COGNITIVE LOAD AND TIME-BASED FORGETTING

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by
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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

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and hereby certify that, in their opinion, it is worthy of acceptance.

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ABSTRACT

Recently, various researchers have claimed that time does not play a direct role in short-term forgetting. Instead, they claim that time is only related to forgetting because it is correlated with other factors that cause forgetting. Although the case against absolute time-based forgetting is strong, we believe this view to be incomplete. In 2 experiments, we show that substantial forgetting occurs due to the passage of time in at least one situation. On each trial, an array of novel characters was followed by a post-perceptual mask, a variable retention interval, and a probe item to be judged changed or unchanged from the array. There was a pronounced effect of the retention interval duration and, independent of it, an effect of the cognitive load or proportion of the interval consumed by an acoustic digit processing task. The results demonstrate that both cognitive load and absolute length of retention play important roles in the loss of information during short-term retention in the present procedure.

Chapter 1: General Introduction

Over the past decade a number of researchers have argued that the passage of time has no effect on forgetting from immediate memory (Lewandowsky, Duncan, & Brown, 2004; Oberauer & Lewandowsky, 2008). Others have argued that what is important is not the absolute amount of time over which information must be retained, but rather that the ratio of time that attention is occupied relative to total retention duration (Barrouillet, Bernardine, & Camos, 2004; Barrouillet, Bernardine, Portrat, Vergauwe, & Camos, 2007; Portrat, Barrouillet, & Camos, 2008). These theories directly contradict the once dominant time-based explanations of forgetting such as trace decay theory (Brown, 1958). A recent study by Zhang and Luck (2009), however, demonstrates forgetting over a short time interval with no interfering task that may be responsible for the loss in memory. In the following pages we give a brief review of the relevant literature and report the findings of our investigations into how interfering events and cognitive load interact with time in order to cause forgetting in a visual working memory task.

Early investigations by Brown (1958), Peterson and Peterson (1959), and others revealed that time is closely linked to the rate at which we forget information over short periods of time. Baddeley (1986)'s influential phonological loop model buttressed belief in time-based forgetting by incorporated these findings into a working memory framework which asserted that items are forgotten from working memory due to the decay of memory traces with time unless they are maintained through overt or covert rehearsal. This assertion was backed up by evidence that the average adult can remember about the same number of items as can be rehearsed in 1.8 seconds. Although the phonological loop model was dominant for many years, it was eventually discredited by evidence that interference and not decay was responsible for many instances of forgetting (Nairne, 2002). Particularly damaging was data showing that with the amount of phonological interference controlled, just as many, or more, long words can be maintained in short-term memory as short words, invalidating the notion that what accounted for memory loss is the amount of decay occurring before rehearsal could occur (Caplan, Rochon, & Waters, 1992; Lewandowsky & Oberauer, 2008; Service, 1998).

With the fall of the phonological loop model, two other major types of approaches now characterize how forgetting is conceptualized. One type, the event-based models, rejects the notion of memory decay whereas the other, the cognitive load models, accepts decay without expecting direct evidence of it. The former, event-based models such as serial-order-in-a-box, SOB for short, (Farrell & Lewandowsky, 2002; Oberauer & Lewandowsky, 2008) and feature models (Nairne, 1990; Oberauer & Kliegl, 2006) claim that the passage of time is predictive of the amount of forgetting that occurs in a short-term memory task because as more time passes between encoding and recall of items, more events occur that cause forgetting. This means that time is correlated with forgetting because longer periods of time tend to contain more interfering events.

An example of the support for event-based models can be seen in Lewandowsky et al. (2004) who strongly rebuked time-based models. In this study participants performed serial recall of letters while uttering the word “super” 1, 2, or 3 times between the recall of each letter. Interference theories generally predict that there should be no increase in forgetting for 2 or 3 utterances between responses because no novel interfering items or processes beyond the first “super” will be introduced. Time-based explanations, however, predict additional forgetting with an increase in the number of utterances between responses because more time will pass before the later items are reported. If this time-based forgetting exists it should be observable as increased fanning of serial response curves as serial position increases. Lewandowsky et al. reported no fanning and thus concluded that time did not play a role in forgetting.

A second type of theory addressing the cause of forgetting from short-term memory is the cognitive load account given by Barrouillet et al. (2004, 2007). Barrouillet et al.'s Time-Base Resource-Sharing (TBRS) model of working memory claims that forgetting occurs because the cognitive load, or the ratio of time during which attention is occupied by non-maintenance tasks to total maintenance time, is too great for all items in short-term memory to be maintained. This is because items are proposed to be activated memory traces that decay quickly with time and must have their activation refreshed by directing attention to them, or they will be forgotten. According to this model, the attention-based refreshing mechanism can only attend to one item at a time. Retrieving items from long- term memory in service of non-maintenance tasks also requires the refreshing mechanism and thereby impose a cognitive load. In the TBRS account the absolute amount of time which passes between encoding of items and recall of items is unimportant, time is only a factor in how it affects the cognitive load. In many instances increasing retention time should actually result in a decrease in forgetting due to the lowered cognitive load. In principle this theory is similar to the phonological loop theory but with two important differences: (1) it specifies attention as the refreshing device rather than covert verbal rehearsal, and (2) more detailed predictions have been stated related to the effects of different schedules of distraction.

Evidence in favor of cognitive load based forgetting is plentiful (Barrouillet et al., 2004, 2007; Lepine, Bernardine, & Barrouillet, 2005; Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008; Portrat et al., 2008). The vast majority of these studies (the exceptions being Experiments 3 & 4 of Liefooghe et al., 2008) have been conducted with a continuous span task procedure in which a list item is presented, followed by a simple processing task which is repeated at a constant rate. This pattern is repeated until all list items have been presented, at which point recall of the whole list is required. The time during which the processing task is conducted is used to determine the cognitive load of the task. In these experiments the cognitive load is strongly predictive of the number of items that can be maintained, with any increase in cognitive load resulting in fewer items being remembered.

Despite the TBRS model's success, an alternative explanation for the cognitive load related forgetting was proposed by Oberauer and Kliegl (2006) in which memory traces are damaged by interfering representations. Free time during maintenance is then used to repair any damage that the memory traces sustained due to interfering events. The critical testable difference between these two accounts of the cognitive load data are that in the TBRS model total occupied time during which forgetting occurs is important, whereas in the interference account the amount of free time available for repair is important. Portrat et al. (2008) appeared to provide evidence against the interference explanation, showing that it was time for memory decay and not time for memory repair that influenced memory performance. Lewandowsky, Oberauer, and Brown (2009), however, claim that reanalysis of the Portrat et al. data in fact provides evidence in favor of the interference explanation. Despite their differences, both explanations predict no effect of total time that a memory item must be remembered, only an effect of time in relation to how it influences the cognitive load of any secondary task.

Recently, Zhang and Luck (2009) demonstrated forgetting over time in a visual array task with no intervening events or cognitive load that could be responsible for the loss of memory items from short-term memory. In visual array tasks multiple items are presented concurrently for a brief duration. The items are then masked to prevent any sensory memory contributions to performance, and after a brief delay one item is presented on the screen. The participant must then judge whether the item is the same as it was in the original multi-item array or different.

We wished to investigate how individual events and cognitive load interacted with this purely time-based forgetting observed by Zhang and Luck. In order to do so we used a visual array task similar to Zhang and Luck, except that, where Zhang and Luck used colored squares and simple shapes as memory items, we used complex character stimuli that were likely to be novel to the participants. We did this in order to minimize rehearsal and other memory strategies that may counteract any time-based forgetting. We also hoped that the lack of or impoverished nature of any long-term memory representation of our stimuli would increase our ability to observe forgetting over time. In addition to the change in memory items from the Zhang and Luck investigations, we also included a secondary task that varied in cognitive demand in order to investigate how interfering events and cognitive load interact with any purely time-based effect.

Chapter 2: Experiment 1

In Experiment 1 we used a visual array of unfamiliar visual stimuli (novel characters) with a variable retention interval to investigate how items are forgotten over time. During the retention interval we also varied the difficult of a secondary task, so that we could observe conditions with relatively no interference and cognitive load, relatively low interference and cognitive load, and relatively high interference and cognitive load. This was accomplished by setting computer speakers to produce spoken digits at a fixed rate during the retention interval. Participants were instructed either, to ignore the digits (no load), repeat the digits (low load), or subtract one from the digits and respond verbally with the result (high load). By maintaining a constant rate and constant set of stimuli across conditions we manipulated both cognitive load and the level of interference together, independent of any other variables in the procedure.

The preceding discussion provided a brief description of several models which have clear predictions about how time and any secondary task should affect performance for a visual array memory task (Figure 1) which we will make explicit. First, a pure effect of time similar to that predicted by early decay theories (Baddeley, 1986; Brown, 1958) would predict a drop in visual array memory performance as retention intervals increase (Figure 1a). While this simple model seems unlikely it may be observed in combination with other models.

A pattern of results in line with event-based forgetting such as that predicted by the SOB model would consist of no forgetting as a function of time for the no load condition, as there are no interfering representations to process, a small amount of forgetting with time in the low load condition, due to the small magnitude of the interfering repetition events, and a greater rate of forgetting in the high load condition due to the greater amount of interference produced by the subtraction events. Thus, the resulting pattern of means should exhibit fanning, as illustrated in Figure 1b, if processes consistent with the SOB description are operating.

The TBRS model on the other hand, predicts no effect of retention interval duration on visual array memory performance, because the cognitive load will be held constant across the entire retention interval. An effect of cognitive load would be predicted, however, with higher load conditions resulting in progressively more forgetting (Figure 1c). Perhaps the most interesting results may emerge from a combination of the time-based models and the TBRS model. If forgetting similar to that found by Zhang and Luck (2009) is found as well as forgetting due to cognitive load, consistent with the findings of Barrouillet and colleagues, we would expect to see two independent effects, one time-based and one load-based (Figure 1d).

Method

Participants. The participants were 32 students from the University of Missouri who participated in exchange for course credit. Data from 2 participants were not analyzed because they demonstrated less than 90% accuracy on the secondary task in one or more blocks, leaving a total *n* of 30. This cutoff was chosen to be consistent with, but more conservative than, complex span task procedures which generally use a cutoff of 85% secondary task accuracy.

Apparatus and Materials. The experiment took place in a sound attenuated booth with participants seated at a comfortable distance from the computer screen. All visual stimuli were displayed on a desktop computer monitor within the center 270 x 201 pixel area of the screen, excluding the center point. Visual array task stimuli were 113 characters from the extended character sets in Microsoft Word 2002, shown in black on a grey background. Each character occupied 30x30 pixels. Characters were selected because they were not easily namable by the authors. Auditory task stimuli were the numbers 1-9 spoken by a computer generated male voice. The spoken digits were presented at a loud but comfortable listening volume. Each digit's individual sound level was determined by altering them to be subjectively the same volume level. The adjusted digits differed by a maximum measured volume of 3 dB(a) at their peaks.

Design and Procedure. The experimental procedure was a dual-task design consisting of a visual array memory task and an auditory secondary task that was performed during the visual array retention interval (RI). Total RI Duration (1500, 3000, or 6000 ms) and Cognitive Load (None, Low/Repeat, or High/Subtract) were manipulated within participants, resulting in a 3x3 within-participant design. Cognitive Load was manipulated by providing instructions consistent with 1 of the 3 load tasks before each block. Participants were instructed not to perform any task associated with the digits in the no-cognitive-load condition, to repeat the digits in the low-cognitive-load condition, or to subtract 1 from the digit and then speak the result in the high-cognitive-load condition.

As shown in Figure 2, each trial started with a fixation cross displayed in the center of the screen for 1000ms. Next, an array of 3 unfamiliar characters (the reference array) appeared on the screen for 750 ms, followed by a blank screen for 250 ms, and then a visual mask which remained for 100ms. After the mask offset, a blank screen was displayed for a variable duration of 1400, 2900, or 5900 ms. During the blank retention interval, participants heard digits spoken over computer speakers at a rate of one digit every 1500 ms. Repetition and subtraction were to be performed as quickly as possible after hearing each digit. The participants spoke each digit out loud as soon as possible at a volume loud enough to be heard by an experimenter who sat in the booth and monitored compliance. After the blank retention interval, a single character was presented on the screen in the same position as one of the characters in the reference array. Two circles appeared along with the single character to mark the positions of the undisplayed characters from the reference array. At this point participants entered a response by pressing the “s” key if they thought the single character was the same character as was displayed in its position in the reference array, or the “d” key if they thought the single character was a different character. In half the trials the character in the test array was the same as it was in the reference array, and in the other half it was a different character that was not found anywhere in the reference array. The order of the same/different trials was randomized.

Experiment 1 started with 10 basic array practice trials with no secondary task. The experimental portion of the procedure consisted of 9 blocks of trials, 1 block for each combination of cognitive load and retention interval duration. Trials were ordered so that participants completed all 3 blocks of trials at each cognitive load consecutively, 1 block for each duration, and then moved on to the next cognitive load condition. A set of 10 practice trials, including both the array task with a 3000ms delay and the secondary task, was performed before the experimental trials for each cognitive load condition. The order of the cognitive load conditions was determined through a latin square design, while the duration order was randomly assigned for each participant.

Results

Mean visual array accuracies for all conditions are shown in Figure 3. A 3x3 within-participants ANOVA of Cognitive Load (None, Low/Repeat or High/Subtract) and RI Duration (1500, 3000, or 6000 ms) produced a main effect of Cognitive Load, F(2, 58) = 19.42, MSE = .0057, $\eta_p^2 = .40$, $p < .0001$, with the None and Low/Repeat condition demonstrating better performance than the High/Subtract condition (means: for None, 0.83; for Low/Repeat, 0.81; for High/Subtract, 0.76). This was confirmed by Newman-Keuls tests of the Load manipulation, with no significant differences in performance between the Low Load and No Load conditions, but significantly worse performance in the High Load condition than in the Low and No Load conditions. There was also a main effect of RI Duration, F(2, 58) = 19.00, MSE = .0069, $\eta_p^2 = .40$, $p < .0001$, due to better performance at shorter delays (means: for 1500 ms, 0.84; for 3000 ms, 0.79; for 6000 ms, .77). This was confirmed by Newman-Keuls tests of the RI Duration manipulation, with significantly better performance in the 1500 ms delay than in the 3000 or 6000 ms delays and a marginally significant performance advantage for the 3000 ms delay over the 6000 ms delay. Importantly, there was no interaction between the two factors, F(4, 116) = 0.295, MSE= .0053, $p > .05$.

Discussion

The results from Experiment 1show a clear effect of RI duration on visual array accuracy, with longer delays resulting in lower performance regardless of the cognitive load. This effect is purely time-based as it is observed to the same degree across all load conditions, including the no load condition. Additionally, there was no fanning across conditions, which would have been observed empirically as an interaction between the RI duration and the cognitive load, indicating that there was no event-related interference contributing to this effect.

Experiment 1 also produced a clear effect of cognitive load driven by impairment in performance when a secondary subtraction task was used to induce a cognitive load during memory maintenance, relative to repeating a spoken digit as the secondary task or performing no secondary task. The subtraction task caused an equal impairment in visual array performance across all delays, producing no interaction between cognitive load and RI duration. This is consistent with predictions from the TBRS model.

Although there was an effect of subtraction, simply repeating the spoken digits did not impair performance on the visual array task relative to doing nothing. [1] At first glance this seems somewhat concerning considering the outcomes of past experiments showing that simply reading a series of numbers or letters induces a cognitive load, and reading a series of numbers or letters at a faster rate results in a greater cognitive load (Barrouillet et al, 2004; Lepine et al., 2005). This is assumed to be because reading a number involves retrieving the representation of the digit from memory requires attention. Given the present results, we believe that hearing a spoken number and repeating it does not involve an attention demanding memory retrieval of the same sort, perhaps because a brain system exists that can convert spoken input easily into motor output. Mcleod and Posner (1984) provide evidence for a system that serves this function and it seems likely that it is used to perform the digit repetition task. The existence of mixed transcortical aphasia (for an example see, Rapcsak, Krupp, Rubens, & Reim, 1990), a disorder in which patients cannot understand or produce speech but can repeat what they hear, also supports this conclusion.

The present results appear to be consistent with the predictions of the hybrid time-based forgetting and TBRS model illustrated in Figure 1d. There is, however, another possible process that could produce the same pattern of results. The present pattern of effects would also be expected if the attention demanding subtraction task simply disrupted further consolidation of the visual array. This seems unlikely because the mask, which precedes the cognitive load, should already have disrupted all sensory memory (Vogel, Woodman, & Luck, 2006). If, despite previous findings, there is further consolidation of abstract attention-based memory representations rather than simply consolidation of sensory memory, then more time available to consolidate the memory should result in better memory performance. A post-sensory consolidation process that is disrupted by subtraction more than by simple digit repetition should be much more damaging when the subtraction occurs early in the retention interval than when the subtraction occurs late in the interval because less time will have passed to allow consolidation to take place. In Experiment 2, therefore, we tested this post-sensory consolidation hypothesis by varying the onset of an attention-demanding and a relatively attention-free secondary task during the RI.

Chapter 3: Experiment 2

Method

Participants. The participants were 36 students from the University of Missouri who participated in exchange for course credit. Any participant who demonstrated less than 90% accuracy in the secondary task or who performed at or below chance level in at least one condition of the primary task was not used in the data analysis. In total we discarded the data from 4 participants placing the total *n* at 32.

Apparatus and Materials. All stimuli were the same as in Experiment 1, except that the measured sound level of the verbal stimuli ranged by 8 dB(a) at peak volume. This was an unanticipated consequence of changing to a different type of loudspeaker. All verbal stimuli were still easily and comfortably perceivable. Otherwise, all testing conditions and materials were the same as in Experiment 1.

Design and Procedure. Experiment 2 was a 3x2 within-participant design in which Distracter Onset Delay (0 ms, 1500 ms, or 3000 ms) and Cognitive Load (Low/Repeat or High/Subtract) were manipulated. The same procedure was used as in Experiment 1 with a few modifications. In the current experiment RI duration was held constant at 6000 ms, with only two spoken digits occurring during the blank interval separated by 1500 ms. Participants were instructed either to repeat the digits they heard or to subtract 1 from each digit they heard and speak the result out loud. The spoken digits began either 0, 1500, or 3000 ms after the offset of the mask.

At the start of the experiment, participants completed a set of 10 practice trials of the basic array task. Participants then performed all 6 blocks of experimental trials. Half of the participants completed 3 subtraction task blocks first, one for each onset condition, and 3 digit-repetition task blocks second. The remaining half of the participants performed the load tasks in the opposite order. The order of the onset blocks was random within each load condition. Before the experimental trials for each condition a set of 10 practice trials was administered using the current load condition as the secondary task with the intermediate, 1500-ms onset delay.

Results

Mean visual array accuracies for all conditions are shown in Figure 4. A 3x2 within-participant ANOVA of Distracter Onset (0, 1500, or 3000 ms) and Cognitive Load (Low/Repeat or High/Subtract) produced a marginal effect of cognitive load, $F(1, 31) = 3.989$, $MSE = .0079$, $\eta_p^2 = .11$, $p = .057$, with the Low/Repeat condition demonstrating better performance than the High/Subtract condition (means: Low/Repeat = 0.78, High/Subtract = 0.75); but no effect of Distracter Onset, $F(2, 62) = 1.179$ $MSE = .0066$ $p > .05$; and no significant interaction between the two factors, $F(2, 62) = 0.113$, $MSE= .0065$, $p > .05$.

Discussion

Experiment 2 provided no evidence for post-sensory consolidation of attention based memory traces. It also provided only marginally lower performance for the Subtract condition than for the Repeat condition. We assume that this is because during half of the RI period no task was to be performed by the participant, resulting in a lower total cognitive load and allowing whatever maintenance strategy or processing the participant wished to carry out. This likely aided performance for the subtraction condition more than the digit-repetition condition, as repetition does not appear to require appreciable working-memory maintenance-related resources, leaving half the period free for memory maintenance strategies. Altogether, Experiment 2 supports our conclusion that the decreased accuracy in the subtract condition of Experiment 1 was due to an increase in cognitive load as described by the TBRS model.

Chapter 4: General Discussion

In the present study of memory for unfamiliar characters we examined how the passage of time affects short-term retention. Additionally, we investigated how cognitive load and interference events interact with the passage of time during short-term retention The results of Experiment 1 (shown in Figure 3) showed that memory for an array of unfamiliar characters decreased with retention time, irrespective of the amount of interference present during the delay between encoding and recall. There also was an effect of cognitive load that did not change with the retention interval. The effect of retention time could be predicted from the interference theories for the cognitive load conditions, but not for the condition in which there was no cognitive load (Figure 1b). The effect of cognitive load could be predicted according to the TBRS theory, but it could not predict the effect of retention interval (Figure 1c). Notably, the entire pattern of results can be predicted on the basis of hybrid account in which there is both a portion of the memory representation that decays regardless of interference or distraction and cannot be rehearsed or refreshed (see Figure 1d) and another portion that operates as specified in the TBRS theory. The findings of the second experiment provide assurance that the latter component does depend on cognitive load per se, and not on the amount of uninterrupted encoding time.

While the findings do not argue against interference based accounts of forgetting, such as the SOB model (Farrell & Lewandowsky, 2002) and feature model (Nairne 1990; Oberauer & Kliegl, 2006), or the cognitive load based account of the TBRS model, it does demonstrate that these models are incomplete. Under some conditions at least, the passage of time does play a causal forgetting, in contrast to some recent claims (Lewandowsky et al., 2004; Oberauer & Lewandowsky, 2008). In the present study it is not clear whether this effect is due to a temporal distinctiveness effect or decay of activated memory traces, but the decrease in accuracy is clearly time based.

Recently, Zhang and Luck (2009) found no difference between 1 and 4 s retention intervals but decreasing memory for both shapes and colors after the 10-s interval. Our findings show a quicker rate of memory loss but, we also used more complex figures than those in Zhang and Luck (2009). Their findings are not necessarily at odds with ours because our complex, novel stimuli may require a richer quality of information to be held within working memory for correct recall to occur.

Theoretical Accounts of the Time-Based Effect

A Temporal Distinctiveness Explanation. Temporal distinctiveness theories argue that items are encoded with temporal context cues and as encoding becomes more distant the similarity between time cues becomes greater (Brown, Neath, & Chater, 2007; Unsworth, Heitz, & Parks, 2008). A helpful analogy to the temporal distinctiveness effect was offered by Crowder (1976) who explained that the viewing the temporal cues for items is similar to viewing a street lined with telephone poles. Nearby, the telephone poles seem to be far apart with distinct separation between them, but as you look farther down the street, the telephone poles appear to be closer and closer together, no longer maintaining a distinct separation from one another. Similarly, the temporal distinctness of an item in memory is a ratio of, the separation in time between the target item and its neighboring items (the distance between telephone poles), and the distance between the current time and the time of encoding (the distance from the telephone pole). This leads to more confusion between the target item and items that were presented on earlier trials when more time has elapsed between encoding and recall.

If time is having an impact on item memory through a loss of temporal distinctiveness, a straightforward explanation of the underlying memory structure emerges. Memory for items could be viewed as activated memory traces that are maintained through trace refreshing or repair. Either of these processes would be impaired by the cognitive load manipulation. Some portion of the trace that is associated with the temporal context in which the item was encoded would also exist. As time passes the temporal distinctiveness effect would act on this temporal aspect of the memory trace and poorer memory performance would result through an increase in proactive interference from items in earlier trials. In this system then, memories traces code for temporal context and as the current time gets further from the time of encoding the temporal trace becomes less distinctive, resulting in a less specific memory. This loss of trace distinctiveness, and the resulting confusion with similar items, would be time dependant and not affected by the attention applied to the memory trace.

A Trace Decay Explanation. Trace decay accounts of working memory posit that memories are activated traces that decay with time until they are forgotten. The present findings suggest the existence of 2 separate types of short-memory storage if trace decay is responsible for the time-based effect. The first storage type seems to be modality-free attention-based storage of information consistent with theories such as the TBRS model (Barrouillet et al., 2004, 2007) and the embedded-process model (Cowan, 1988, 1995). This information is affected by removal of attention from the to-be-remembered items as was manipulated in this study by increasing the cognitive load. A second storage type is necessary as well because some aspect of the memory trace cannot be maintained through attention based methods even when no secondary task is required. This second memory type seems to be a form of non-sensory visual memory that is not attention-dependant and is lost over time. This memory may be similar to the visual cache, a passive storage buffer for visual patterns, described by Logie (2003), although it may not be as modular as Logie suggests. Alternatively, it may be a collection of visual features which are bound into an item similar to the conceptualization of Sakai and Inui (2002). Sakai and Inui posit that visual items are stored as a set of perceptual features that decay with time due to increasing memory noise. We believe that these two types of memory models, in which the memories are related to the perceptual qualities of the stimuli, are most likely given the attention free nature of this storage.

Theoretical Account of the Load-Based Effect

The cognitive load manipulations in the present study generally support the TBRS model's description of maintenance and forgetting within the working-memory system. Although the addition of the time based effect is not present in the TBRS model in any form that we are aware of, there is no reason that it cannot be added for a more comprehensive explanation of forgetting across different tasks. In contrast, event-based theories of forgetting, such as SOB, do not predict the pattern of results observed here. Additional presentations of unpredictable digits and their use in simple subtraction problems did not produce additional forgetting as would be expected if they were providing discrete interference events. Although the present study supports the TBRS account of attention-based refreshing and refutes basic event-based models, it does not rule out an interference-and-repair explanation of our cognitive load findings, similar to the argument offered by Oberauer and Kliegl (2006). With such a fundamental mechanism for cognition being debated it is clear that future investigations should be undertaken to clarify which of these explanations is correct.

The present study also extends the paradigms used to test cognitive load models beyond continuous span tasks and delayed recall of verbal materials. Our task was a visual array memory task that used verbal materials to impose a cognitive load, affirming that the refreshing mechanism is a domain general feature. Continued demonstrations of cognitive load effects in more diverse situations are necessary in order to affirm the generality of cognitive load to working memory in general.

Concluding Remarks

A note of caution must be applied to our current findings. Our stimuli consisted of visual characters that are likely unfamiliar to college students in Missouri, such as the less commonly known Greek letters, Cyrillic letters, and Arabic letters. These stimuli may produce forgetting patterns that cannot be generalized to more familiar stimuli. The lack of a long term memory representation for our characters may have left participants more vulnerable to proactive interference or without a preexisting memory trace to activate and refresh. Instead they may have been forced to maintain all characteristics of the letters in an attention demanding binding which was impossible to maintain without loss. Further research is clearly needed to identify why we observed the loss in memory performance with time and whether it is confined to items that lack long-term memory representations or is ubiquitous throughout the working-memory system.

Despite the open questions, in 2 experiments we have demonstrated the influence of time on forgetting over the short-term. Critically, the time-based forgetting we observed was independent of the effect of cognitive load, which affected a separate component of the memory trace. In contrast to the recent assertions of some theorists (Lewandowsky et al., 2004; Oberauer & Lewandowsky, 2008), it is clear that time is an important factor in short-term retention in at least some situations. Further studies are necessary to determine the exact mechanisms through which time effects working and short-term memory, but the role of time cannot simply be dismissed.

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Footnotes

1. In the course of analyzing the results we discovered that a programming error was made in the no-secondary-task condition so that the correct answer for each trial alternated according to the pattern “same, different, same, different…” in perfect alternating order. A detailed analysis of the each participant’s data did not produce any evidence that participants recognized this pattern, most likely because the task was difficult and no feedback about their responses was given. The effect of the error should be to make this condition easier, so that any inferiority of the digit-repetition condition fortunately would be exaggerated, not obscured. That being said, our results in relation to this condition should be viewed with caution.

Figures

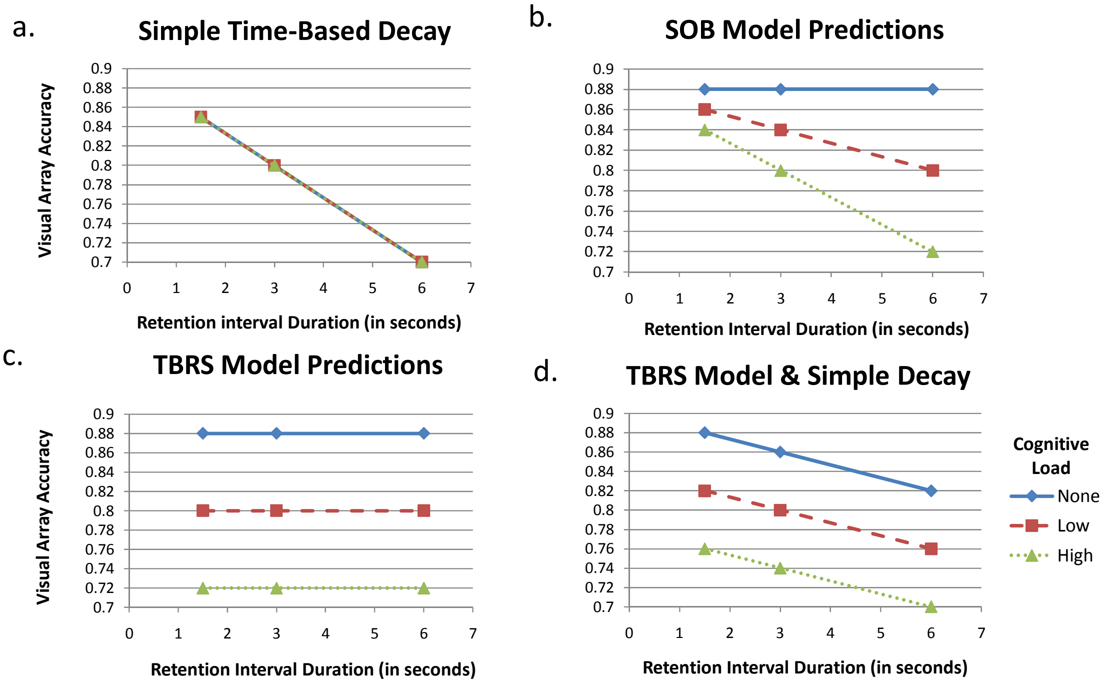

Figure 1. Predictions from several models. Although the above figures show a linear forgetting function, a non-linear (e.g., exponential or logarithmic) function is more probable and would not change the relationship between the load conditions.

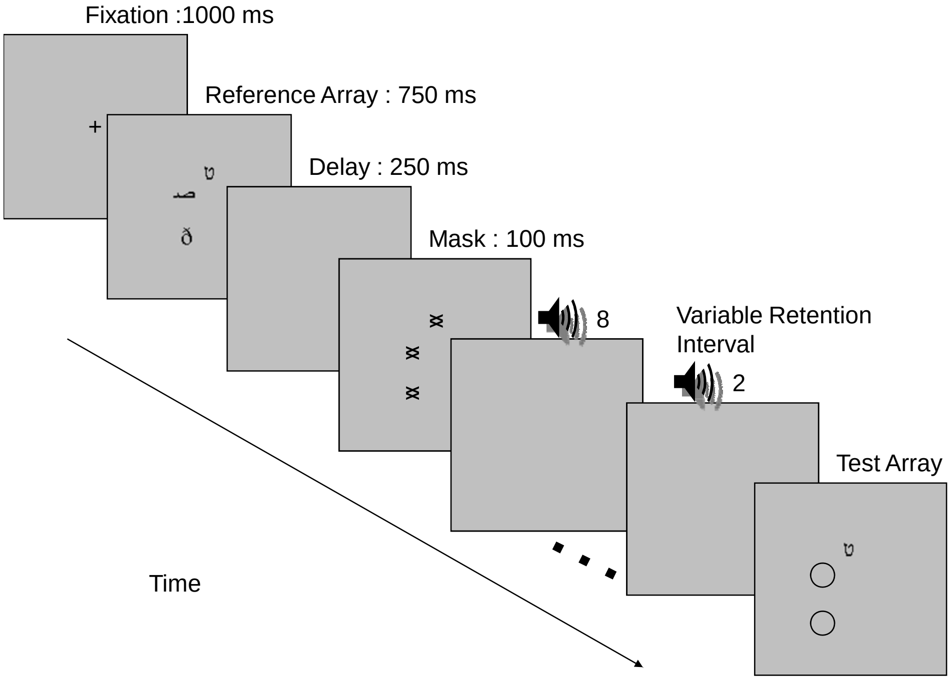

Figure 2. Above is an example of a single trial in Experiment 1. During the retention interval a blank screen was displayed for a variable duration of 1400, 2900, or 5900 ms. Throughout this retention interval participants heard digits spoken over computer speakers at a rate of either one digit every 1500 ms. Participants were to immediately repeat these digits.

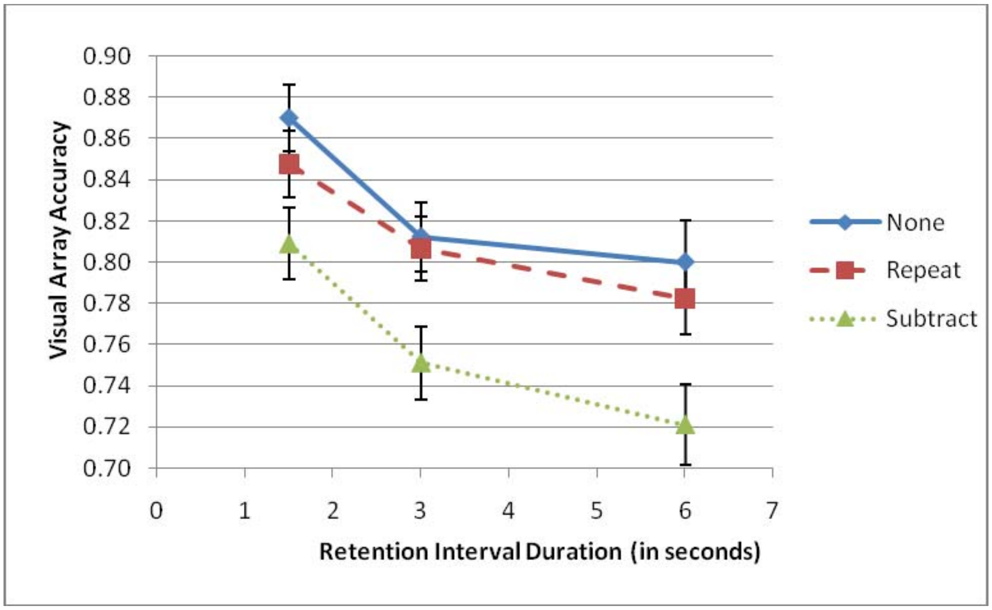

Figure 3. Mean percent correct on the visual array accuracy task as a function of retention interval duration for each load condition (graph parameter) in Experiment 1. Error bars are standard errors.

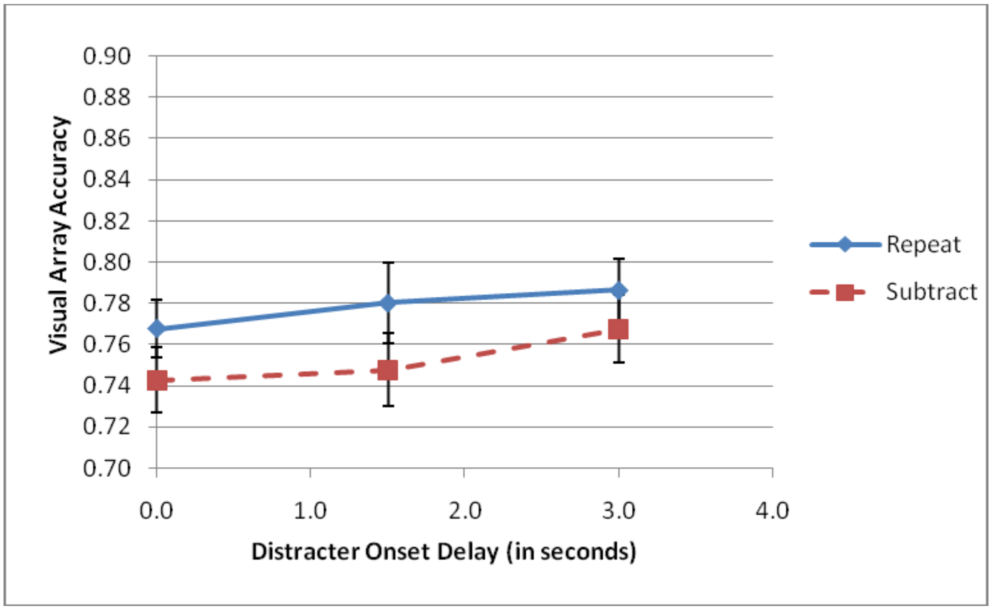

Figure 4. Mean percent correct on the visual array accuracy task for each distracter onset delay and load condition (graph parameter) in Experiment 2. Error bars are standard errors.