No Evidence for Temporal Decay in Working Memory

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Abstract

What drives forgetting in working memory? Recent evidence suggests that in a complex-span task in which an irrelevant processing task alternates with presentation of the memoranda, recall declines when the time taken to complete the processing task is extended while holding the time for rehearsal in between processing steps constant (Portrat, Barrouillet, & Camos, 2008). This time-based forgetting was interpreted in support for the role of time-based decay in working memory. This article argues the contrary position, by (a) showing in an experiment that the processing task in Portrat et al. gave rise to uncontrolled post-error processes which occupied the attentional bottleneck, thus preventing restorative rehearsal, and (b) by showing that when those post-error processes are statistically controlled, there is no evidence for temporal decay in the study by Portrat et al. We conclude that currently there exists no direct evidence for temporal decay in the complex-span paradigm.

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There has been much recent interest in the variables determining forgetting over the short term. Why do we forget a stranger's name only seconds after being introduced? Why do we transpose digits so readily between looking up a phone number and dialing it? Does forgetting occur through the mere passage of time, by some passive decay process, or does it require interference from subsequent events that disrupt the memory trace? Understanding forgetting is crucial because it underpins the pervasive and well-known capacity limitations of "short-term" or "working" memory. This capacity limitation, in turn, is a strong predictor of people's higher-level cognitive abilities (e.g., Oberauer, Süß, Wilhelm, & Sander, 2007), suggesting that understanding forgetting over the short term will ultimately offer a window into the very core of cognition.

To date, the issue of forgetting has been studied largely independently in two arenas—short-term memory (STM) vs. working memory (WM)—that despite their obvious empirical and theoretical linkages have been pursued in parallel and without much attempt at integration. In the STM literature, there has been considerable recent interest in the underlying causes of forgetting (e.g., Berman, Jonides, & Lewis, 2009; Lewandowsky, Duncan, & Brown, 2004; Oberauer & Lewandowsky, 2008), with the debate focusing on whether memories inexorably fade over time as suggested by some theorists (e.g., Burgess & Hitch, 2006; Page & Norris, 1998), or whether they may persist over time unless interfered with by subsequent events as suggested by others (e.g., Lewandowsky & Farrell, 2008; Nairne, 1990). Recent evidence favors the latter alternative. For example, Berman et al. (2009) showed that no-longer relevant materials persist in STM over time. They exploited the fact that in short-term recognition, negative probes that were study items on the preceding trial are rejected considerably more slowly than novel lures, reflecting their persisting familiarity. Berman et al. found that the persistent familiarity of no longer relevant items diminished only negligibly when the inter-trial interval was increased from .3 to 10 s or more, whereas it was eliminated by insertion of a single intervening study-test trial of equal (10 s) duration. Similarly, Lewandowsky et al. (2004) manipulated retention time during recall by training participants to recall at three different speeds (.4, .8, and 1.6 s/item). Rehearsal, which could counteract decay, was blocked by articulatory suppression (i.e., overt articulation of an irrelevant word). Although recall of the last item was delayed by over 5 s at the slowest compared to the fastest speed, this added delay caused no appreciable decrement in performance. This result has been replicated with children as participants (Cowan et al., 2006) and it has been found to persist even if a further, attention-demanding secondary task is introduced during retrieval (thus blocking even attentional forms of rehearsal; Oberauer & Lewandowsky, 2008).

In the WM literature, by contrast, recent evidence appears to implicate time-based decay. This is best illustrated within the framework of the time-based resource sharing model (TBRS; Barrouillet, Bernardin, & Camos, 2004), which relies entirely on decay to explain forgetting in the complex-span task that is at the core of much WM research. In a complex-span task, a processing task (e.g., reading a sentence, solving an arithmetic equation, or performing a choice task) alternates with encoding of to-be-remembered items. Thus, people might be presented with a sequence such as $2 + 3 = 5?$, A, $5 + 1 = 7?$, B, ..., where the equations have to be judged for correctness and the letters must be memorized for immediate serial recall after the sequence has been completed. Not surprisingly, the additional processing task impairs memory performance, and typical WM span values are considerably lower than STM spans. Is this impairment due to the additional time taken up by the processing task—thus delaying recall and creating an opportunity for decay—or is it due to the interference associated with performing another task? The TBRS firmly endorses the former option, and it does so in an elegant and intriguing manner. In particular, the TBRS does not necessarily predict increased forgetting as the duration of the processing task is extended. The TBRS assumes the presence of an attentional mechanism that can be deployed for multiple purposes, but it cannot handle more than one attention-demanding task at a time, and therefore creates a bottleneck. This attentional mechanism is thought to rapidly alternate between "refreshing" of the memory traces and performing the processing task. Thus, although memory is thought to decay while people engage in the processing task, the model also postulates that brief pauses in between processing steps can be used for attentional refreshing. Forgetting is thus thought to be a function not of absolute duration of the processing period in between presentation of two memory items, but of the *proportion* of that time that the attentional mechanism is actually devoted to the processing task. This proportion is referred to as "cognitive load" and is a joint function of the pace at which individual processing operations are demanded, and the duration of these operations. When operations take long to complete and are required at a fast pace, such that there is little or no time between successive operations, then the model must predict time-based forgetting. However, if there is ample time for refreshing in between processing steps (we refer to this time period as "restoration time" from here on), then the model predicts little forgetting because decay during the processing time can be counteracted by refreshing during the restoration time.

The core piece of evidence for the TBRS consists of the pervasive finding that complex span is indeed a function of cognitive load, that is, of the balance between processing duration and restoration time, exactly as predicted by the model (e.g., Barrouillet et al., 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007). In particular, there is no doubt that increasing restoration time in between processing steps increases memory performance, all other variables being equal. For example, in Barrouillet et al.'s Experiment 7, span increased from around 2.5 to nearly 4 when the total restoration time interspersed between 12 processing steps was increased from 840 ms to nearly 5 s. This finding demonstrates that pauses in between processing steps can indeed be used to improve memory for the list items, thus counteracting short-term forgetting. The beneficial effect of extending restoration time does not, however, have any implications for the source of forgetting, as was first noted by Oberauer and Kliegl (2006). Forgetting could be caused by decay, but it could equally be caused by interference. Regardless of whether traces are degraded by decay or interference or some other cause, some type of restoration process appears mandated by the observed beneficial effects of additional restoration time.

Stronger evidence for decay as the cause of short-term forgetting would come from a complementary manipulation of cognitive load, in which the duration of each processing step is varied while holding everything else constant. The first evidence that directly bears on this issue was provided by Portrat, Barrouillet, and Camos (2008). They tested participants on a complex span paradigm in which encoding of letters alternated with a "burst" of several trials of a spatial judgment task. Portrat et al. varied the processing duration of each spatial judgment while holding the number of judgments and the restoration time following each choice constant. The methodology is summarized by the time-lines of events in the top two panels of Figure 1.

The judgment task involved a decision about the location of a square (i.e., whether it was in the upper or lower portion of the screen). The difficulty of the task—and hence processing duration—was manipulated via the spatial proximity of the two possible stimulus locations. When the two locations were close together, processing duration was longer than when the two locations were further apart. Processing duration was measured by the latency of individual judgments (recorded by participants pressing one of two keys). Judgment difficulty was manipulated between trials, so that on trials with difficult judgments, the retention interval was up to 5 s longer (for the first item on 8-item lists) than on trials with easy judgments. This timing manipulation engendered a small but significant decrement in memory performance of around 4 percentage points. At first glance, as shown by the hypothesized evolution of memory strength in Panels A and B of Figure 1, this result seems to provide evidence for time-based forgetting in a complex-span task. However, as we show next, there are reasons to doubt this conclusion.

The crucial manipulation in the study by Portrat et al. (2008) consisted of the difficulty of the processing task: In addition to the intended increase in total processing duration, another consequence of the difficulty manipulation was a considerable increase in error rates on the processing task itself (from 1% to 13%). We suggest that this increase in error rate introduced a confound that prevents an unambiguous interpretation of the results.

There is much consensus in the literature that responses following an error are considerably slower than responses that are preceded by a correct response (e.g., Laming, 1979). This post-error slowing is presumed to arise because people often self-detect an erroneous response, even in the absence of overt feedback. More recently, Jentzsch and Dudschig (in press) analyzed the cause of this pervasive post-error slowing and showed that it arises from a process that follows after an error response (viz. evaluating the response and making appropriate adjustments), which temporarily occupies a central attentional bottleneck. We call this an attentional postponement effect because it delays processing of the next stimulus (provided it follows in rapid succession) while post-error processing occupies the bottleneck.

This result is of considerable relevance in the present context, because it provides an alternative explanation for the finding of Portrat et al. (2008) which is sketched in Panels C and D of Figure 1. A crucial premise in the argument of Portrat and colleagues was that they held the restoration time after each processing step constant, thus manipulating the potential time for decay independently of the time available for restoring memory traces. This premise holds only if the attentional bottleneck is free to refresh memory traces as soon as participants entered their response to the processing stimulus (i.e., the location judgment). The results of Jentzsch and Dudschig clearly show that this cannot be the case on error trials. It follows that because the difficult spatial judgments led to more errors than the easy ones, they more often engendered post-error processing (labeled PE in Figure 1) that occupied the bottleneck during the restoration time following the overt response, thereby shortening the time available for refreshing memory traces (represented by the narrower upward triangles in Panel D than in Panel C in the figure). By implication, the differences in memory performance between the easy and difficult processing tasks that were observed by Portrat et al. (2008) may have reflected differences in the time available for restoration by the attentional bottleneck rather than the differences in time during which memory traces could decay.

In the remainder of this article, we first present an experiment that establishes the presence of post-error processing in the distractor task used by Portrat et al. (2008). We then report a re-analysis of their data and show that when errors are statistically controlled, the study by Portrat et al. provides no evidence for temporal decay: Performance is a sole function of processing accuracy not processing time. We conclude that at present there is no direct evidence for time-based forgetting in working memory.

Establishing the Presence of Post-Error Processing

We next present an experiment that examines whether the square-location task used by Portrat et al. ((2008); see also Barrouillet et al., 2007) entailed a postponement effect resulting from post-error processing. We therefore modeled our procedure on the method of Portrat et al. and incorporated only a few changes necessary to detect post-error processing. Analysis focused primarily on the consequences associated with committing an error.

Method

Participants and apparatus. The participants were 16 members of the campus community at the University of Western Australia who participated voluntarily in the 7-minute experimental session. A Windows computer running a Matlab program designed using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) was used to present stimuli and for the recording of responses. The same apparatus was used in all remaining experiments.

Materials. Stimuli consisted of an unfilled square with a black boundary (18×18 *mm*) that was presented either in the top or bottom half of the screen. Participants' task was to determine which half of the screen stimuli appeared in. For easy stimuli, the two possible screen locations were 68 *mm* apart vertically, whereas for difficult stimuli the vertical separation was 15 *mm*.

In addition, each square was horizontally offset from the screen's center by a random amount ranging from .61 *cm* to 6.06 *cm*. This offset was introduced because without it, judgments become very easy when a difficult stimulus follows another difficult stimulus on the opposite half of the screen—in this case, due to the short response-stimulus interval, observers could detect the change as a vertical apparent motion from just above to just below the midline. This judgment short-cut was prevented by the random horizontal shifts of the squares between successive trials.

Procedure. Participants were presented with two blocks of 250 trials reach. Following Portrat et al. (2008), all stimuli in a block were either easy or difficult, with the order of the two blocks randomly determined for each subject. On each trial, participants saw a single square which remained visible until a response was made. Participants pressed the '/' key to indicate a "below centerline" response, and they used the 'Z' key for the opposite response. Each response was followed by presentation of the next stimulus after 100 *ms*. The rapid succession of stimuli constituted an important departure from the methodology of Portrat et al. and was necessary to maximize the opportunity for detection of postponement effects.

The total sequence of 500 trials was divided into four segments that were separated by a self-paced break period.

Results

Trials whose response time (RT) fell below 150 *ms* or exceeded a participant's mean RT for that task and level of difficulty by more than 3 intra-individual standard deviations were eliminated from consideration (2% of all responses). The difficult condition gave rise to slightly lower accuracy (.96) than the easy condition (.97), and correct responses in the difficult condition were considerably slower (502 *ms*) than in the easy condition (411 *ms*). The remainder of the analysis focused on the consequences of errors on subsequent trials.

We considered two types of trial pairs: A correct response that was preceded by an error response ($E - C$ from here on), and a correct response preceded by another correct response ($C - C$). The mean RTs for the two pair types and both levels of difficulty are shown in Table 1.

A 2×2 (Difficulty $\times$ Trial pair) within-subjects ANOVA confirmed the obvious pattern in the table, with a significant main effect of difficulty, $F(1, 15) = 8.18$, $MSe = .034$, $p \simeq .01$, $\eta_p^2 = .35$, and a significant main effect of trial pair, $F(1, 15) = 62.96$, $MSe = .012$, $p < .0001$, $\eta_p^2 = .81$. The interaction failed to reach significance, $F(1, 15) = 1.87$, $MSe = .019$, $p > .10$, $\eta_p^2 = .11$.

Discussion

We prefix our discussion by noting that the procedural differences between this experiment and the study by Portrat et al. (2008) were mandated by the focus on post-error processing. Thus, here there were no memoranda and the stimuli followed each other in rapid succession. The rapid succession, in turn, mandated the introduction of a random horizontal offset of each stimulus. In all other respects, the study was nearly identical to the procedure of Portrat et al.

The experiment suggests a very clear conclusion: The processing task used by Portrat et al. (2008) demonstrably entailed a substantial attentional postponement effect, such that errors caused a slowing of subsequent correct responses. The results of Jentzsch and Dudschig (in press) strongly implicate the attentional bottleneck as the locus of this postponement effect. It follows that the imbalance in error-rates between conditions in the study of Portrat et al. almost certainly entailed a differential engagement of the attentional bottleneck during the restoration time, thus giving rise to the *appearance* of time-based forgetting. To further test this alternative possibility, we now present a re-analysis of the data of Portrat et al. (2008).

A Re-Analysis of Portrat et al.: No Time-Based Forgetting

We re-analyzed the results of Portrat et al. (2008) in two ways. First, for comparability, we repeated their analysis of recall performance, including only trials on which participants made few errors on the processing task. For the empirical reasons just reported, we expect these trials to involve less post-error processing that could diminish the available restoration time, and we therefore expect the effect of the difficulty manipulation on memory to be much reduced.

We included only trials on which performance fell at or above an accuracy criterion of .84 on the processing task. This criterion was chosen because it was the most stringent possible criterion that still retained all participants in the analysis; use of more stringent criteria would have eliminated an increasing number of subjects, thus reducing statistical power and raising the possibility that only well-performing participants contributed to the observed pattern.

The mean correct-in-position recall performance (averaging across all list lengths) was .855 and .852, respectively, for the easy and difficult processing stimuli (this compares to .82 vs. .78 in the original unconditionalized analysis reported by Portrat et al., 2008).[1] The tiny difference in the conditionalized data was nowhere near statistically significant, notwithstanding the fact that the processing times continued to differ substantially; 344.4 *ms* vs. 403.2 *ms* per stimulus, for the easy and difficult location judgments, respectively. Thus, whereas the difference in time available for temporal decay was unchanged from the values presented by Portrat et al., the differences in memory performance disappeared upon (a very lenient) conditionalization on accuracy on the processing task.

In a second re-analysis, we did not conditionalize on accurate performance on the processing task but used both accuracy and latency on the processing task as a predictor of recall performance. Specifically, we entered participants' correct-in-position recall scores (averaged across serial positions and all replications for a given list-length and processing-difficulty condition) as dependent measure into a multi-level regression. Multi-level regression (also known as "hierarchical" regression or "mixed-effects" modeling; see, e.g., Pinheiro & Bates, 2000) permits an aggregate analysis of data from all participants without confounding within- and between-subject variability, and has been used previously to analyze data on the role of time in short-term memory (for details, see Lewandowsky, Brown, Wright, & Nimmo, 2006; Lewandowsky, Nimmo, & Brown, 2008; Lewandowsky, Brown, & Thomas, 2009). One advantage of multi-level regression is that it maximizes statistical power because it enables researchers to use all available data on a low level of aggregation and without the loss of information incurred by dichotomizing continuous variables (for a discussion, see Hoffman & Rovine, 2007).

In the present case, multi-level regression enabled us to use the actual measured time spent on the processing task as a continuous predictor, rather than using the experimental manipulation of difficulty as a dichotomous proxy. We predicted memory performance on each list by three variables: list length (squared to capture its non-linear effect), processing duration for the spatial judgment task, and accuracy on the spatial judgment task (the latter two were averaged across all processing stimuli within a list). If our reasoning above is correct, memory performance should be predicted by accuracy but not time spent on the spatial judgment task. The results of this analysis are shown in Table 2 and are unambiguous: In confirmation of the earlier conditionalization, there was no effect of processing duration once processing accuracy was also entered into the analysis.

We conclude that the data of Portrat et al. (2008) provide no evidence for time-based forgetting in working memory. Instead, their results arose from an attentional postponement effect that occurred whenever people detected an error during the processing task, thus shortening the period available for attentional refreshing of memory traces.

Discussion

Is forgetting in WM driven by time-based decay? The TBRS model of Barrouillet and colleagues assumes that it is. The seemingly most compelling evidence so far for decay in WM comes from the finding of Portrat et al. (2008) that a more difficult—and hence more time-consuming—processing task leads to more forgetting in the complex-span paradigm even when the time for restoration of memory traces following each processing step was held constant. We suggest that this finding calls for a different explanation that does not involve decay: When the processing task was made more difficult, participants committed more errors, and these errors led to post-error processing, thus taking away part of the restoration time. As a consequence, there was less opportunity for restoring memory traces in the condition with the difficult processing task than in the condition with the easy task, thus creating the false appearance of temporal forgetting when in fact the observed performance differences reflected differences in the time available for restoration.

The evidence for this alternative interpretation comes from two sources. First, our experiment, in conjunction with the work of Jentzsch and Dudschig (in press), provided direct evidence that in the spatial judgment task used by Portrat and colleagues, post-error processes occupy an attentional bottleneck, and thereby slow down further processes immediately after an error. Second, our re-analysis of the data of Portrat et al. showed that memory was predicted by the number of errors on the processing task, not its duration. When the analysis was limited to trials with few errors on the processing task, there was no difference in recall between trials with fast (easy) and trials with slow (difficult) spatial judgments.

The apparent absence of forgetting when processing time was manipulated provides direct evidence against time-based decay as the cause of forgetting in the complex-span paradigm: Portrat et al. extended the total processing duration by several seconds, during which the WM system was busy processing material unrelated to the memoranda, and yet found no effect on memory accuracy when errors on the processing task were controlled. The absence of forgetting as a function of longer processing durations cannot be explained by compensatory rehearsal or some other compensatory process because it is a key assumption of the TBRS model, as of all other theoretical accounts of the complex-span paradigm that appeal to decay (e.g. Towse, Hitch, & Hutton, 2000)), that the processing task prevents such compensatory activity. Our finding is, however, fully compatible with alternative views that attribute forgetting in the complex-span paradigm, and related paradigms in STM and WM research, to interference between representations (Farrell & Lewandowsky, 2002; Oberauer & Kliegl, 2006; Oberauer & Lewandowsky, 2008; Saito & Miyake, 2004).

Conclusions

The present article supports two messages for researchers on WM, one methodological and one substantive. The methodological conclusion is that, to study the causes of forgetting in paradigms that combine memory maintenance with a concurrent processing task, it is essential to control not only the timing of the processing events (a point forcefully made by Barrouillet and colleagues), but also the errors on the processing task. Errors on the processing task can have consequences for the time available for restoration of the memory representations, and as we have learned from the TBRS model, this time is a crucial limiting factor for memory performance.

The substantive conclusion concerns the cause of forgetting in working memory. Since the work of Brown (1958) and Peterson and Peterson (1959) it is known that STM representations are quickly forgotten during a delay filled with a distracting processing task. A popular explanation of that finding has been that memory traces quickly decay, while the distracting task prevents rehearsal to maintain them. The same explanation has been applied to the complex-span paradigm (Barrouillet et al., 2004, 2007; Towse et al., 2000). An inevitable prediction of that account is that when the duration of processing steps on the concurrent task is increased while holding all other task parameters constant, more forgetting must occur. This was not found in the only experiment to have tested this prediction (Portrat et al., 2008), once the effect of errors on the processing task was controlled. Thus, in confirmation of other recent surveys (Lewandowsky, Oberauer, & Brown, 2009; see also Lewandowsky & Oberauer, 2008), there is no direct evidence that decay is responsible for the rapid forgetting of information from WM. The generality of this effect remains to be ascertained, and alternative accounts of the exact mechanisms by which forgetting occurs remain to be developed.

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Notes

[1] We thank Sophie Portrat for providing us with the raw data for this analysis. The re-analysis is based on the data from 22 subjects; 2 further subjects had to be eliminated from consideration here because data on their responses for the processing task were either corrupted or could not be unambiguously matched to their memory performance.

Note that unlike Portrat et al. (2008), we did not collapse across list length but retained that important variable by computing a separate proportion correct for each subject and list length using the trials that satisfied our accuracy criterion for the processing task. Our conditionalization retained all trials for the easy processing stimuli, and retained 50, 50, 44, 45, 36, and 40 trials, respectively, for list lengths 3 through 8 with the difficult processing task.

Table 1

Mean response times in ms *(and standard errors) obtained in the experiment as a function of difficulty and trial pair.*

	Difficulty	
Trial pair	Easy	Difficult
$C - C$	405 (11)	492 (24)
$E - C$	582 (31)	760 (75)

Table 2

Summary of the re-analysis of the results of Portrat et al. (2008) via multi-level regression.

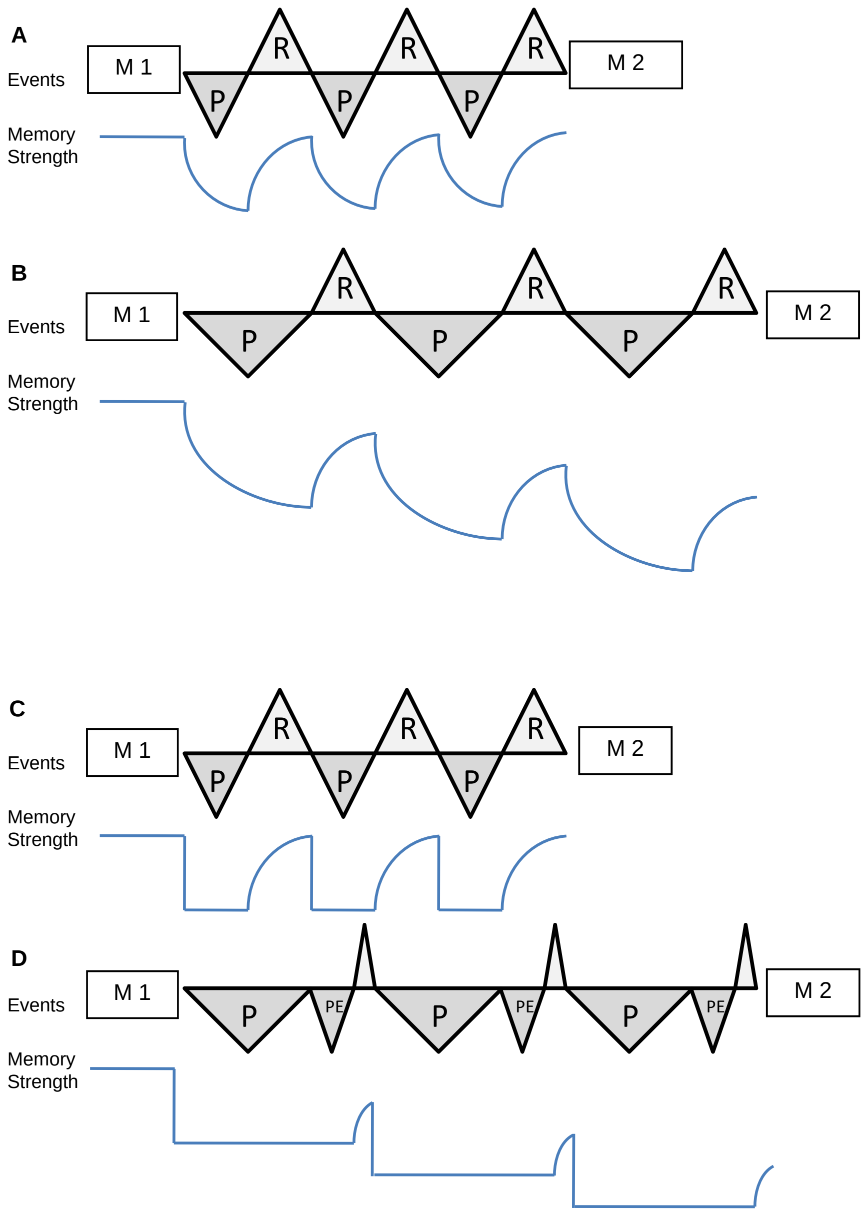
Effect	Estimate	SE^a	t^b	p
Intercept	.64	.19	3.35	.003
Processing accuracy	.37	.14	2.62	.016
Processing time	.0002	.0002	.80	$> .10$
List length (squared)	-.006	.0006	-10.10	$<.0001$

[a] SE = Standard error of the estimate

[b] All $df = 21$

Figure Captions

Figure 1. Time-line of events during one processing episode in between two memory items (M1 and M2) in a complex-span trial with a manipulation of processing difficulty (e.g., Portrat, Barrouillet, & Camos (2008)). Panels A and C show easy, and Panels B and D difficult, processing stimuli (downward pointing triangles, labeled P). Constant restoration times (shown by upward pointing triangles) follow each processing stimulus. In each panel, the assumed evolution of memory strength of item M1 is shown below the events. Panels A and B illustrate the assumption of the TBRS; panels C and D illustrate an alternative explanation not involving decay. A: During short processing durations (P), memory decays; in the following restoration time (R), traces are attentionally refreshed, thus fully compensating decay. B: During longer processing (more difficult distractors), memory decays more, such that the following refreshing episode of unchanged duration cannot fully restore memory. C: Distractors interfere with memory, reducing its strength independent of processing duration. In the following restoration time, memory traces are repaired. D: Difficult decisions take longer but cause no additional interference. Difficult decisions entail more errors, triggering post-error processing (downward pointing triangles PE) that occupies part of the restoration time. In the short remaining restoration time (peaked upward triangles), memory cannot be fully restored. See text for further details.


A
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Memory
Strength