task performance. For example, Halford et al. (1994; Expt. 1 & 2) claimed that different tasks were matched for duration but did not cite data confirming this. Finally, to provide a more complete description of performance, the present experiments also manipulate interpolated task duration.

Use of an interpolated task paradigm circumvents some individual-difference effects in the time period over which working memory span processes are completed. Hitch et al. (2001, Fig. 2) illustrate the potential extent of these. Even within each age group, their slowest children took at least twice as long to process each stimulus as their quickest children, with some differentials substantially greater than this. In the interpolated task paradigm, one can fix processing time. Thus, children who work slowly receive fewer stimuli over that period. This in turn permits an analysis of the relationship between processing speed and memory, that is whether the number of stimuli processed affects retention (Case, personal communication, 1994). Interference from processing computations may be a function of the number of such computations, each processing event generating interference. If so, children who make more interpolated decisions in a particular period of time may be subject to more interference.

As a further experimental motivation, consider an extreme version of the task-switching model, according to which memory development can be explained entirely by reference to the processing speed advantage enjoyed by older children (see also Kail, 2000). Although we do not favour such an interpretation (Hitch et al., 2001), to the extent that it is tenable, it predicts that children at different ages will show the same forgetting profile as a function of the duration of a filled retention interval. Since the working memory span paradigm does not lend itself to analysis of performance at different retention intervals, it cannot be used to address this question.

Experiment 1

This study investigates whether the type of interpolated task affects the rate of forgetting, as predicted by Posner and Rossman (1965) but not Halford et al. (1994). To vary task type, children were required to perform integer addition or multiplication as the interpolated task. Multiplication is a skill that is learnt later than addition, appears subjectively more effortful, and likely involves less routine response procedures[1]. The experiment also examines age differences; Towse et al. (1998) speculated that there might be a developmental transition away from task-switching towards resource-sharing (but see Towse et al., 2000). Finally, the experiment analysed individual differences in processing speed to assess whether the 'dosage' of interfering activity affects the ability to recall items over a given time period. Is there a penalty to be paid for being a fast processor, by dealing with more cognitive events (these events interfering with the quality of internal representations)? Such a finding would pose a challenge to Towse et al. (1998), who argue for the functional independence of retention and ongoing processing.

Method

Participants and Design

There were 123 children, segregated into 6 age groups by school class; see Table 1. Except for the youngest age group, all children completed memory trials with addition and

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[1] We shall have more to say about this manipulation later, but discussion will be facilitated by the availability of data.

multiplication as intervening activities in separate testing blocks. The youngest children experienced only addition trials. The duration of the interpolated activity (6, 11, or 16 seconds) was manipulated as a within-subject factor.

--------------------------------------- Table 1 about here ---------------------------------------

Procedure

Children were tested individually in a quiet area of their school. The experimenter introduced the task running on a Macintosh Powerbook 5300c computer, framed in terms of a secret agent game. Children took the role of a commander, with responsibility for sending signals to two pictured agents who worked under their control. An arithmetic equation appeared in a centrally placed screen window (called the 'home base'). When the equation was correct (e.g., 5+2=7), children sent a signal to one secret agent (labeled ‘Yes’) by clicking on the agent's image with a mouse. When the equation was incorrect (e.g. 3+4=8), children sent a signal to the other agent (labeled ‘No’) instead. A large green tick or a red cross over the selected agent provided feedback, and remained visible until a subsequent decision was made. Children also learned that occasionally a single digit appeared in the home base window. When this happened, children clicked the mouse cursor over a 'top secret' folder, spatially adjacent to the secret agents. Subsequently, children attempted to remember the digits they had placed in the top secret folder (see below). Instructions emphasised that children should avoid sending the wrong signals to their agents and that they should work as quickly as possible. They were also told not to say anything while they made their decisions. At the end of each trial, children received visual feedback about the number of correctly dispatched signals to agents. There were four practice trials involving arithmetic decisions only, allowing children to familiarise themselves with the response process.

The sorting task involved either addition problems or multiplication problems, presented as two separate games in counterbalanced order. For approximately half of the problems, the stated answer was correct (e.g., ‘2 + 8 = 10’, ‘4 x 8 = 32’). When the answer was incorrect, it was either close to the true answer (‘2 + 8 = 9’, ‘4 x 8 = 24’), or more distant (‘2 + 8 = 10’, ‘4 x 8 = 21’) with incorrect answers distributed above and below the true value. In the case of multiplication, incorrect answers were always correct responses to an alternative multiplication question (for the stimulus pool, see Towse, Hutton & Hitch, 1998).

Figure 1 presents a simplified schematic of the trial sequence. The memory stimuli, three non-repeating digits, were preceded by between one and three arithmetic problems (this was chosen at random), so that the memory task was embedded in a stream of processing events. Following presentation of the memory items, further arithmetic problems were displayed until 6, 11, or 16 seconds had elapsed (this experimental factor varied quasi-randomly across trials). When the prescribed retention interval was reached, the problem on display remained on-screen until it was solved, and was followed immediately by the recall cue. Thus, the actual retention interval equated to the nominal retention interval plus the delay while the child responded to the final problem. Children recalled verbally and the experimenter typed their responses into the computer, which provided feedback on serial-order accuracy. There were five trials for each experimental condition. Among 12-, 14- and 17-year-olds, the two arithmetic tasks were administered in a single session. Among 9- and 11-year-olds, each interpolated task was undertaken in a separate session separated by no more than 7 days, to maintain task concentration and motivation for these younger children.

--------------------------------------- Figure 1 about here ---------------------------------------

Results

To facilitate presentation, we focus here on memory performance, and merely summarise interpolated task performance (considered in more detail in the appendix; see also Towse, Hutton & Hitch, 1998). Effect sizes and statistical significance are reported.

Addition as the interpolated task.

One hundred and twenty three children completed the memory task with addition problems as the intervening cognitive activity. In the main, older children made quicker response decisions, therefore completing a greater number of problems at each retention interval, and experiencing shorter overall trial times. However, because some children frequently made computational errors, data were screened, retaining only those children for whom the ratio of correct to incorrect responses exceeded the 95% bounds estimated from a normal approximation to the Sign test (Sachs, 1978). This left 108 children in the data set, although analyses with the full complement of participants produced the same results. Analysis of variance on the proportion of items correctly recalled with age and nominal retention interval as factors, confirmed a significant effect of age, $F(5, 102) = 2.98$, $p<.05$, partial $\eta^2 = .127$ and retention interval, $F(2, 204) = 5.53$, $p<.01$, partial $\eta^2 = .051$, but no interaction, $F<1$, partial $\eta^2 = .028$, see Figure 3. The linear trend for retention interval was significant, $F(1, 102)=11.05$, $p<.01$, partial $\eta^2 = .098$, but the quadratic trend was not, $F<1$, partial $\eta^2 <.001$. Finally, analysis of individual difference revealed a modest, *positive* correlation between memory performance and number of interpolated decisions made, $r(106) = .326$, $p<.01$.

Multiplication as the interpolated task

Ninety-nine children performed multiplication as the interpolated task. Again, older children responded more quickly, and so completed more problems. Prior to analysis of recall data, children were screened for accuracy on multiplication (though analyses with all participants replicated the pattern of results). Figure 2 illustrates performance among the remaining 70 children. Analysis of variance confirmed significant effects of age, F(4,65) = 3.33, $p < .05$, partial $\eta^2 = .167$, and retention interval, F(2, 130) = 4.83, $p = .01$, partial $\eta^2 = .069$ but there was no interaction, F < 1, partial $\eta^2 = .043$. As for multiplication, the relationship between memory performance and the number of interpolated decisions was positive, but in this case it fell far short of significance, r(68)=.09.

--------------------------------------- Figure 2 about here---------------------------------------

Comparison between interpolated tasks

Seventy children completed both addition and multiplication conditions and reached threshold accuracy criteria. Analysis of the number of problems solved showed an effect of age, F(4, 65) = 21.25, $p < .01$, partial $\eta^2 = .567$ and task, F(1, 65) = 16.6, $p < 01$, partial $\eta^2 = .203$, with more addition problems completed than multiplication problems. Age and task did not interact significantly, F < 1, partial $\eta^2 = .024$. Overall, the data confirm that multiplication was the harder task. Thus, as well as taking longer, more children failed to meet inclusion criteria, and multiplication problems produced a higher error rate (15.8% of trials vs. 7.54%), t (69) = 5.48, $p < .01$, $\eta^2 = .303$.

Table 2 describes recall accuracy, pooled over age groups, as a function of whether the interpolated task was addition or multiplication, and retention interval. A three-way (age x task x retention interval) analysis confirmed the effect of age, F(4, 65) = 2.75, $p < .05$, partial $\eta^2 = .145$ and the effect of interpolated task duration, F(2, 130) = 12.5, $p < .01$, partial $\eta^2 = .166$. However, there was no reliable evidence that type of interpolated activity influenced memory accuracy, F < 1, partial $\eta^2 = .003$. All interactions were non-significant, Fs <1, partial $\eta^2 < .048$. Furthermore, these results were also replicated when using data from all children. Analysis of individual differences in processing speed indicated no significant relationship between memory accuracy and number of interpolated decisions, r(68)=.04.

-------------------------------------- Table 2 about here--------------------------------------

Further analysis of memory and the interpolated task

As an alternative method of analysing whether there is any contingency between performance on the interpolated task and retention, recall at the 11 seconds retention interval was studied for the full complement of children. A comparison was made of trials when all sums were verified correctly, and trials when at least one sum was verified incorrectly. As this involves a response-contingent analysis, some participants did not provide data in both conditions. Figure 3 describes the distribution of correct recall proportions for the addition task. The upper panel describes recall when sums were completed correctly, the lower panel reflects (the less frequently obtained) recall performance after errors in the addition task. Given the distribution, response profiles of children with data for both conditions were compared with a Wilcoxon test. Recall was less successful when an addition verification was incorrect, $\underline{z} = 2.21$, $\underline{p} < .05$. Analyses on multiplication task data, see Figure 4, showed no corresponding difference, $\underline{z} = .72$.

-------------------------------------- Figure 3 & 4 about here --------------------------------------

Discussion

To the extent that recall was unaffected by the nature of the intervening activity, the data fail to support resource-sharing models of working memory. That is, addition and multiplication tasks resulted in the same levels of retention for memory items, despite substantial differences in the speed and accuracy of these operations. Older children showed higher levels of recall, but age effects (which were not monotonic) did not interact with the nature of the intervening activity. Thus, there was no support for the hypothesis that resource-sharing emerges during the course of development. In terms of individual differences, children who solved more problems during the retention interval tended to produce better memory performance, although only in the case of addition was this significant. There was also some evidence that forgetting was greater on trials in which errors were made on the interpolated task , but this was only observed for addition. Thus, the only consistent factor to affect recall was the duration of the retention interval.

This importance of the duration for which memory items must be maintained and the unimportance of the difficulty of interpolated processing operations is compatible with the task-switching model of working memory (Towse et al., 1998), extending its purview to situations where the memory stimuli are separate from, but concurrent with, ongoing cognition. Less anticipated, the decline in retention over time was comparable between the ages of 8 and 17 years of age. One important caveat to this conclusion is that the amount of forgetting was not particularly dramatic. Thus, there was only a restricted opportunity for developmental variations in the forgetting function. Furthermore, there was not a clear and consistent pattern of developmental change. One reviewer of this paper pointed out that 9 and 11-year-old children were tested over two sessions, whereas older children took one session. One post-hoc explanation for the relatively poor performance of 12-year olds, then, is that they in particular struggled with the single test session demands. A further potential consideration is that some paradigms may allow older children to reap greater benefits from their processing speed advantage, either to reach the recall phase sooner (e.g. in working memory span) or to have longer unfilled intervals between the encoding of stimuli (e.g. in short-term memory tasks with fixed presentation rates). In the present study, such opportunities were reduced. Notwithstanding this point, the task-switching model is largely silent about these developmental differences in memory performance. Age differences in recall were found despite roughly controlling the experienced retention durations of memoranda, pointing to the contribution of additional factors in developmental change.

We have suggested that the equivalence of memory performance following both addition and multiplication tasks is problematic for the notion of general resources shared between processing and storage (e.g., Daneman & Carpenter, 1980). Perhaps, though, the results simply indicate that it is misleading to use processing time and accuracy – which pointed to multiplication as being a more demanding task – as markers of ‘task difficulty’? These variables may signal a difference in cognitive processing, but this could arise from additional or more error-prone processing routines and computations, that are not inherently more 'resource demanding'. Yet, this argument is circular (Allport, 1980) - whenever a manipulation affects processing but not memory performance, (as here) it is assumed that the manipulation is not observably resource-demanding but just resource different. Whenever a task manipulation does affect memory it is assumed to arise from a shift in resource allocation. With resources being an abstract concept, the issue becomes quite intractable. Thus, without an independent yardstick for judging resource expenditure (other than time and accuracy as used here) one has to question the value of this conceptual approach.

One aspect of the present data is suggestive of an interaction between processing operations and memory storage, namely the observation that recall was poorer when children made an error on the interpolated task. This observation was made for addition but not multiplication and is considered in the General Discussion.

Experiment 2

The next study extends the interpolated activity to a non-mathematical domain by using a lexical decision task in which children indicated whether a stimulus was a real word. Task difficulty was varied by altering the non-words, which were either pseudo-homophones (e.g., ‘werme’) or non-homophones (e.g., ‘gled’). It was anticipated that pseudo-homophones would present a more demanding stimulus set because of children's use of phonological processing (see e.g., Arthur, Hitch & Halliday, 1994). The memory load comprised either words or digits, so as to allow an assessment of whether the similarity between items for recall and interpolated stimuli is relevant to performance. At issue, then, is the sensitivity of recall to retention interval, the difficulty of interpolated processing, and the overlap between memory items and the interpolated stimuli. A smaller age range was sampled because of the nature of the interpolated task and the results from the preceding study. To simplify task administration, only two retention intervals were employed (set at 4 and 14 seconds).

Method

Participants and Design

A group of 8-year-olds (18 children, mean age 8; 8, range 8;2 to 9;1) and a group of 10-year-olds (17 children, mean age 10; 8, range 10;2 to 11;1) were recruited. Two additional 10-year-olds were excluded because they were unavailable to complete all experimental conditions. Age and interpolated task (lexical decision with either pseudo-homophones or non-homophonic non-words) were between-subjects factors. Type of memory item (words or digits) and nominal retention interval (4 or 14 seconds) were within-subject factors.

Procedure

The task framework and general procedure were the same as in Experiment 1. In this case children had to send a signal by a mouse click over the relevant secret agent according to whether the item in the home base, printed in black on a white background, was a word (‘Yes’) or not (‘No’), with feedback provided on each decision. When the stimulus in the home base appeared in red on a blue background, children place it in the red ‘top secret’ folder. They were told that they would be asked to recall the secret information later. As an additional attempt to discourage rehearsal during the interpolated task, children were required to say ‘Yes’ or ‘No’ aloud as they responded to the lexical decisions with a mouse click.

The stimulus pool for lexical decisions comprised 40 words, 40 pseudo-homophones, and 40 non-homophonic non-words selected from the Arthur, Hitch, and Halliday (1994) corpus. The stimulus pool was subdivided into two sets by random assignment, and a sampling algorithm was developed to ensure that there were at least 20 responses separating any stimulus repetition (while some items did not repeat at all). The memory stimuli comprised four non repeating digits or, in an attempt to match retention levels, three words selected at random without replacement from the set cow, day, bar, leaf, hot, pen, man, doll, bus. Memory stimuli varied across trial blocks. Between 1 and 3 lexical decisions were made prior to the appearance of the memory items; then lexical decision stimuli re-appeared until 4 or 14 seconds had elapsed (this varied quasi-randomly across trials). Then, after a decision had been made for the current stimulus, the home base area turned brown and a message in the screen ‘status’ window cued verbal recall of the memory items. At the end of each trial, children received information on their recall accuracy and the number of agent messages dispatched. There were four practice trials with no retention requirement in which children had 8 sec to make as many lexical decisions as possible. Children received six experimental trials with each type of memory item at each retention interval.

Results

As before, the observed retention interval corresponded to the nominal interval plus the delay in completing the final lexical decision. However, in this study the elapsed time between onset of memoranda and the point of recall did not differ significantly across age groups or tasks[2]. Nonetheless, older children made more response decisions in the available time, and significantly more response decisions were made with non-homophonic than homophonic stimuli (mean=4.3 vs. 3.4 responses), $F(1, 31) = 5.40$, $p < .05$, partial $\eta^2 = .148$,

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[2] See appendix for more details of interpolated task performance.

although the corresponding effect using error rates (.8 vs. 1.4 errors per block) was not significant, F(1, 31) = 1.1, partial η^2 = .034. Overall, the nature of memory stimuli (whether words of digits) did not affect interpolated task characteristics.

The proportion of correct recalls, shown in Table 3, was examined as a function of age, interpolated task, retention interval and memory items. There was a marginally significant effect of age, F(1, 31) = 4.07, p = .052, partial η^2 = .116, a significant effect of retention interval, F(1, 31) = 16.8, p < .01, partial η^2 = .352, but no main effects of interpolated task, F < 1, partial η^2 = .014 or memory items, F < 1, partial η^2 = .023. All other effects were non-significant, including therefore, the interaction between task difficulty and retention interval. Thus, older children remembered more items than younger children, and all children remembered less at longer retention intervals. However, the nature of the memory items and the type of interpolated activity failed to influence recall reliably.

-------------------------------------- Table 3 about here-------------------------------------

The correlation between the number of interpolated response decisions and recall performance was once again positive, but non-significant, r(37) = .18. Finally, as in Expt. 1, recall was considered as a function of whether any errors were made on the interpolated task. There were insufficient errors for a substantial analysis. However, with digits to remember, the proportion correct recall following accurate lexical decisions was similar to that following an error (means =0.54 and 0.57 respectively). With words to remember, recall was slightly better following accurate lexical decisions than inaccurate decisions (means =0.56 and 0.47).

Discussion

The results largely converge with the first study. Thus the difficulty of interpolated activity did not make a reliable difference to recall, but its temporal duration did. Individual differences in the number of stimuli processed between presentation and recall were also not related to recall levels. Once more there was little evidence for qualitative age-related changes. In essence, the main conclusions from Experiment 1 are robust across different forms of material being remembered and interpolated task. Although it may seem from inspection of Table 3 that, for word memoranda, there may have been some evidence for a difficulty effect, this was not significant. Of course, an effect might emerge with more children, and its specificity to one type of memory stimuli suggests that interference or confusion between remembered and non-remembered items may play a part (Li, 1999). The trend could be construed as being consistent with a resource-sharing interpretation, however.

Both the present results and those of Experiment 1 are consistent with Halford et al. (1994) but at variance with the Posner and Rossman (1965) findings with adults, where forgetting was a function of both the duration and the difficulty of an interpolated task. We initially entertained the possibility that this discrepancy reflects developmental change. However, there were no developmental trends in Experiments 1 or 2 to support such an explanation. Another possibility is that the discrepancy reflects methodological differences in the way the difficulty of the interpolated task was manipulated. In Posner and Rossman's original experiments, task difficulty was quantified in terms of information reduction. As described in the introduction, different interpolated tasks involved a variety of response types and classification rules. To reiterate, one of the difficult tasks required the application of a complex conjunctive rule concerning size and parity, followed by classification of the stimuli using an arbitrary response mapping. It seems possible that forgetting of the memory stimuli may have arisen from the competing memory demands of these interpolated tasks rather than differences in information processing per se. The argument here is that interpolated tasks, that were assumed to involve a greater amount of information reduction, also involved a higher temporary memory load. Tasks involving a small amount of information reduction, such as writing a pair of digits in the opposite order from their presentation, also incurred lower memory demands. The final experiment sought to address this issue.

Experiment 3

Children completed either two-choice or four-choice processing tasks. In the two-choice tasks, children responded to the parity of a target numeral (even/ odd) or its accuracy as a solution to an arithmetic sum (right/ wrong). In the four-choice task, both dimensions were considered in conjunction. However, responses were verbal, and children did not have to remember complex S-R mappings. In this way we attempted to reduce the confound between informational difficulty of the interpolated task and the memory load it entailed. It was then possible to examine whether differences in processing complexity (involving 2- or 4-choice responses) affect the quality of recall. Children were given four digits to remember and a single age group was sampled in the light of the absence of informative developmental differences in the preceding findings. The number of stimuli presented before delivery of the memory items was increased, to allow a comparison of processing before and after stimulus presentation, and the retention intervals were adjusted to reflect the potentially time-consuming nature of the interpolated tasks.

Method

Participants and Design

The study was completed by 25 children from a Surrey primary school. Mean age was 10;0, ranging from 9;8 to 10;6. The interpolated task (assessing the parity of a number, accuracy of an equation, or both dimensions together) and the duration of the retention interval (6 and 15 seconds as nominal intervals) were within-subject factors.

Procedure

The procedure was similar to the preceding experiments. Children again played the role of a secret agent commander. Arithmetic sums (e.g. ‘6 + 9 = 15’) appeared centrally in the home base area, with the candidate answer printed in red and remaining text in black. On half the trials, the answer was correct. Incorrect answers were equally likely to be one more or one less than the correct value. All sums involved single digit additions with either one or two digit answers. Children produced a verbal response to the answer to each problem, in terms of one of the following criteria: (1) the parity of the answer (odd or even), (2) its accuracy (correct or incorrect), (3) its parity and accuracy (the four possible responses being even and correct, even and incorrect, odd and correct, odd and incorrect).

Children were given task instructions verbally, with laminated sheets used to illustrate task events and practice responses. On experimental trials, the experimenter transcribed the child's verbal response with a predetermined computer keystroke. This cued the next experimental event. Because the child made a verbal rather than spatial-based manual response, the screen display no longer included ‘secret agent’ images. As previously, however, messages in the status window continued to provide feedback on the accuracy of classification. Children were asked to repeat aloud the memory items when they appeared.

At the start of a trial, the status window indicated the type of classification required (presented in blocks randomly ordered across children). Children completed 3 or 4 classification decisions prior to being presented with a sequence of four digits, which were sampled at random without replacement. Children then made further classification decisions for either 6 or 15 seconds followed by ordered verbal recall of the four digits. The computer indicated recall success and the frequency of correct task classifications (combining responses before and after presentation of the memory items). Children completed twelve sorting trials, two trials for each sorting task at each interpolation delay.

Results and Discussion

Children took less time to make parity judgements (mean =1.81s) than to verify an answer (mean=4.16s). Judgments of both accuracy and parity produced the longest response delays (mean=6.78s), these decision times significantly exceeding the sum of parity and accuracy responses, $t(24) = 2.82$, $p = .01$, $\eta^2 = .249$. Thus, combining the two tasks was more demanding than performing both when considered separately. As shown in Table 4, the longer responses for the four-choice task resulted in longer retention intervals for that condition. Analysis of variance on observed retention intervals, with classification task and nominal retention interval as factors, showed significant effects of classification task, multivariate $F(2, 23) = 50.2$, $p < .01$, multivariate $\eta^2 = .813$ and inevitably, nominal retention interval, $F(1, 24) = 838.1$, $p<.01$, partial $\eta^2 = .972$. These factors did not interact, multivariate $F < 1$, multivariate $\eta^2 = .03$. More sorting errors were made on the four-choice task (mean = 1.48) than parity (mean=.76) or accuracy (mean=1.28) tasks alone, although the skewed nature of the data, with many children showing no errors, constrained analysis here.

--------------------------------------- Table 4 about here ---------------------------------------

Analysis of variance on recall focused on classification task and retention interval. Memory deteriorated at longer retention intervals, $F(1, 24) = 12.8$, $p < .01$, partial $\eta^2 = .348$ but there was no significant effect of classification task, $F(2, 48) = 1.72$, partial $\eta^2 = .067$, and no reliable interaction, $F < 1$, partial $\eta^2 = .022$. Figure 5 displays recall performance and appears to show a more noticeable difference between classification tasks at the longer interpolation interval. However, analysis of variance at the longer interval alone also showed no significant effect of classification task, $F(1, 24) = 2.19$, partial $\eta^2 = .083$. Memory accuracy was not significantly correlated with the number of interpolated decisions, $r(23)=-.10$.

--------------------------------------- Figure 5 about here ---------------------------------------

It may be noted that the actual retention interval in the 4-choice task was significantly longer than the other tasks, while the drop in recall was not significant. Among other possibilities, this may arise because memory performance is more variable than decision making speed. Nonetheless, it illustrates the conclusion that one cannot assume that changes in retention interval will always induce corresponding changes in retention. Computationally, the task-switching model could be specified in different ways that might accommodate the results (in particular, by using non-linear parameters in modelling the forgetting function). Nonetheless, the data reveal the under-specification of the model insofar as it fails to make straightforward quantitative predictions.

Given that children made three or four responses prior to presentation of the memory items, one can consider whether concurrent memory requirements affect response speed. Response time analysis, with classification task, retention interval and task phase (before or after presentation of the memory items) as factors, confirmed a significant effect of task with the four-choice task taking longest, multivariate $F(2, 23) = 120.7$, $p <.01$, multivariate $\eta^2 = .913$. Also, decision times were significantly longer after presentation of the memory items, $F(1, 24) = 35.17$, $p <.01$, partial $\eta^2 = .594$. There was no main effect of retention interval, $F < 1$, partial $\eta^2 = .024$, but there was a significant interaction between retention interval and task phase, $F(1, 24) = 4.81$, $p <.05$, partial $\eta^2 = .167$, such that classification decisions following presentation of the memory items were slowed most at the shorter interval (see Figure 6). There was also a significant interaction between phase and classification task, multivariate $F(2, 23) = 9.99$, $p <.01$, multivariate $\eta^2 = .465$, with a greater increase in classification time for the four-choice task following presentation of the memory items (see Table 5).

------------------------------------Figure 6 and Table 5 about here----------------------------------

The finding that decisions took longer following presentation of the memory items could be interpreted as showing that the concurrent memory load impaired processing efficiency, consistent with resource-sharing. However, experimental observation (e.g., lip movements suggestive of rehearsal or children not focusing their gaze on the computer screen) suggested that the effect might occur because children failed to recommence the interpolated task immediately after presentation of the final memory item. In other words, children may have used rehearsal to consolidate their memory before making response decisions, despite instructions to the contrary. If so, the slowing effect would be expected to be more marked after a short retention interval because the contribution of any delay would be proportionately greater. A resource-sharing account, however, predicts that trade-off between processing and storage would be carried throughout the processing phase. Thus, the significant interaction between task phase and retention interval in decision times is more consistent with the idea of a delay immediately after encoding the final memory item.

The interaction between task and phase in classification times could also be interpreted as consistent with resource-sharing, which correctly predicts that the greatest cost from a concurrent memory load should fall on the more difficult processing task. However, it is also consistent with an initial delay in returning to the classification task. Any such delay would be distributed across a smaller number of decisions when classification is slower. With quicker decisions, a one-off delay time would be ‘soaked up’ over more responses.

---------------------------------------Table 6 about here---------------------------------------

Approximately 5% of classification decisions were incorrect. Table 6 shows mean error rates as a function of task phase and retention interval; the difference across retention duration was non-significant, $\underline{z} = .28$, and error rates did not significantly vary before and after memory items appeared for either retention interval, Wilcoxon tests, zs < .12. According to a resource trade-off account, errors should be more frequent in decisions made after presentation of the memory items, when memory load was high. The delay account predicts no differences in error rates. However, floor effects constrain interpretation.

Thus, as in previous experiments, interpolated tasks differed significantly in terms of their processing requirements. There were a priori reasons for expecting the four-choice task to be more demanding, and indeed, responses were longer than the summed processing time for both two-choice tasks. However, memory performance was equivalent across interpolated task, showing a comparable decline as retention interval increased. While this contrasts with the original findings of Posner and Rossman (1965), it is consistent with Halford et al. (1994) and supports our suggestion that the original Posner and Rossman processing manipulation exacted a nontrivial memory requirement.

General Discussion

In each of three experiments, the duration of interpolated or background activity has been varied, as has the interpolated activity itself. The correspondence between the memoranda and the processing events has been manipulated and individual differences in interpolated response rate have been considered. The consistent effect of the duration of the interpolated task, irrespective of manipulations of its difficulty, underscores the importance of forgetting over a filled interval in working memory. In contrast, the difficulty of background task processing has not been directly relevant for item retention. Thus, significant variation in the difficulty of arithmetic, lexical decision and number classification tasks had no impact on recall. These results parallel previous observations based on the working memory span paradigm, where span was also sensitive to the duration but not the difficulty of the processing operations (Towse & Hitch, 1995).

This convergent pattern of results, from two different paradigms, provides no support for the notion that working memory is limited by a trade-off between resources available for either memory or processing. This is perhaps all the more impressive for the variety of difficulty manipulations employed, and in turn calls for a more objective measure of resource demand, whether through careful task analysis or otherwise. However, the results can be readily explained by a task-switching account that (in its simplest form) assumes children do not attempt to maintain memory items during processing. Instead they switch between phases of activity devoted to either processing or retention, reflecting the way a task is structured. Given the uncontroversial assumption that memory traces undergo forgetting when they are not actively maintained, this account provides a simple explanation of the importance of the duration but not the difficulty of processing operations.

Despite the consistency of the present observations, drawing conclusions from a set of null effects obviously requires caution. Furthermore, we do not advocate the conclusion that interpolated activity merely provides a time-filler that allows forgetting to take its course. Indeed, we have already noted that Posner and Rossman's (1965) findings can be re-interpreted as showing that forgetting is accelerated when interpolated activity involves a substantial memory load. This possibility is also relevant to the interpretation of recent research by Barrouillet and Camos (2001). In their final study, a span task involving articulatory suppression was matched in duration with an arithmetic operations span test. Despite this temporal equivalence, operations spans were slightly but reliably smaller. This was attributed to competition for shared resources for processing and memory, with more resources required for arithmetic operations than articulatory suppression. However, given that the arithmetic operations involved retaining intermediate solutions to a multi-term addition problem, one could argue that intrinsic memory demands within the processing task contributed to the observed results. Future research could usefully address how to separate out effects of the memory and processing demands of concurrent tasks.

The response contingency analyses offer a further perspective on the results. In Experiment 1, recall was depressed when children committed an error on the addition verification task, although this did not occur for the more error-prone, multiplication task, nor were comparable results found in the Experiment 2. One speculative interpretation is that children generally expected addition verifications to be correct. They may therefore have become distracted by an error, which lead to forgetting. Reduced confidence on the multiplication task meant errors were less unexpected, or distracting in this sense. According to this view, then, it is not difficulty per se that is relevant, but whether action programmes are interrupted by unexpected events (for a similar analysis, see Hitch & Baddeley, 1976). Notwithstanding, the size of the effect was quite small, reflecting either the limited consequence of the underlying mechanism, or the signal: noise ratio in the data.

Analyses of individual differences did not support the conjecture that memory decays with the number of intervening events (interfering elements or doses) between presentation and recall. This might be regarded as a variant on a resource-sharing framework, insofar as it maintains a dependency between retention and processing, understood as the number of events rather than the intensity of resource requirements. However, the memory of children who are fast processors does not appear to have been hampered by the additional computations that they performed. This is, however, not a direct test of the hypothesis, being based on individual differences. As such, it is readily acknowledged that other mediating variables may be important in the pattern of results.

Although the data are generally consistent with the task-switching model of children's performance in working memory span tasks, it is worth highlighting that this account is under-specified in its present state. For example, further theoretical elaboration will be required (1) to explain why recall was sometimes better when there were no errors on the interpolated task (Experiment 1) and (2), if our reinterpretation of Posner and Rossman (1965) following Experiment 3 is correct, specify the sensitivity of recall to the incidental memory load associated with an interpolated task. As already noted, elaboration of the model will also be required to explain the developmental improvements in memory performance observed in Experiments 1 & 2.

In conclusion, the present data provide further evidence that the duration rather than the difficulty of intervening processing activity influences the probability that children can successfully retain information in working memory. This finding seems to have some generality as it applies to both working memory span and the interpolated task paradigm used here. We interpret it as a challenge to the assumption that children's performance in working memory tasks reflects a trade-off between resources for information processing and information storage. However, while the task-switching model provides an effective explanation for the relationship between recall and the duration and difficulty of separate processing operations, it is not a complete account. At the same time, the model has potential subtleties, for the scheduling of independent task attributes can give rise to considerable complexity. Consequently, as shown in the present studies, processing and retention may not be in direct competition with each other, but nonetheless they may be linked.

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Table 1. Age groups of children in Experiment 1. Numbers in parentheses indicate how many children passed screening criteria for the arithmetic task, multiplication task, and the combination of both tasks, respectively. Mean age refers to the full age group

Group	Number of children	Mean age	SD (months)
1	24 (20/ -- / --)	7;10	5
2	20 (15/ 10/ 11)	8;10	5
3	18 (16/ 16/ 15)	10;9	5
4	23 (23/ 15/ 15)	11;9	4
5	21 (17/ 14/ 14)	13;9	6
6	17 (17/ 15/ 15)	17;0	5

Table 2. Proportion of correctly recalled sequences (standard deviation in parentheses).

	Nominal delay		
	6 s delay	11 s delay	16 s delay
Addition	.830 (.21)	.773 (.21)	.737 (.20)
Multiplication	.814 (.18)	.767 (.21)	.731 (.20)

Table 3. Memory performance (standard deviation in parentheses).

	Set interpolated duration			
	4 seconds	14 seconds	4 seconds	14 seconds
	non-words		pseudo-homophones	
Proportion of correct recalls with word memoranda				
8-year-olds	.74 (.15)	.67 (.25)	.65 (.21)	.49 (.31)
10-year-olds	.86 (.23)	.82 (.21)	.81 (.14)	.73 (.21)
Proportion of correct recalls with digit memoranda				
8-year-olds	.76 (.16)	.64 (.33)	.74 (.30)	.62 (.34)
10-year-olds	.80 (.27)	.76 (.27)	.87 (.16)	.76 (.15)

Table 4. Elapsed time between presentation of memoranda and recall in Experiment 3 (standard deviation in parentheses).

		Task	
	Parity	Accuracy	Both
Nominal 6 seconds length	7.42 (1.58)	8.80 (1.64)	10.48 (3.83)
Nominal 15 seconds length	16.1 (1.00)	17.6 (1.58)	18.6 (2.29)

Table 5. Time to complete sorting decisions (standard deviation is parentheses).

	Task		
	Parity	Accuracy	Both
Pre-memoranda	1.68 (1.07)	3.71 (1.14)	6.13 (2.92)
Post-memoranda	2.12 (1.70)	4.96 (1.66)	8.06 (3.73)

Table 6. Percentage of errors on the arithmetic problems

	Preceding memoranda	Following memoranda
6 second delay condition	4.40 (4.79)	5.32 (8.59)
15 second delay condition	4.44 (5.57)	4.40 (5.12)

Appendix

Analysis of interpolated tasks in Experiment 1.

Addition task

The observed retention intervals for each of the nominal intervals (6, 11, and 16 s) are shown in Table A1. Analysis of variance on the observed delays, with nominal retention interval and age as factors, inevitably produced a significant effect for retention interval. But more meaningfully, the analysis also showed an age effect, such that observed retention intervals were shorter among older children, F (5, 117)= 11.6, $p<.01$, partial $\eta^2 = .332$. Tukey HSD tests indicated significant differences between the youngest age group and all others ($p<.05$). Thus, in terms of memory performance, older participants were at a certain advantage, in that their greater numerical processing speed meant they began recall somewhat earlier than younger children (though this was not as substantial as would be found on prototypical working memory span tasks). There was no significant interaction between nominal retention interval and age, $F < 1$, partial $\eta^2 = .021$.

--------------------------------------- Table A1 & A2 about here --------------------------------------

Table A2 shows the number of problems attempted as a function of retention interval and age. Inevitably, the number of problems attempted increased as a function of retention interval, multivariate F(2, 115) = 366.7, $p< .01$, multivariate $\eta^2 = .864$. Number of problems attempted also increased with age, F(5, 117) = 13.2, $p< .01$, partial $\eta^2 = .361$. Tukey tests ($p<.05$) indicated that 17 year-olds completed significantly more problems than 8, 9, 11, and 12-year-olds, and 14-year-olds completed more problems than 8-year-olds. There was also a significant interaction whereby age differences became larger at longer retention intervals, F(10, 232) = 6.43, $p<.01$, multivariate $\eta^2 = .218$.

Multiplication task

Analysis of the elapsed time between presentation of the memory stimuli and recall, see Table A2, confirmed the inevitable effect of nominal retention interval. There was also a significant reduction in observed retention interval for the older subjects, $F(4, 94) = 4.14$, $p < .01$, partial $\eta^2 = .150$. Tukey tests established that observed delays were significantly shorter for the 17-year-olds compared with other age groups. There was no significant interaction between age and nominal retention interval, $F(8, 188) = 1.68$, partial $\eta^2 = .067$. Table A2 describes the number of problems attempted. Number of problems completed varied with age, $F(4, 94) = 5.46$, $p < .01$, partial $\eta^2 = .188$ (Tukey tests mirrored addition analyses), and retention interval, multivariate $F(2, 93) = 163.9$, $p < .01$, multivariate $\eta^2 = .779$. These variables interacted, multivariate $F(8, 186) = 4.07$, $p < .01$, multivariate $\eta^2 = .149$, with increasing age differences at longer retention intervals.

Experiment 2: Lexical decision task

Analysis of the observed elapsed time with age, retention interval, interpolated task (pseudo-homophones or non-homophonic non-words) and memory stimuli (digits or words) as factors, see Table A3, showed no significant effect of age, $F < 1$, partial $\eta^2 = .011$, lexical task, $F < 1$, partial $\eta^2 = .015$, or memory stimuli, $F < 1$, partial $\eta^2 = .022$. Nominal retention interval necessarily affected elapsed time but there was also an interaction between age group and memory stimuli, $F(1, 31) = 4.73$, $p < .05$, partial $\eta^2 = .132$ such that elapsed times tended to be longer with words to remember for the younger group, while longer with numerals to remember for the older group. Other effects were non-significant (Fs<1.86, partial $\eta^2 <.057$) .

--------------------------------------- Table A3 about here---------------------------------------

Analysis of the number of completed correct lexical decisions, with age, retention interval, interpolated task, and memory items as factors, indicated that older children made more responses, $F(1, 31) = 5.39$, $p < .05$, partial $\eta^2 = .148$, and fewer responses were made on pseudo-homophone non-word trials, F(1, 31) = 5.40, $p < .05$, partial $\eta^2 = .148$. There was no significant interaction between these effects, $F < 1$, partial $\eta^2 = .009$. There were more responses at the longer retention interval, F(1, 31) = 395.2, $p < .01$, partial $\eta^2 = .927$, as expected. There was a reliable interaction between age and retention interval, F(1, 31) = 4.79, $p < .05$, partial $\eta^2 = .134$ reflecting an increased advantage for older children at the longer retention interval. There was an interaction trend between task and retention interval, F(1, 31) = 3.91, $p < .06$, partial $\eta^2 = .112$ arising from an increased advantage for the non-homophonic non-word condition at the longer retention interval. The three way interaction between age, task, and retention interval was not significant, $F < 1$, partial $\eta^2 = .022$. Number of lexical decisions made was unaffected by whether the memory items were words or digits, F(1, 31) = 1.14, partial $\eta^2 = .036$. Fewer lexical decisions were made at the short interval with digits to remember, but more decisions at the longer interval with words to remember, F(1, 31) = 4.83, $p < .05$, partial $\eta^2 = .135$. Other interactions involving type of memory item were non-significant (all Fs < 1.72, partial $\eta^2 < .054$).

The proportion of errors made on the interpolated task was examined. Analysis of variance on errors, with age, retention interval, interpolated task and memory items as factors, failed to reveal any significant results (all Fs < 2.97, partial $\eta^2 <.088$). Thus, the version of the lexical decision task that contained non-homophonic non-words was less demanding, as measured by the number of decisions completed within a set time period, but the two versions did not differ in terms of error rates.

Table A1. Elapsed time between memory stimuli and recall signal for addition and multiplication (standard deviation in parentheses).

	Set interpolated duration		
	6 seconds	11 seconds	16 seconds
Addition			
8-year-olds	11.6 (4.29)	17.4 (4.57)	21.9 (5.63)
9-year-olds	9.67 (2.34)	14.7 (2.35)	19.8 (2.15)
11-year-olds	9.09 (2.02)	13.8 (1.45)	18.9 (1.76)
12-year-olds	8.67 (1.29)	13.5 (1.28)	18.8 (1.25)
14-year-olds	7.81 (0.58)	12.8 (0.81)	17.9 (0.91)
17-year-olds	7.77 (0.80)	12.8 (0.70)	17.4 (0.32)
Multiplication			
8-year-olds	--	--	--
9-year-olds	9.63 (2.40)	14.0 (1.20)	19.5 (2.00)
11-year-olds	9.23 (1.88)	15.2 (2.56)	19.2 (1.87)
12-year-olds	9.44 (2.05)	13.9 (1.26)	19.3 (1.95)
14-year-olds	8.71 (1.61)	13.6 (1.56)	19.2 (2.09)
17-year-olds	7.98 (0.75)	12.8 (0.68)	17.8 (0.56)

Table A2. Mean number of problems attempted during interpolated activity for addition and multiplication (standard deviation in parentheses).

	Set interpolated duration		
	6 seconds	11 seconds	16 seconds
Addition			
8-year-olds	1.60 (0.72)	2.37 (1.40)	2.88 (1.57)
9-year-olds	2.09 (1.00)	3.07 (1.62)	4.26 (2.21)
11-year-olds	1.95 (0.48)	3.01 (0.67)	4.18 (1.01)
12-year-olds	1.92 (0.49)	3.10 (0.80)	4.28 (1.16)
14-year-olds	2.45 (0.49)	4.00 (0.78)	5.44 (1.00)
17-year-olds	2.82 (0.33)	4.60 (0.77)	6.42 (0.92)
Multiplication			
8-year-olds	--	--	--
9-year-olds	2.01 (0.68)	2.85 (1.18)	4.28 (2.59)
11-year-olds	1.64 (0.43)	2.50 (0.59)	3.38 (1.11)
12-year-olds	1.92 (0.65)	2.97 (1.12)	3.95 (1.69)
14-year-olds	2.07 (0.56)	3.43 (1.30)	4.79 (1.85)
17-year-olds	2.45 (0.48)	4.22 (0.87)	5.76 (1.31)

Table A3. Performance on the lexical decision task (standard deviation in parentheses).

	Set interpolated duration			
	4 seconds	14 seconds	4 seconds	14 seconds
	non-words		pseudo-homophones	
Elapsed time with word memoranda				
8-year-olds	5.59 (0.88)	15.4 (0.57)	5.71 (0.89)	15.4 (0.39)
10-year-olds	5.00 (0.69)	15.2 (0.44)	5.44 (0.33)	15.5 (0.42)
Elapsed time with digit memoranda				
8-year-olds	5.24 (0.76)	15.3 (0.34)	5.39 (0.34)	15.2 (0.28)
10-year-olds	5.33 (0.73)	15.4 (0.88)	5.36 (0.56)	15.4 (0.46)
Mean correct sorts with word memoranda				
8-year-olds	1.88 (0.67)	5.10 (2.01)	1.55 (0.34)	4.54 (0.56)
10-year-olds	2.30 (0.54)	6.92 (2.15)	1.88 (0.48)	5.64 (0.85)
Mean correct sorts with digit memoranda				
8-year-olds	1.90 (0.49)	5.96 (1.25)	1.48 (0.33)	4.91 (1.32)
10-year-olds	2.15 (0.66)	7.16 (2.17)	1.81 (0.31)	5.50 (1.11)

Figure captions

Figure 1. Schematic sequence of events in Experiment 1.

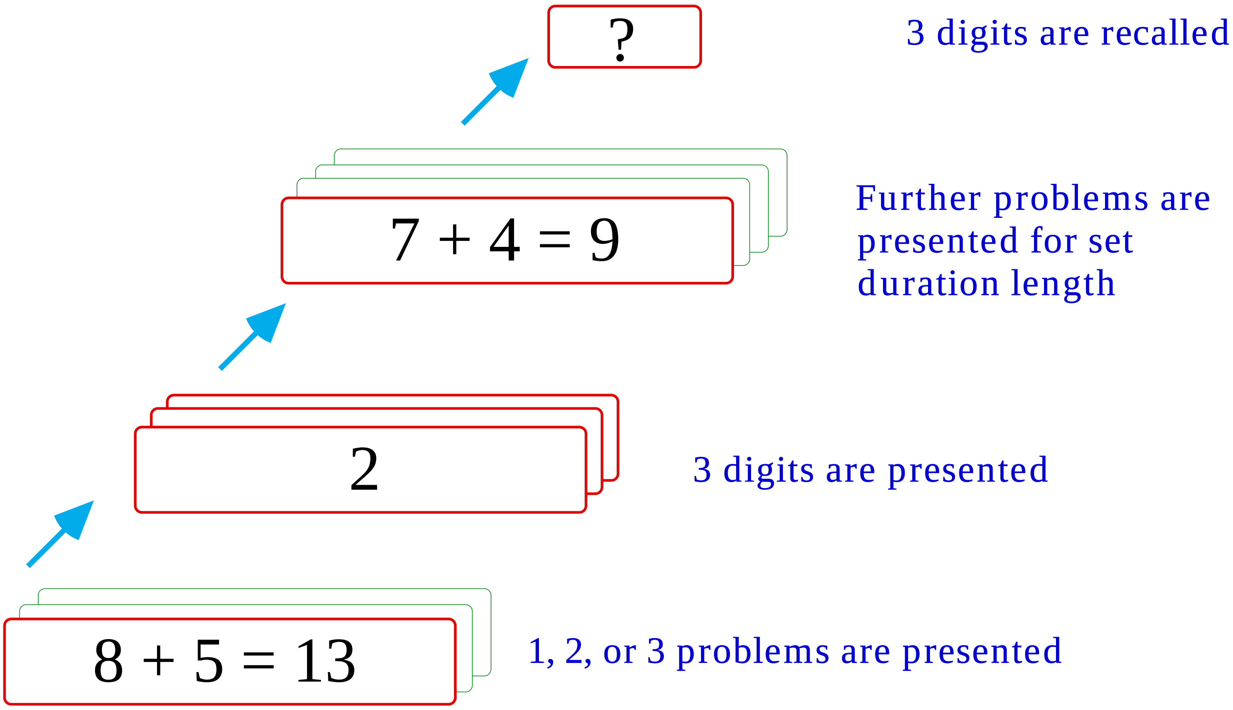
Figure 2. Effect on memory of addition (upper panel) and multiplication (lower panel) as interpolated activity in Experiment 1. The proportion of items recalled correctly is plotted against the measured retention interval.

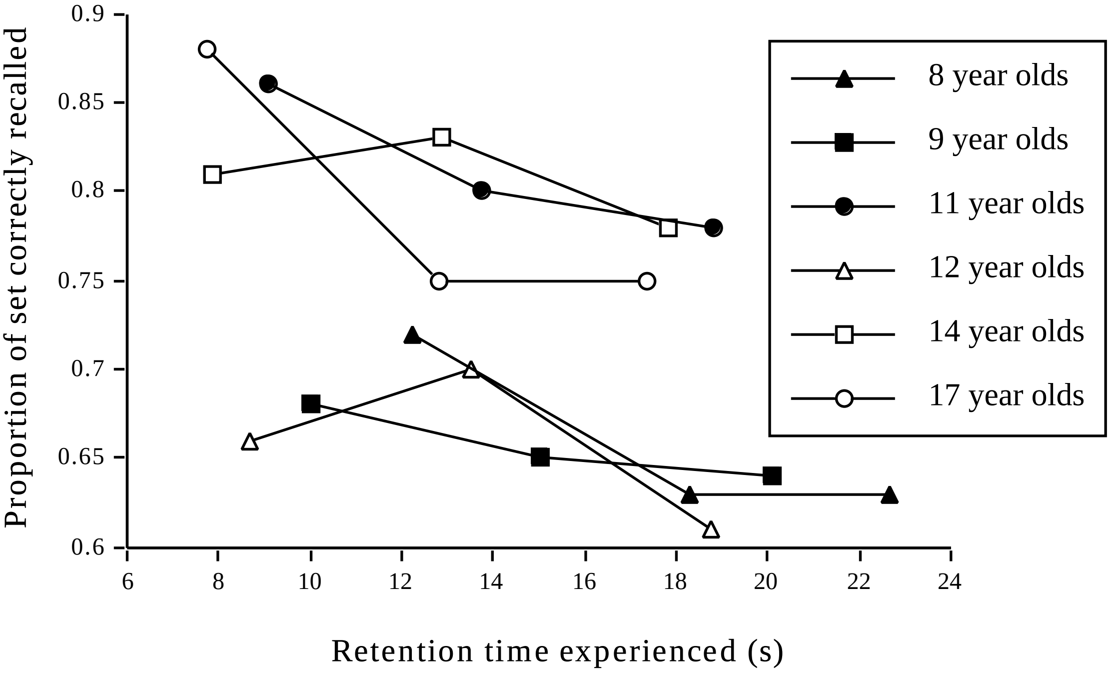
Figure 3. Distribution of recall accuracy levels across subjects when addition problems are attempted successfully (upper panel) and when an error occurs (lower panel).

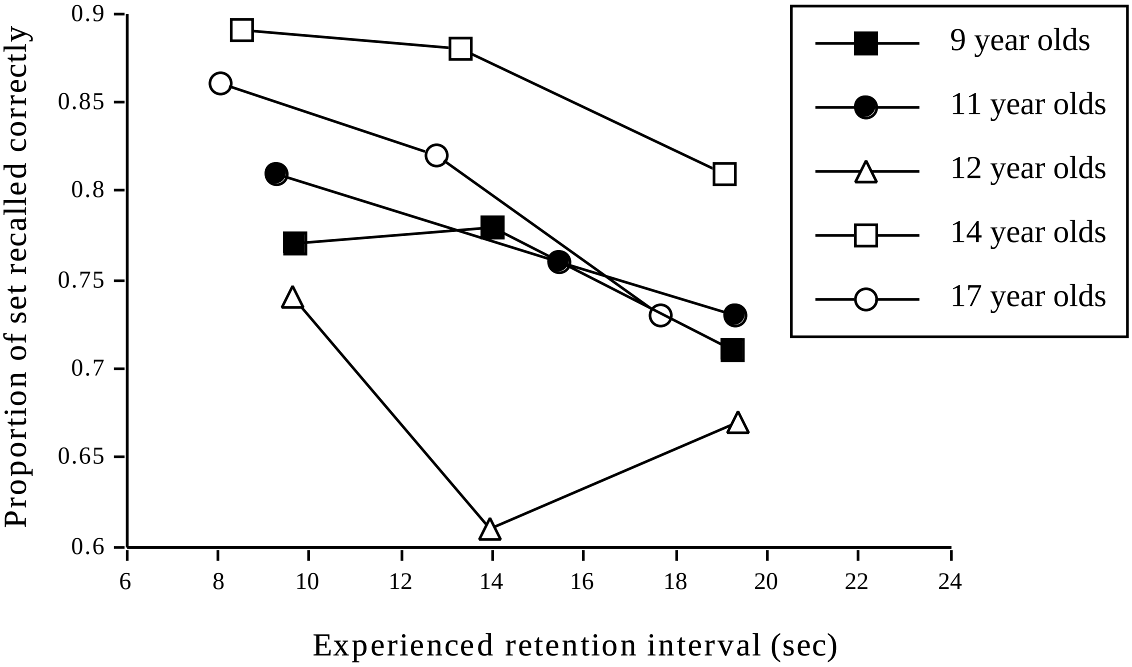
Figure 4. Distribution of recall accuracy levels across subjects when multiplication problems are attempted successfully (upper panel) and when an error occurs (lower panel).

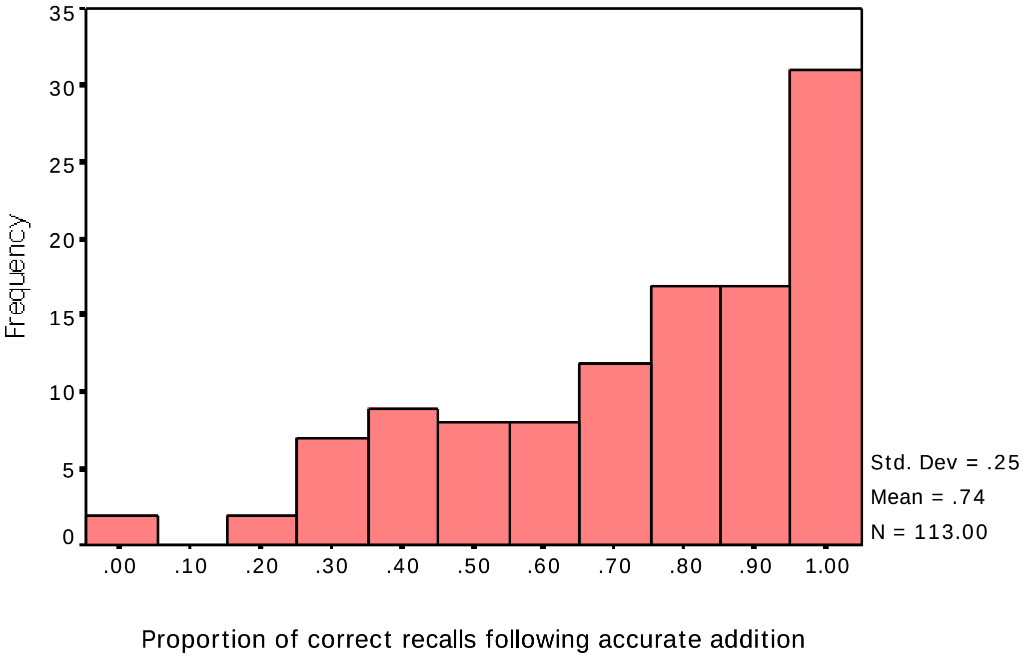
Figure 5. Memory performance as a function of interpolated task and duration. Error bars encompass two standard deviations.

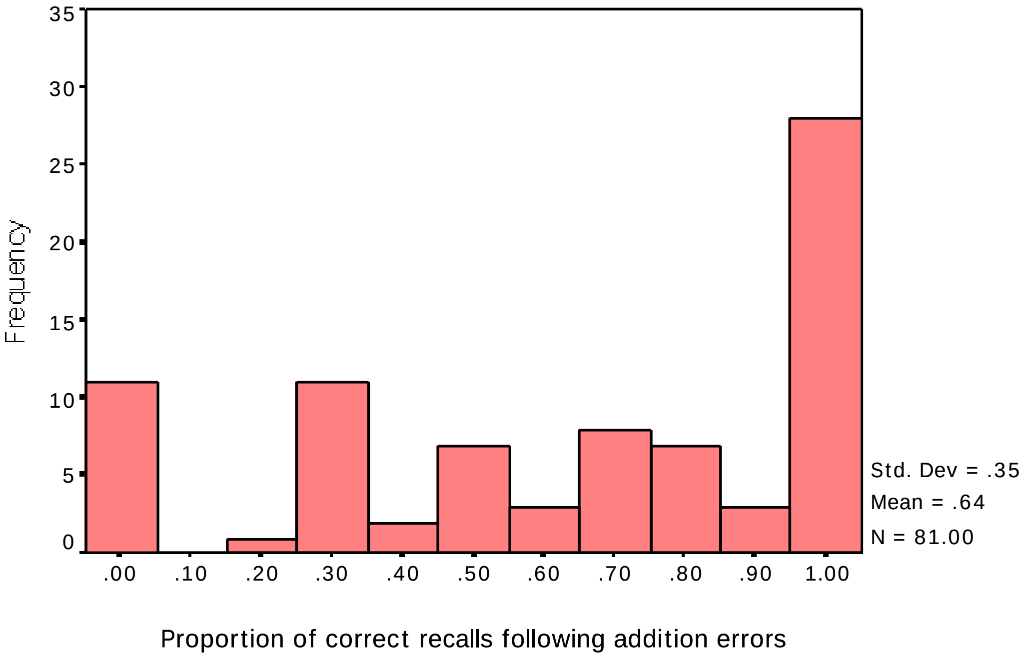
Figure 6. Mean sorting speed as a function of interpolation task length and memory requirement. Error bars encompass two standard deviations.

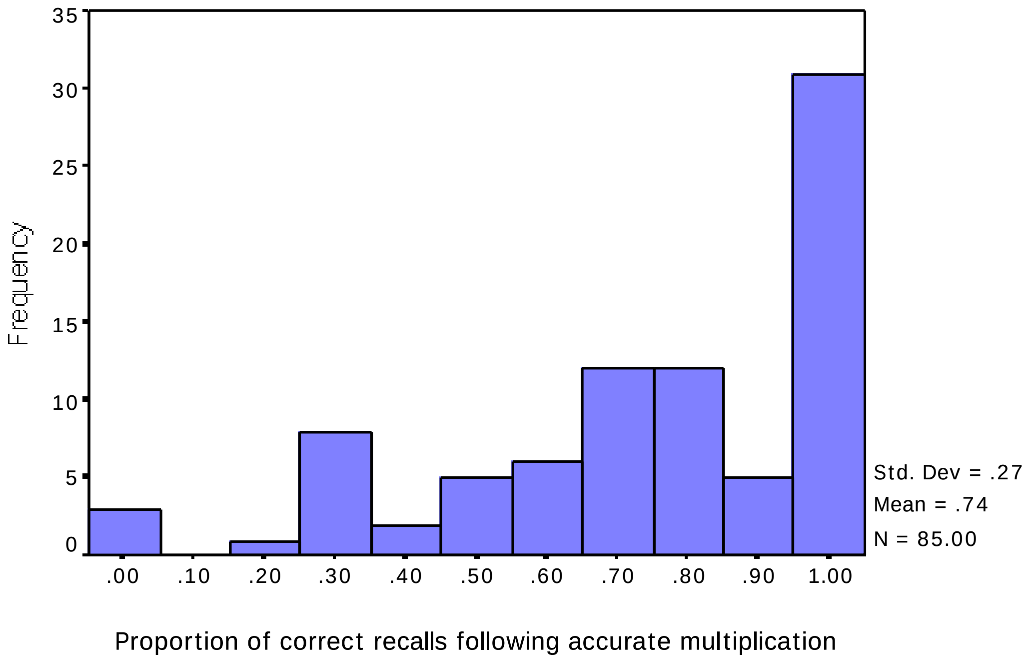

?
3 digits are recalled
7 + 4 = 9
Further problems are presented for set duration length
2
3 digits are presented
8 + 5 = 13
1, 2, or 3 problems are presented

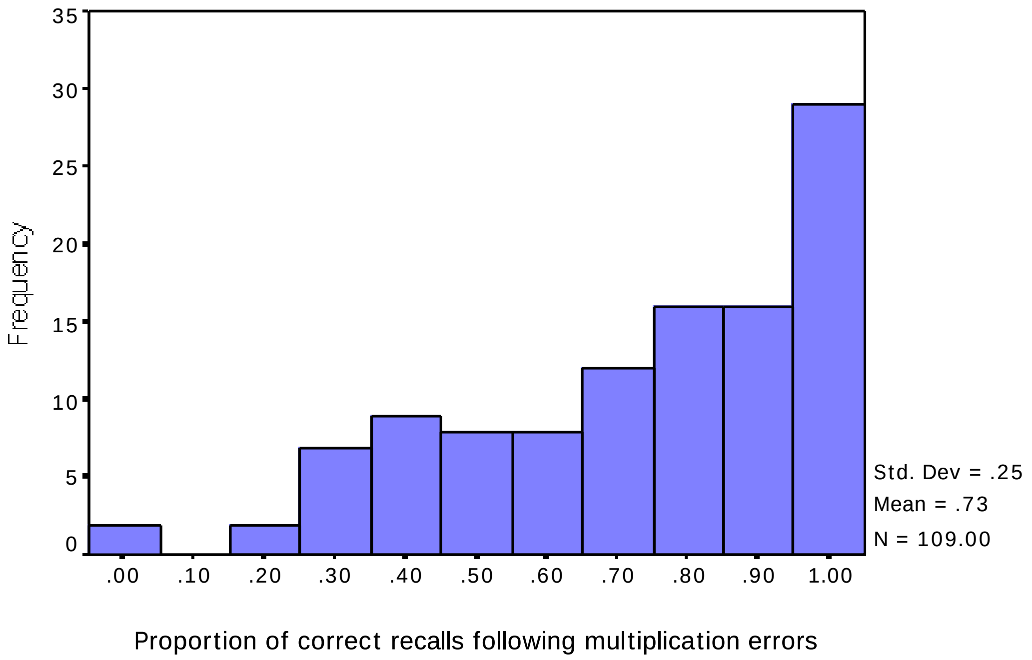

Proportion of set correctly recalled
0.9
0.85
0.8
0.75
0.7
0.65
0.6
6
8
10
12
14
16
18
20
22
24
Retention time experienced (s)
8 year olds
9 year olds
11 year olds
12 year olds
14 year olds
17 year olds

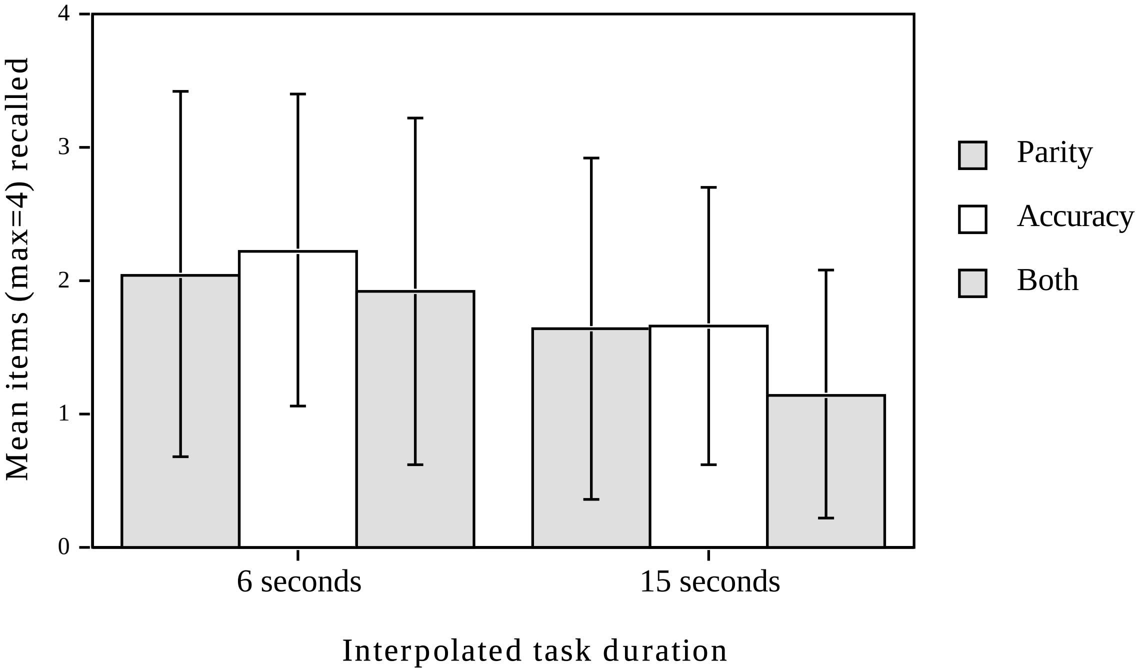

Proportion of set recalled correctly
0.9
0.85
0.8
0.75
0.7
0.65
0.6
6
8
10
12
14
16
18
20
22
24
Experienced retention interval (sec)
9 year olds
11 year olds
12 year olds
14 year olds
17 year olds

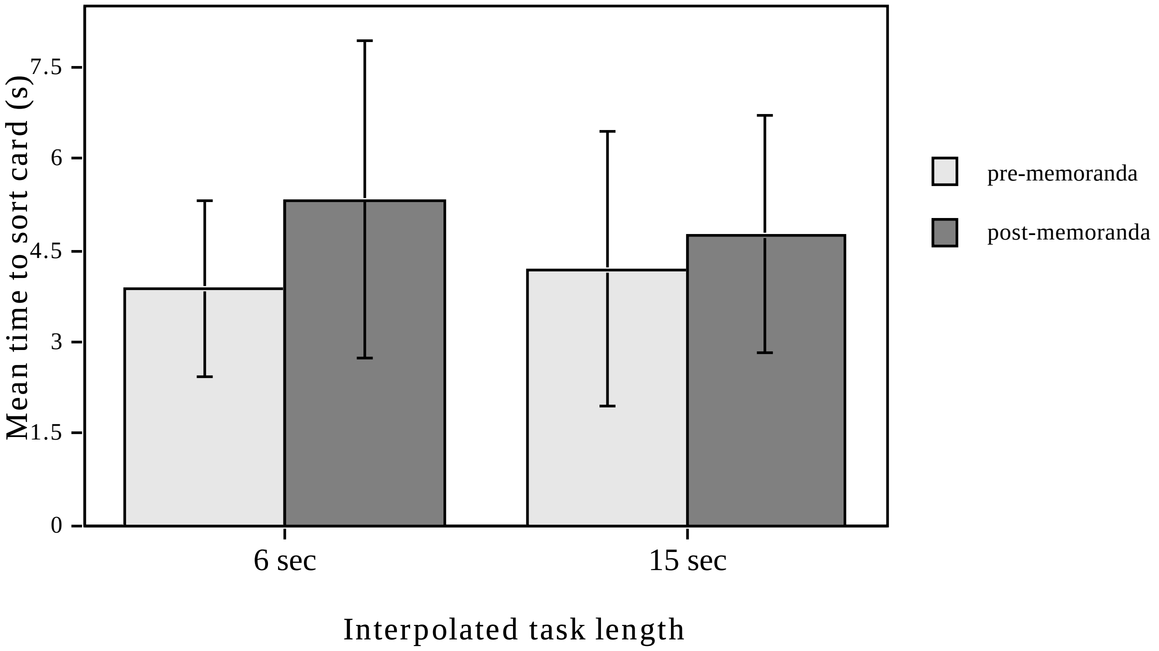

35
30
25
20
15
10
5
0
Frequency
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
Std. Dev = .25
Mean = .74
N = 113.00
Proportion of correct recalls following accurate addition


35
30
25
20
15
10
5
0
Frequency
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
Std. Dev = .35
Mean = .64
N = 81.00
Proportion of correct recalls following addition errors


35
30
25
20
15
10
5
0
Frequency
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
Std. Dev = .27
Mean = .74
N = 85.00
Proportion of correct recalls following accurate multiplication


35
30
25
20
15
10
5
0
Frequency
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
Std. Dev = .25
Mean = .73
N = 109.00
Proportion of correct recalls following multiplication errors


4
3
2
1
0
Mean items (max=4) recalled
6 seconds
15 seconds
Interpolated task duration
Parity
Accuracy
Both


Mean time to sort card (s)
0
1.5
3
4.5
6
7.5
6 sec
15 sec
Interpolated task length
pre-memoranda
post-memoranda