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How verbal memory loads consume attention

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Abstract

According to a traditional assumption about working memory, participants retain a series of verbal items for immediate recall using covert verbal rehearsal, without much need for attention. We reassessed this assumption by imposing a speeded, nonverbal choice reaction time (CRT) task following the presentation of each digit in a list to be recalled. When the memory load surpassed a few items, performance on the speeded CRT task became increasingly impaired. This CRT task impairment depended only on attention-related components of working memory; it was not alleviated by the presence of an auditory memory trace that automatically helped the recall of items at the ends of spoken lists. We suggest that attention-demanding refreshing of verbal stimuli occurs along with any covert rehearsal.

What is the role of attention in retaining verbal items in working memory (the small amount of recently processed information that is temporarily very accessible; Baddeley & Hitch, 1974; Miller, Galanter, & Pribram, 1960)? In most of the research on this topic, the role of attention has not been made clear. In this article, we first review research on the role of attention in the maintenance of information in verbal working memory. We conclude from this literature that, surprisingly, there is still a need for evidence from a dual-task experiment examining the increasing consumption of attention by a memory load across serial positions of a list to be recalled. We then report such evidence.

The role of attention was not completely clear in the description by James (1890) of *primary memory*, an early term for what is now usually termed *working memory*. Neither was the role of attention clear in Miller (1956) on the limits of immediate recall.

The theoretical model of working memory that has been predominant in the field includes the assumption that there is little or no use of attention in memory for about 2 sec of speech or phonological elements maintained using covert rehearsal (Baddeley, 1986; Baddeley, Thomson, & Buchanan, 1975). Baddeley (1986) summarized numerous studies in which higher order processes, such as reasoning, were combined with a verbal memory load, and the amount of conflict between tasks was limited. To account for such findings, he proposed a model in which the role of attention was limited to the processing of information in a central executive mechanism responsible for directing processing, with all storage occurring automatically. In this model, a task such as short-term recall of a verbal list was assumed to make few demands on attention in nondisabled adults because both the storage and the mnemonic process of covert rehearsal of the list were thought to be mostly automatic and effortless in nondisabled adults. Consequently, the maintenance of information in verbal working memory was not supposed to conflict much with another concurrent task in adults unless it, too, required verbal processing. Indeed, it has been shown by Guttentag (1984), using list recall with a secondary finger-tapping

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task, that the amount of attention needed for verbal rehearsal dramatically decreases between the second and sixth grades.

In other seminal work in which individual differences in working memory were considered, the role of attention was left undecided. Expressing this indecision, Daneman and Carpenter (1980) stated that a task that has heavy processing requirements should decrease the amount of additional information that can be maintained. One way this could occur is if the execution of more demanding processes required more attention and hence consumed a larger proportion of the capacity otherwise available for storage. Another way is if the processes in the demanding task generated intermediate products that displaced the additional information. (p. 451)

The more recent literature, as well, has been divided on the issue of the role of attention in both verbal and visual–spatial working memory maintenance. Some researchers reach the conclusion that storage and processing trade-offs stem mostly from their competition for domain-specific, automatic, verbal and visual–spatial working memory buffers (e.g., Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002) or, similarly, from interference between stimuli with similar representations (Saito & Miyake, 2004). However, even within the view that storage is automatic, some researchers have suggested that attention-demanding central executive processes may be needed for maintenance after the memory load becomes high (Baddeley et al., 1999). There is some research suggesting that very different types of material, such as verbal and visual–spatial material, do share a common resource (Kane et al., 2004) and do interfere with one another in working memory (e.g., Cowan & Morey, 2007; Morey & Cowan, 2004, 2005; Saults & Cowan, 2007). In these studies, however, it is storage in two domains that is required, and one could argue that the verbal material relies on a spatial recoding or vice versa (e.g., Conrad, 1964).

The motivation of our study was to directly test the hypothesis that a verbal memory load consumes attention. To achieve this goal, we manipulated memory load in a primary task and measured its attentional cost in a secondary task across serial positions. We chose a secondary task that was attention demanding because of the short time in which a response could be made but that shared as little as possible with the memory task materials in terms of the form of representation. The key prediction was that, if the attention demand of working memory storage increases with the load on working memory, the detrimental effect of the memory task on performance of the concurrent secondary task should increase across serial positions of the list as the load increases.

Theoretically, this emphasis on an attention-demanding memory load is in line with the position of Barrouillet, Bernardin, Portrat, Vergauwe, and Camos (2007). Barrouillet et al. (2007) presented lists to be recalled and varied the duration between list items and the number of items in a secondary task carried out during the delay. They observed that the proportion of time between items taken up by an attention-demanding task was linearly, negatively related to recall. This was true even when the list was verbal and the secondary task was spatial (direction judgment). The theory of performance was one in which attention-demanding processes are needed to refresh the representations of the list items in working memory, which tend to decay when that refreshing process cannot be used because of the secondary task distraction. In the present study, we further tested this type of hypothesis in several ways. First, we examined the effects of increasing memory load across serial positions. Second, we focused on the effects of memory load on performance on the secondary task, even when the memory task was performed correctly. We increased the number of list items to be refreshed across serial positions, which should lead to an increase in the conflict between memory and the secondary task across serial positions.

There is previous evidence suggesting that the attention demand may, in fact, increase during the reception of the list as the memory load increases, but that evidence can be questioned. Maehara and Saito (2007) had participants do spatial (or verbal) processing tasks during a verbal (or spatial) working memory span test and found that the processing speed slowed for the later processing positions in the span test list, where participants were holding more memory items in mind. Such an apparent domain- general interference cannot be satisfactorily accounted for solely by Saito and Miyake's (2004) representation-based interference theory. Instead, Maehara and Saito offered an account with an attention-based central limit in working memory. The effect of memory load in Maehara and Saito's study is uncertain, however, given that there was no control condition in which the memory load did not increase across serial positions (e.g., no condition in which the list sequence was a known sequence—like 1, 2, 3, 4 —that would not impose a working memory load). Consequently, there is no way to rule out the possibility that it was mental fatigue from the secondary processing task across serial positions, rather than increasing memory load, that increasingly interfered with processing across serial positions.

In two other studies, researchers examined the increase in cognitive load across serial positions, but the methods and findings of these studies are also problematic. Kahneman and Beatty (1966) used pupil dilation as a measure of effort and showed that effort goes up across the list with increasing verbal memory load. However, this study does not indicate whether the resource that is apparently used up is then unavailable for behavior, as a behavioral secondary task could show. In a follow-up study, Karatekin, Couperus, and Marcus (2004) did use a secondary task and found no load effect across serial positions (despite a pupil dilation effect). This, however, could have been because they used simple rather than choice reaction time (CRT) as the secondary task, whereas CRT is a much better index of attentional cost (Logan, 1979; Tombu & Jolicœur, 2003).

Taking into account the limitations of previous studies, we employed a variant of the speeded CRT task that uses accuracy instead of latency of responses as the primary indicator of attention cost in the primary task. Because we required a response within a very limited time window, speed was needed in addition to accuracy, and we were able to adjust the task difficulty to individual abilities by moderating the time allowed to respond. A drain of attention by the memory load could therefore result in one of three types of incorrect response on the CRT task: (1) a wrong response within the response time window, (2) an absence of response, or (3) a response after the response time window. We also examined the effect of increasing memory load across the serial positions of a verbal list and used a secondary task that was nonverbal, so that any dual-task interference was not attributable to competition for common memory buffer or domain-specific representations.

We adopted a three-stage paradigm. In the first stage, we provided four trials of random digit list immediate serial recall. In the second stage, a CRT task was used, and its difficulty level was individually calibrated for maximal sensitivity of the task to avoid ceiling and floor effects in individuals. In the third stage, the list recall and CRT tasks were to be carried out together as a dual task, with CRT trials during the period after the presentation of each list item. In addition to trials with random digit lists, naturally ordered digit lists (e.g., 1, 2, 3, 4) and lists of zeros (e.g., 0, 0, 0, 0) were included as control conditions that did not create a memory load. Finally, for both the list recall stage and the dual-task stage, all digit lists were presented either acoustically or visually in two counterbalanced sessions, so that we could examine any modality effect of working memory on attention, which was informative regarding the nature of a dual-task conflict.

METHOD

Participants

A total of 37 undergraduates (21 female and 16 male, 35 right-handed and 2 left-handed) participated in the experiment in exchange for course credit. They were native speakers of English with normal hearing and normal or corrected-to-normal vision.

Stimuli and Procedure

The participants went through two sessions of a three-stage computerized test, individually, in a sound-attenuated booth. The only difference between the two sessions was the stimulus modality of the memory task, one with visual and the other with auditory stimuli. The order of the two sessions was counterbalanced among participants. For either session, the three stages were (1) list recall of four or five digits under full attention, (2) a speeded CRT task under full attention, and (3) a dual task combining digit list recall and the speeded CRT task.

List recall stage—This initial stage included two trials with lists of four random digits and then two trials with lists of five random digits. If visually presented, the digits were in white, in 30-point font (about 1 cm in height), against a black background at the center of the screen. If acoustically presented, the digits were played back from two loudspeakers flanking the computer screen with the volume individually adjusted to be comfortable for the participant. The entire computer screen remained black throughout the auditory presentation.

The participants were informed of the length of the upcoming list and initiated the trial when they were ready. Each digit was displayed for 500 msec (or, for acoustically presented digits, centered within a 500-msec window), followed by a blank interval of 1,500 msec. The participants were instructed to recall the digit list in the presented order by typing it into the keyboard. Feedback included the correct response, the actual response, and the response accuracy (the proportion of items correct).

Speeded CRT task stage—This stage included 93 trials of a speeded CRT task. At the beginning of a trial, the participants saw a fixation sign in 30-point font size at the center of the screen. Around the center, three boxes appeared (15 mm × 12 mm) with their sides parallel to the edges of the screen. One of them was centered 60 mm above the fixation sign, and the other two boxes were centered at a distance of 75 mm from the fixation sign, one on each side. A box was randomly selected out of the three as the target and was shown in red, whereas the other two were in white. The task was to press the arrow key that corresponded to the location of the target box (upper, left, or right arrow). Feedback was given on the status of the response. If the correct key was pressed before the boxes disappeared, the target box was framed in blue, and only such a response was counted as successful; if a keypress response was absent or executed too late, a red rectangle frame around the fixation sign flashed; and if a wrong key was pressed, no change occurred to the display.

The display duration for the boxes, which was also the window within which a response had to be made, was initially set at 500 msec but underwent continuous adjustment. It would be reduced by 10 msec every time the participants made three successful responses in a row; otherwise, it was increased by 10 msec. The participants were instructed to rest the middle three fingers of their right hand on the three arrow response keys in a comfortable manner and to initiate the task by pressing the down arrow key with the middle finger when they were ready. Ninety-three trials were then automatically delivered in a row with no break. At the end of this stage, the average of the shortest and the last display durations determined the single display duration to be used for each participant in the dual-task stage.

Dual-task stage—This stage included 48 trials that integrated the list memory task with the speeded CRT task episodes carried out during the list maintenance intervals. A trial is illustrated in Figure 1. These 48 trials included a block of four-digit lists and a block of five-digit lists, with the order of the blocks counterbalanced. Within each block, there were three list conditions, each with 8 trials, randomly mixed. The three list conditions included lists of randomly ordered digits, along with two control conditions: a progression of numerals in the natural order (1–4 or 1–5), and a redundant list of four or five zeros.

The list length (four or five) and the list type (i.e., random, natural, or zeros) were known to the participants at the outset of each trial. The participants were instructed to do their best on both the memory and the speeded CRT tasks. The participants had their fingers in a ready position for the speeded CRT task before they pressed the down arrow key to start the dual task. Each trial started with a 500-msec presentation of a digit and a 300-msec pause, which should be sufficient for stimulus encoding in either the auditory (Massaro, 1975) or the visual (Turvey, 1973) modalities, and then three speeded CRT trials with no break for a period expected to be about 1,200 msec according to pilot data. Thus, the onset-to-onset time for the presentation of digits was comparable to the 2-sec interval used in the list recall stage. Upon finishing the last speeded CRT trial, the participants were then asked to recall all list items in their presented order by typing them into the keyboard. Feedback was given at the end of a trial on accuracy in both the list recall and CRT tasks (i.e., the proportion of list items recalled in their presented order and the proportion of successful CRT responses).

RESULTS

Recall Performance in the List Recall and Dual-Task Stages

For memory trials in both the list recall stage and the dual-task stage, we counted an item correct only if it was recalled in the correct serial position. In the list-recall stage (with no speeded CRT task), the participants perfectly recalled 99% of all four-digit lists and 95% of all five-digit random lists. In contrast, given a dual task, the participants perfectly recalled 89% and 82% of the four-and five-digit random lists, respectively. A series of *t* tests on lists of the same length (i.e., four-digit or five-digit lists) and modality (i.e., auditory or visual) showed that recall performance decreased significantly (ps $< .05$) in the dual-task stage relative to that in a single task in this condition. The corresponding percentages in the naturally ordered digits were 98% for both list lengths and, for the zeros condition, 96% for four-digit lists and 95% for five-digit lists. The occasional errors in the naturally ordered and zeros control conditions could reflect mistyping, including typing too many or too few digits.

Accuracy on Speeded CRT Task for Trials Free of Recall Errors in the Dual-Task Stage

We examined the speeded CRT task performance for those trials in which there were no errors, separately for the four- and five-digit lists (Table 1). In this analysis, the dependent variable was CRT task accuracy (i.e., the proportion correct on the CRT task) and the independent variables included list modality (auditory or visual), list type (random digit, natural digits, or zeros), and serial position (1, 2, 3, 4, or 5). A four-digit memory load only weakly affected the secondary CRT task performance level. The interaction of the list type and the serial position was not significant in an ANOVA [$F(6,216) = 1.33$, $p = .25$, $\eta_p^2 = .04$]. An interaction between list type and serial position is critical for our investigation, because a main effect of list type or serial position alone cannot ascertain that the effect on attention is really from an increasing memory load rather than from other factors, such as the urge to remember or fatigue. Except for a serial position main effect, none of the other main effects or interactions was significant. Therefore, we concentrate on the trial blocks with five-digit lists.

For trials with errorless recall of five-digit lists, there was a pronounced effect of a memory load on the speeded CRT task. In this analysis, the factors were the same as for the four-digit list analysis. As Figure 2 shows, the CRT task performance declined across serial positions for random digit lists much more than for the two control conditions (i.e., natural digit lists and zeros lists), in which the lists did not impose a memory load. An ANOVA showed no effect of list modality (auditory or visual) on the speeded CRT task, but it showed main effects of list type (random, natural, or zeros) [$F(2,72) = 8.78$, $p < .001$, $\eta_p^2 = .20$] and serial position (1, 2, 3, 4 or 5) [$F(4,144) = 20.31$, $p < .001$, $\eta_p^2 = .36$]. Most important, the interaction between these variables [$F(8,288) = 9.88$, $p < .001$, $\eta_p^2 = .22$] confirms the pattern in Figure 2, in which the deterioration in the speeded CRT task performance across serial positions was much more severe in the random digits condition than in the control conditions. This interaction was significant even when the last serial position was omitted from the analysis [$F(6,216) = 5.44$, $p < .001$, $\eta_p^2 = .13$]. Pairwise Newman–Keuls tests showed both that the random digits condition produced poorer CRT task accuracy than either of the other two conditions at Serial Positions 4 and 5 (i.e., under maximal memory load), but not at the earlier serial positions, and that in the random digits condition, all serial position means differed from one another except those for Serial Positions 1 and 2. The control conditions did not differ from one another. None of the other main effects or interactions was significant.

Analyses of Trials With Recall Errors in the Dual-Task Stage

We next examined the memory load effect on the speeded CRT task performance for five-digit trials in which errors were made in the memory task in the random digits condition. A comparison of memory and the speeded CRT task proportions correct across serial positions was especially interesting; it illustrated that at least one factor contributing to recall performance did not contribute to the memory load affecting CRT task performance. Specifically, an auditory sensory memory trace raised performance for items at the end of spoken lists (for a review of this auditory recency advantage, see Cowan, 1984, and Penney, 1989) without reducing the memory load during maintenance of the list (Figures 3A and 3B). This suggests that the participants maintained items at the end of the list using an attention-demanding process, even though sensory memory also was available. Analysis of the recall performance revealed an effect of serial position [$F(4,76) = 8.19$, $p < .001$, $\eta_p^2 = .30$] and also, because of the auditory recency advantage, an interaction of that effect with the list modality [$F(4,76) = 4.72$, $p < .01$, $\eta_p^2 = .20$]. Analysis of the speeded CRT task accuracy, however, revealed no such effect of modality, only the overall serial position effect from poorer CRT task performance at later serial positions [$F(4,76) = 7.64$, $p < .001$, $\eta_p^2 = .29$] (Figures 3A and 3B). Newman–Keuls tests showed that the CRT task performance was lower in the fifth serial position than in the fourth. Thus, the effective load continued to increase, regardless of the presence or absence of an auditory memory representation. None of the other main effects or interactions was significant.

DISCUSSION

The goal of our study was to examine the effect of verbal working memory load on attention cost. We adopted a dual-task paradigm in which the memory load increased along a random digit list to be recalled and the attention cost of the memory task was inferred by measuring the speeded CRT task accuracy. The results showed that the increasing memory load caused a significant accuracy decrement on the speeded CRT task after the third serial position on five-digit lists—that is, when the list exceeded the three or four verbal items that can be held in a core working memory capacity according to our understanding of past work (Chen & Cowan, 2009; Cowan, 2001).

The present results demonstrate a conflict between retention of spoken or printed digits and an attention-demanding task, the speeded CRT task, which requires rapid manual responding to a nonverbal visual stimulus. The primary evidence of this conflict was impaired CRT performance in the presence of a memory load. The explanation of this CRT impairment must take into account two additional facts. First, much less interference with CRT performance was observed in the control conditions, in which there was almost no memory load. Second, in the high-load condition, there was more interference with CRT performance at later serial positions of the list. Mechanisms of the interference between tasks could include the need for attention in working memory to integrate the representation of each new digit with representations of already presented digits (Cowan, Morey, Chen, Gilchrist, & Saults, 2008) or the need for attention in working memory to refresh the already presented digits (Raye, Johnson, Mitchell, Greene, & Johnson, 2007), since either of these mechanisms correctly predicts increasing effects on CRT performance across serial positions of a list of random digits.

Let us further consider why a verbal memory load requires attention, despite the apparent automaticity of covert phonological rehearsal in adults (Baddeley, 1986; Guttentag, 1984). Attention may allow lexical or semantic codes for words in a list of verbal stimuli to be retrieved from long-term memory and maintained in working memory. The recall of lists of words that have lexical and semantic codes in long-term memory is far superior to the recall of lists of nonwords with no such codes (e.g., Baddeley, 1986). The lexical/semantic codes place constraints on the sequence of phonemes in memory and may therefore help to bind the phonemes into the correct sequence in the phonological representation (Hoffman, Jefferies, Ehsan, Jones, & Lambon-Ralph, 2009). Verbal recall may therefore require an attention-based mechanism that holds the lexical and/or semantic memory and supplements automatic phonological rehearsal, which in turn helps in the retention of serial order. This concept is theoretically consistent with the idea of a focus of attention guiding the use of activated elements from long-term memory (Cowan, 1999) or, in slightly different terms, with the idea of information in an episodic buffer, maintained by the central executive, complementing the use of a phonological store (Baddeley, 2000).

The memory load effect on attentional processing that we observed in the present study is consistent with the processing time effect in a verbal–spatial span test reported by Maehara and Saito (2007). The nature of these effects points to an attention-based interference between storage and processing within the framework of working memory. Using response accuracy rather than the latency of a speeded CRT task as an indicator of attention cost, our present study further demonstrates that the magnitude of this interference is a function of memory load, which suggests that working memory per se might be a product of active attentional processing rather than a function of some passive memory buffers.

It has been suggested by a number of investigators that there is an important attention-related component of working memory that accounts for its correlation with intelligence (e.g., Cowan et al., 2005; Kane, Bleckley, Conway, & Engle, 2001; Vogel, McCollough, & Machizawa, 2005). The present finding across serial positions is consistent with that suggestion, inasmuch as Unsworth and Engle (2006) found that simple memory spans correlate with intelligence only after the list length reaches about four items and that the correlation grows stronger across list lengths. Although we believe that the maintenance of items in working memory probably requires attention, a greater taxing of attention may occur when the core capacity of three or four items is surpassed. At that point, a different processing strategy might have to be used, in which considerable excess attentional capacity is devoted to refreshing items by bringing them back into the focus of attention as they fall out through interference or decay. Past research, as well, has proposed that an attention-demanding refreshment process is necessary to circulate items into the focus of attention as they leave it because of interference or decay (Cowan, 1992; Hulme, Newton, Cowan, Stuart, & Brown, 1999)—that is, to refresh their representations (Raye et al., 2007).

Our finding is complementary to the observation that retention of an array of nonverbal visual items is impaired by a tone identification task (Stevanovski & Jolicœur, 2007) and therefore seems to require attention. It also seems to converge with the finding in previous work by Barrouillet et al. (2007) that memory for consonants depends on the amount of time engaged in an attention-demanding secondary task. They proposed that the memory of items in a working memory task imposes a cognitive load. The maintenance of that cognitive load appears to be susceptible to interruption by tasks interpolated in the period between items in recall in a time-dependent manner—the higher the proportion of interitem time that is taken by the interpolated task, the more distraction and the poorer the recall of items in the list. The present research turns those procedures around by measuring, rather than manipulating, the effects of memory maintenance on the attention-demanding secondary task, which in this case was a speeded CRT task. The results indicated that it is the memory load that is important; the impairment in the CRT task increases steadily as the load increases to three, four, and five digits (Figure 2). It may be that an even more sensitive measure could show a difference in the attention needed for one versus two items in memory (Cowan, 2001). If so, the assumption would be that, in the present task, there were attentional resources left over that were sufficient for the CRT task until there were at least three digits in memory. Overall, this effect of memory load should be in line with the time-based resource-sharing model (Barrouillet, Bernardin, & Camos, 2004), which conceives that *working memory* may be essentially equivalent to *working attention*: the more time attention works on refreshing memory representations, the better the recall performance and vice versa.

CRT performance can be accounted for by the need for more attentional resources or the greater amount of time spent using those attentional resources at the point at which the core working memory capacity (Chen & Cowan, 2009; Cowan, 2001) is exceeded. There are, however, at least two slightly different models that could theoretically include this same basic mechanism to account for the data. One model is Cowan's (1999) embedded-processes model of working memory, and the other is Oberauer's (2002) concentric model. These models both hold that there is a currently activated portion of long-term memory and a limited-capacity region within that currently activated portion. Cowan (1999) terms that limited-capacity region the *focus of attention*, whereas Oberauer proposed that there is a one-item focus of attention within the limited-capacity region. According to Cowan (1999), as the memory load increases across serial positions, the storage of items in the focus of attention can draw more and more resources away from the CRT task. According to Oberauer, under the assumption that the limited-capacity region is not part of the attentional resource, this conflict between storage and processing would not increase across items. However, according to either model, the use of attention to refresh items would increase as the working memory load increased, taking attention away from the CRT task. This process is similar to what Barrouillet et al. (2004; Barrouillet et al., 2007) proposed. The Cowan (1999) and Oberauer models thus make similar predictions. They also become less distinct from one another if one assumes that Oberauer's limited-capacity region consumes attention for the storage of items even though most of those items are not in what is called the focus of attention. The distinction between the models therefore depends to some extent on a clarification of the Oberauer model, and must probably rest on evidence other than that in the present study.

Another aspect of our results warrants further research. We do not know why the memory load effect that emerged as a significant interaction across the first four serial positions in five-digit lists and was significant at Serial Position 4 within those lists was not also significant for four-digit lists. Given that the list length was known to the participants at the outset of each trial, it appears that expectation of a fifth digit diminished the attention allocated to the CRT task at the fourth position and possibly to prior positions to a lesser extent. Under the assumption of a fixed amount of attentional capacity, this could in principle occur for two reasons. First, expectation of a fifth digit could cause more attention to be devoted to the digits at the fourth position and possibly to prior positions than when only four digits were expected, at the expense of concurrent CRT performance. This might occur in anticipation of attention's being needed to prevent retroactive interference with memory because of the presentation of the fifth digit. Second, expectation of a fifth digit could cause some attention to remain unused during the presentation of the first four digits, in order to make it easier to allocate that attention to the fifth digit along with the concomitant CRT task.

The present data shed light on several other fundamental issues. One has to do with the availability of multiple memory codes at once. An auditory sensory memory code for the most recent event or two persists automatically for a few seconds (Cowan, 1984; Penney, 1989) and could therefore make it unnecessary for an attention-based code to be saved for those items. The present data show, however, that the memory load increases throughout a spoken list, as was judged by monotonically decreasing performance on the speeded CRT task across serial positions, despite the availability of auditory sensory memory at the end of the list (Figure 3B).

Finally, this study demonstrates a microanalytic approach that may potentially benefit research on individual differences in working memory capacity. It has been suggested that working memory span is related to the ability of attentional control. For example, Kane and Engle (2000) found that an attention-demanding secondary task affected recall performance differently for people with low versus high working memory spans and under different levels of proactive interference. For a deeper understanding of the attentional mechanisms underlying those individual differences, the present procedure will be useful in determining how people differ in terms of the amount of attentional resources available and/or in terms of the pattern of attention allocation for holding a transient memory load.

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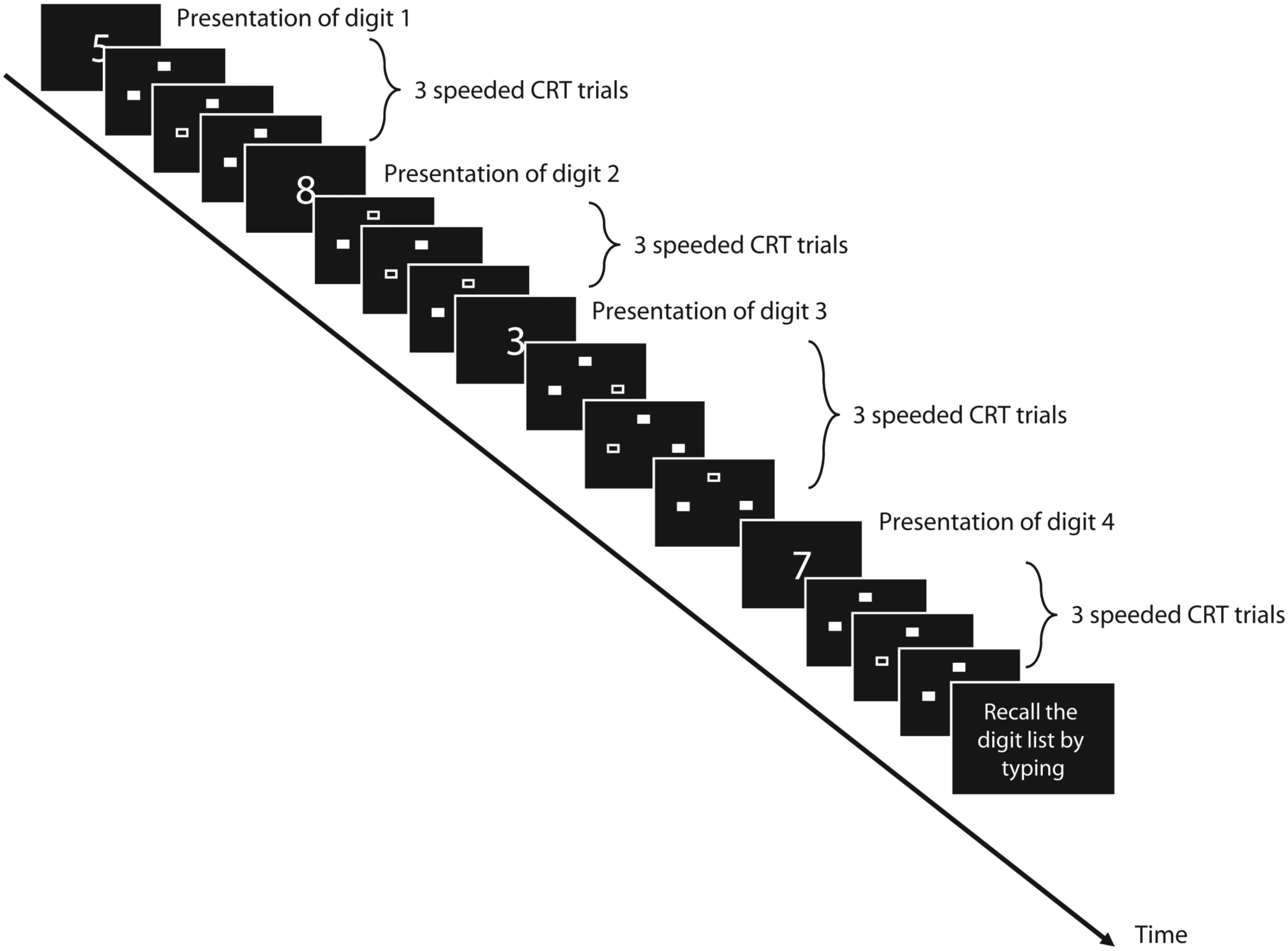

Figure 1.
An illustration of the procedure on a four-digit trial in the dual-task stage. The digits were auditory or visual, depending on the trial block. Target squares shown here in outline were red in the experiment.

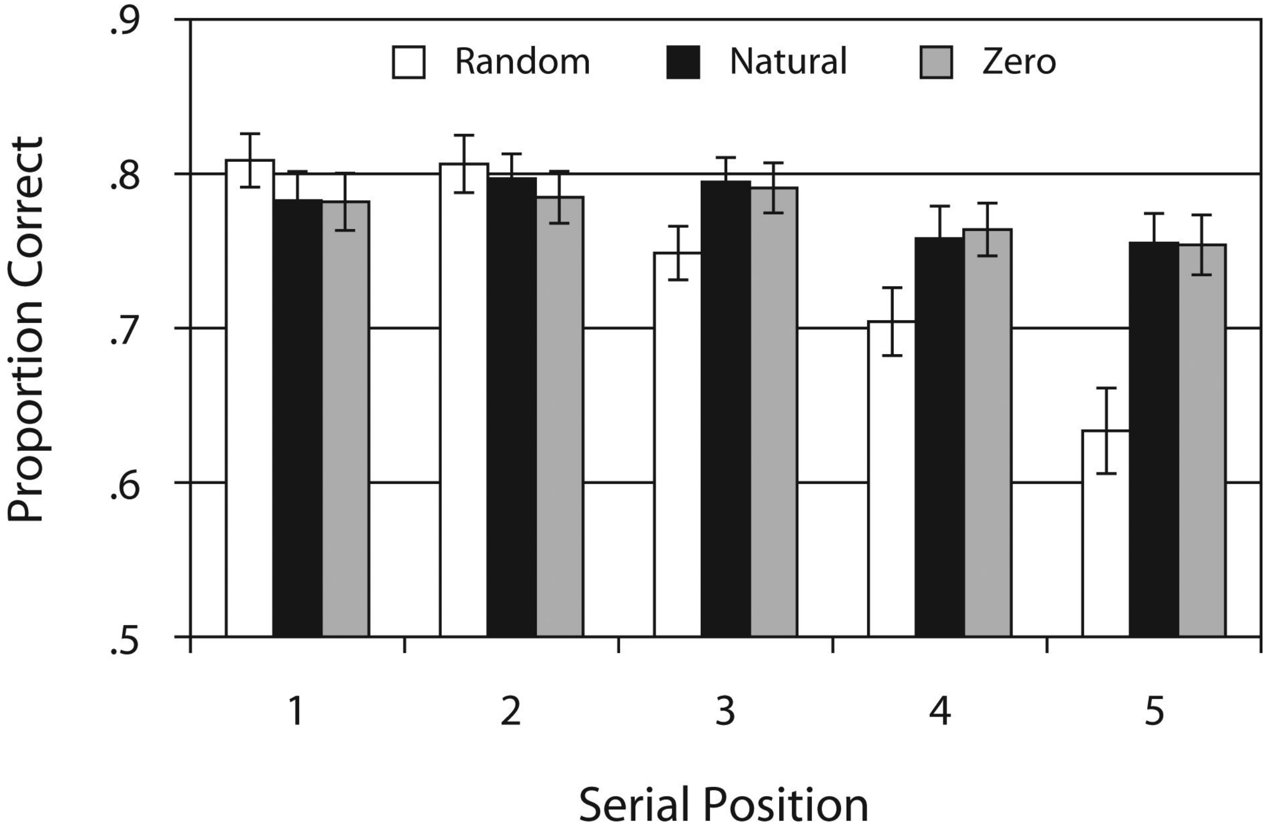

Figure 2.
Proportion correct choice reaction time (CRT) task performance at each serial position in the five-digit condition collapsed across modality (visual or auditory) during the dual task. Error bars represent ±1 *SEM*.

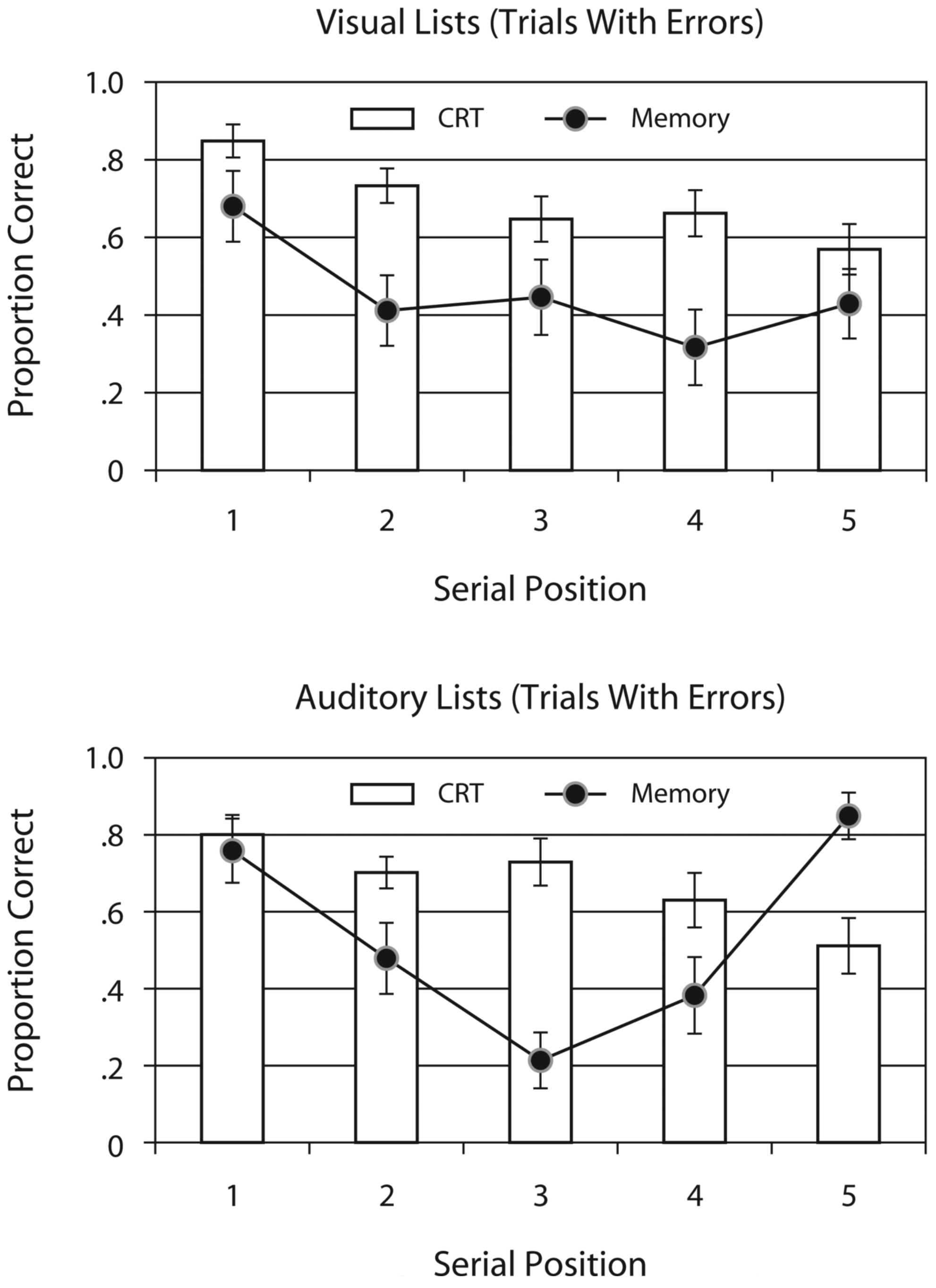

Figure 3.

Proportion correct of choice reaction time (CRT) performance (bars) and recall performance (lines) at each serial position for trials in which there was a memory error. The number of trials with recall errors per participant was *M* = 1.54 (*SD* = 1.63) for the auditory digit trials and *M* = 1.30 (*SD* = 1.16) for the visual digit trials. There were 24 and 28 participants contributing at least one trial with recall errors to the auditory digit trial block and the visual digit trial blocks, respectively. (A) Visual digit trial blocks. (B) Auditory digit trial blocks. Error bars represent ±1 *SEM*.

Table 1

Mean Accuracy of Speeded Choice Reaction Time (CRT) Task for Error-Free Trials in the Dual-task stage

		Serial Position									
		1		2		3		4		5	
Condition	**List Length**	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Auditory Lists											
Natural	4	.80	.14	.78	.16	.79	.15	.74	.18		
	5	.76	.15	.79	.14	.77	.13	.76	.16	.77	.13
Random	4	.77	.17	.80	.15	.74	.17	.71	.18		
	5	.79	.15	.79	.17	.74	.15	.70	.15	.62	.21
Zeros	4	.80	.14	.81	.11	.79	.12	.75	.16		
	5	.78	.14	.79	.13	.80	.13	.75	.15	.73	.16
Visual Lists											
Natural	4	.82	.10	.81	.11	.79	.11	.79	.10		
	5	.80	.14	.80	.10	.82	.09	.76	.15	.74	.15
Random	4	.85	.12	.80	.01	.76	.12	.75	.13		
	5	.83	.10	.82	.12	.76	.14	.71	.17	.64	.16
Zeros	4	.80	.11	.78	.15	.76	.16	.76	.16		
	5	.78	.13	.78	.12	.78	.11	.78	.15	.78	.13

Note—List length is expressed as a number of digits per list. Mean accuracy is expressed as the proportion correct of the speeded CRT task responses.