Published in final edited form as:

J Exp Psychol Learn Mem Cogn. 2015 May ; 41(3): 872–880. doi:10.1037/xlm0000084.

No Recovery of Memory when Cognitive Load is Decreased

Timothy J. Ricker, Evie Vergauwe, Garrett A. Hinrichs, Christopher L. Blume, and Nelson Cowan

University of Missouri

Abstract

There is substantial debate in the field of short-term memory as to whether the process of active maintenance occurs through memory-trace reactivation or repair. A key difference between these two potential mechanisms is that a repair mechanism should lead to recovery of forgotten information. The ability to recover forgotten memories would be a panacea for short-term memory and if possible, would warrant much future research. We examine the topic of short-term memory recovery by varying the cognitive load of a secondary task and duration of retention of word pairs. In our key manipulation we lighten the cognitive load partway through the retention interval, resulting in an easier task during the later portion of retention and more time for active maintenance processes to take place. Although the natural prediction arising from a repair mechanism is that memory accuracy should increase after transitioning to an easier load, we find that accuracy decreases or levels off at this point. We see this pattern across three experiments and can only conclude that the panacea of short-term memory recovery does not exist. Implications for the debate over memory maintenance mechanisms are discussed.

Keywords

Short-term Memory; Working Memory; Cognitive Load; Interference; Decay

The debate over what causes forgetting in short-term memory has been contentious since the inception of modern experimental psychology. One of the largest schisms among current researchers is whether time leads to forgetting in working memory under some or all circumstances (Barrouillet & Camos, 2012; Ricker & Cowan, 2014; Ricker, Spiegel, & Cowan, 2014) or whether interference from irrelevant stimuli and processing alone can account for all forgetting (Lewandowsky, Oberauer, & Brown, 2009; Oberauer & Kliegl, 2006; Souza & Oberauer, 2014). One rather successful approach to conceptualizing time-based forgetting has been using the cognitive load (CL) approach proposed by Barrouillet, Bernardin, & Camos (2004). This approach characterizes memory items as activated memory traces which decay with the passage of time. If decay of any given item is completed then that item is forgotten from short-term memory and cannot be recovered on that trial. This decay-based forgetting is counteracted by an attention-based refreshing mechanism that reactivates items, temporarily preventing forgetting.

The main finding in support of this approach is that a CL, defined as the proportion of time occupied by attention-demanding non-maintenance activities, imposed during memory retention, limits the number of memory items that can be correctly recalled (see Barrouillet & Camos, 2012, for an overview). The CL finding is important beyond itself because it has been taken as strong evidence in favor of time-based memory decay. Other researchers have responded by claiming that it is not interplay between decay and refreshing that determines the contents of memory, but rather interplay between interference-based forgetting and attention-based repair of the memory traces (Lewandowsky et al., 2009; Oberauer & Kliegl, 2006). Thus, it has been proposed that the CL effect can be explained without the need to call upon time-based decay as the source of forgetting.

An interesting aspect of the interference and repair approach to CL is that it should also predict recovery of memory performance when the CL is eased in the middle of retention. This is because easing the CL during the later portion of retention allows the repair mechanism relatively more time to rebuild the memory trace compared to earlier in the retention interval when the load was harder. This would lead to a less disrupted memory trace, and therefore better performance, as the duration of the easier task continues (for a graphical depiction see, Lewandowsky et al., 2009 Figure 2; Oberauer & Lewandowsky, 2011 Figure 4). A decay and refreshing approach to CL does not predict an increase in performance when CL is eased because the refreshing mechanism is only theorized to maintain the presently held memory; it cannot reconstitute a forgotten memory.

Unfortunately, little research has been done which can shed light on this interesting divergence of predictions. The studies that do exist provide mixed evidence on the existence of memory recovery within a trial. Some evidence against a repair model can be found in Dillon and Reid (1969), who conducted a series of experiments under which a relatively difficult and time-demanding task was followed by an easy and less time-consuming task. A repair approach should predict that when the difficult task is followed by an easy task during the retention interval the easing of the CL would allow relatively more time for repair during the later portion of retention, resulting in memory recovery. This, however, is not what Dillon and Reid observed. They observed that the main determinant of performance was the length of the difficult task during the retention interval, and that some forgetting continued even after switching to an easy task. A decay approach, such as that outlined by Ricker and Cowan (2010, 2014), provides a natural account of this data. On the other hand, White (2012) reported finding memory recovery after easing the CL during retention, as predicted by the interference-only repair approach. Despite using a similar task structure, these two studies seem to be in conflict and imply different models of short-term memory.

Aside from the implications for memory models of decay and interference, the finding of recovery of forgotten information in short-term memory would be remarkable in and of itself. If this phenomenon is real, it could prove to be one of the most important research findings on short-term memory. The ability to change learning conditions so that any forgetting that occurs during high CL portions of learning could later be reversed would challenge the notion of short-term memory as a separate mechanism. Because of the potential implications of these results for a broad class of theoretical models of short-term memory and learning, we decided to reexamine this memory recovery effect. In three

experiments we attempted to find memory recovery effects using a procedure in which a secondary task is performed during retention of a modest memory load. The secondary task was either easy throughout, hard throughout, or started at the hard level and then switched to the easier level at some point during retention. In all three of our experiments we see a very consistent pattern of results demonstrating that decreasing the CL part way through a retention interval stopped some or all further forgetting from that point on, but never led to the recovery of memory performance.

Experiment 1

In our first attempt to find memory recovery we use two cognitive loads. On some trials, the hard load switched to the easier load half way through the retention interval. In this way our method is similar to both Dillon and Reid (1969, Experiment 4) and White (2012) in the important theoretical manipulation. On some trials, the CL is eased after a period of difficult task performance during retention. The predicted pattern of results on these switch trials varies based upon which theoretical approach to memory maintenance one takes. Following the interference and repair approach (Lewandowsky et al., 2009; Oberauer & Kliegl, 2006) predictions are that memory should recover on the switch trials with accuracy increasing after the switch relative to its level before the switch occurred. Following the standard decay interpretation of CL effects (Barrouillet & Camos, 2012) one would expect to see a stabilization of any ongoing forgetting, meaning that there would be no increase or decrease in accuracy after the switch relative to performance levels before at the point before the switch occurred. Ricker & Cowan (2010, 2014; Ricker et al., 2014a) have also argued that decay may affect more than just CL effects. Following this interpretation one may expect to see continued forgetting after the switch, but certainly no recovery.

We wish to be clear on what is meant by the term recovery. In many cases accuracy under some conditions is higher than accuracy under other conditions. For a difference to be classified as recovery more is needed. Information must first be lost before it can be recovered. In other words, the lower memory state must precede the higher memory state. Similarly, in our experiments higher accuracy in a switch condition than in a hard condition with the same retention interval length would not be memory recovery because the hard condition does not reveal a state precursory to the switch condition. Accuracy in the switch condition could be said to be higher, but not recovered because it was never in the lower state observed under the always hard condition. In order to qualify as recovery memory performance must first decrease and then increase once the cognitive load has been eased, forming a U-shaped function.

Method

Participants—Twenty-eight students from the University of Missouri (11 female, on average 19 years of age) completed Experiment 1 in exchange for partial course credit. All participants had normal or corrected-to-normal vision and were native speakers of English.

Materials—The memory items consisted of ninety-seven English nouns. These words were always six letters and two syllables in length. All words were taken from the MRC database (Fearnley, 1997) and had similar within-list ratings for concreteness (mean=589, sd=27),

imagability (mean=589, sd=30), familiarity (mean=549, sd=36), and word frequency (mean=48, sd=98). All word was presented in size 16 font.

Design—The basic experimental design consisted of retention of a single word pair across a variable interval of 2, 4, 8, or 16 s. During the retention interval one of two CL tasks was imposed, differing in how long they took to execute each step, with the high-CL task taking longer. This part of the basic design was a 4 (Retention-Interval Duration) x 2 (Cognitive Load) fully crossed design. Critically, though, there were two additional conditions, one with an 8-s retention interval and one with a 16-s retention interval. In these conditions the CL started at the high level and then switched to the low level after half the retention interval was complete (after 4s with the 8s retention interval and after 8s with the 16s retention interval).

Experiment 1 had one additional manipulation. One of the words in the word pair was a novel word that was only presented in the current trial, while the other word (always the one presented on the right) was one of four repeated words. We included this manipulation because we thought it possible that the recovery effect observed by White may happen with novel verbal items but not with items chosen repeatedly from a small set. The theory was that during periods of decreased load participants may have been able to recover novel verbal stimuli through a recollection process that would fail under high levels of proactive interference assumed to occur for repeating words. This manipulation of word type turned out to have no effect, and therefore we do not discuss it further.

Procedure—An example of a single experimental trial is depicted in Figure 1. Each trial was initiated by a participant button press. A fixation cross then appeared for 500 ms, followed by two words simultaneously presented on the screen for 2 s. One word was presented 6 cm to the left of fixation while the other was presented 6 cm to the right, with both words centered on the screen vertically. Upon memory item offset the secondary task began. This task consisted of either two or three numbers being presented on the screen, in the low and high CL conditions respectively, separated by an addition symbol. The participants were instructed to add these numbers together and speak the result out loud. A new set of numbers was presented every two seconds for the entire duration of the retention interval, which lasted for 2, 4, 8, or 16 s. After the retention interval participants were prompted to make a response by presentation of the phrase “What were the words?” on the screen. Participants were instructed to respond by speaking the word pair out loud within 6 s of the response prompt appearing. Responses were recorded by an experimenter who sat next to the participant throughout the experiment. When no response was made or only one word was spoken within the 6-s period the experimenter requested a response from the participant, even if it was a guess.

There were 3 practice trials consisting of only the memory task and 20 practice trials consisting of both the word task and the secondary CL task. Practice trials were all in the 4-s retention interval condition and did not include switch trials. The experimental portion consisted of 7 blocks of 10 trials, with one trial of each type per block.

Analysis—To examine the effects of our manipulations we compute Bayes factors for all of our ANOVA and t-test statistics. The ANOVA and t-test statistics themselves are computed using the standard method. The Bayes factors are added because they provide an inferential tool that is better than null hypothesis significance testing inasmuch as it allows us to assess evidence both for and against an effect (i.e., against or in favor of the null). We would like to stress an important aspect of this statement; Bayes factors give positive evidence in favor of no effect when they are greater than 1 in the direction favoring the null. This statistic does not suffer from failure-to-accept problems when lack of a significant difference between conditions is produced because the likelihood of the data coming from a distribution representing the null is explicitly compared to the likelihood of the data coming from a distribution representing the alternative (for more detail see Rouder, Speckman, Sun, Morey, & Iverson, 2009).

The Bayes factor statistic gives the probability of the observed data under one hypothesis relative to the same probability under an alternative hypothesis. Bayes factor has been recommended for inference in the psychological domain by a number of sources (Edwards, Lindman, & Savage, 1963; Rouder, et al., 2009; Wagenmakers, 2007). We follow the method described by Rouder, Morey, Speckman, and Province (2012) to compute Bayes factors in factorial designs and perform computations with the “BayesFactor” package (Version 0.9.4; Morey & Rouder, 2012) for the R statistical-analysis language. In Bayes factor computations a reasonable range of possible effect-size values under alternatives are specified. Here we used the default settings in the package and a standard deviation of effect size at $(2)/2$ for ANOVA testing. When performing a Bayes Factor t-test we follow the development of Rouder et al. (2009), and use the “BayesFactors” package for the R statistical-analysis language with the default settings including a standard deviation of effect size at .5 for one-tailed tests.

Results

Mean accuracy for each condition (except Word Type) is shown in Figure 2. The manipulation of Word Type (either novel or repeated) had no effect on accuracy and as such we collapse across this dimension in all descriptive statistics and analyses. Performance clearly declined as a function of Retention Interval Duration and CL. When the CL was switched from a high load to a low load halfway through the retention interval, performance appeared better relative to when the CL stayed high throughout the entire retention interval. (Note that these observations are based on descriptive statistics, whereas we restrict the use of inferential statistics for the effects critical to the recovery hypothesis.)

Despite the improved accuracy when the CL was eased, accuracy did not recover, which would have appeared as an increase in accuracy as the retention interval continued to increase. Instead, accuracy continued to decrease, although at a slower rate than was observed for the high CL. Below, our use of inferential statistics based on the Bayes Factor establishes the presence of loss over retention intervals, and also the absence of recovery following that loss.

The Bayes Factor ANOVA of proportion correct, excluding the switch condition trials, demonstrated an effect of Retention Interval Duration, (means: 2s=0.90, 4s=0.86, 8s=0.80,

16s=0.76), $F(3,81)=13.69$, $p<.001$, $\eta_p^2=0.34$, with a Bayes factor well over 3 million to 1. This means that the data are more than 3 million times more likely under a model with this effect than a model without it. An effect of Cognitive Load was also observed, (means: Low=0.91, High=0.76), $F(1,27)=58.12$, $p<.001$, $\eta_p^2=0.68$, with a Bayes factor of more than 4×10^{17} to 1. The two main effects also interacted, $F(3,81)=5.50$, $p<.005$, $\eta_p^2=0.17$, with a Bayes factor of 85 in favor of this effect. The statistical support is unambiguous; accuracy decreases with a longer retention interval and with a greater level of load. Additionally, when the cognitive load is greater there is a greater effect of retention interval duration under the conditions of this experiment.

When examining Figure 2 it is clear that accuracy did not recover when the CL was decreased in the switch conditions. Mean performance levels shows that the eased load in the switch condition never led to improved performance as compared to the time-point before the load was eased (4s-High=0.81 compared to 8s-Switch=0.76; 8s-High=0.71 compared to 16s-Switch=0.69). We confirmed this lack of recovery statistically using a one-tailed Bayes Factor t-test examining whether proportion correct was greater when probed after the 8s-switch condition as compared to the 4s-high condition. This test contrasts the hypothesis that recovery took place with the null hypothesis that there was no recovery (i.e., that performance in the switch condition is at least as low as performance in the hard condition). This test gave strong support against recovery, $t(27)=-1.33$, $p>.9$, $d=-0.25$, with a Bayes factor of 7.67 in favor of a null result. The same test comparing the 16s Switch condition to the 8s High condition also gave support for a null effect, $t(27)=-0.48$, $p>.6$, $d=-0.09$, with a Bayes factor of 5.07 in favor of a null result. If memory recovery occurred during decreased cognitive load states then these switch conditions should have resulted in greater accuracy levels after the period of low load. This clearly did not happen.

Discussion

In our first experiment both visual inspection of mean performance levels across conditions and statistical analysis of performance reveal evidence against any memory recovery when the cognitive load is eased. This is in conflict with the concepts underlying repair accounts of short-term memory, but in harmony with decay and refreshing accounts. Given the importance of the topic, we wished to replicate our results under somewhat different conditions before drawing any strong conclusions.

Experiment 2

Although we did not observe memory recovery in Experiment 1, it was possible that it may require a longer period of time at an eased load for recovery to occur than we allowed in that experiment. In Experiment 2 if a switch occurred at all it always occurred after 4s, leading to switch conditions with more time for recovery to occur than in Experiment 1.

Method

Participants—Thirty students from the University of Missouri (21 female, on average 18 years of age) completed the experiment in exchange for partial course credit. All participants had normal or corrected-to-normal vision and were native speakers of English.

Materials—The memory items were 186 English nouns from the list of 200 nouns used in White (2012). All words were three or four letters in length.

Design—The basic experimental design was the same as in Experiment 1, except for the following changes. In this experiment the CL switch happened in the switch conditions after 4s in both the 8s and 16s retention interval switch conditions.

Procedure—The procedure was the same as in Experiment 1, except for the small design change to the switch trials as noted in the Design section above.

Results

Mean accuracy for each condition is shown in Figure 3. Performance clearly declined as a function of both Retention Interval Duration and Cognitive Load. When the CL was switched from high load to low load after 4 s of retention, performance appears better relative to when the CL stayed high throughout the entire retention interval. Despite the improved accuracy when the CL was eased, accuracy did not recover, but instead continued to decrease at a slower rate, or possibly leveled off.

To examine the overall effects of Retention Interval Duration and Cognitive Load we conducted a Bayes Factor ANOVA on proportion correct with these manipulations as factors, excluding all trials on which a switch occurred. This analysis demonstrated an effect of Retention Interval Duration, (means: 2s=0.83, 4s=0.75, 8s=0.64, 16s=0.64), $F(3,87)=22.40$, $p<.001$, $\eta_p^2=0.44$, with a Bayes factor well over 500 thousand to 1. An effect of Cognitive Load was also observed, (means: Low=0.82, High=0.61), $F(1,29)=74.85$, $p<.001$, $\eta_p^2=0.72$, with a Bayes factor of more than 1.5×10^{13} to 1. The two main effects also interacted, $F(3,87)=8.67$, $p<.001$, $\eta_p^2=0.23$, with a Bayes factor of 195 in favor of this effect. The statistical support is clear; accuracy decreased with a longer retention interval and with a greater level of load. When the cognitive load was greater there was a greater effect of retention interval duration under the conditions of this experiment. All of this is as in Experiment 1.

Critically, also as in Experiment 1, no recovery is evident when the CL was decreased (see Figure 3). Mean performance levels show that the eased load in the switch conditions never led to improved performance as compared to accuracy at the time-point before the load was eased (means: 4s-High=0.67, 8s-Switch=0.59, 16s-Switch=0.59). Instead mean accuracy levels dropped. To examine the statistical support against recovery after the cognitive load was eased we conducted several Bayes Factor t-tests on proportion correct for comparisons relevant to determining loss in the switch condition. A one-tailed Bayes Factor t-test of proportion correct comparing whether accuracy was greater in the 8s-Switch condition as compared to the 4s-High condition gave strong support against recovery, $t(29)=-1.85$, $p>.9$, $d=-0.34$, with a Bayes factor of 9.58 in favor of a null result. The same test comparing the 16s Switch condition and the 4s High condition produced a similar result, $t(29)=-2.12$, $p>.9$, $d=-0.37$, with a Bayes factor of 10.40 in favor of a null result. In addition, there was evidence against an increase in proportion correct between the 8s and 16s switch period, $t(29)=-0.06$, $p>.5$, $d=-0.01$, with a Bayes factor of 3.98 in favor of the null. Both visual

inspection and the statistical evidence strongly support a lack of recovery when the cognitive load was eased.

Discussion

In our second experiment, we again found evidence against the existence of recovery of forgotten short-term memories. In this experiment the switch conditions provided as much as 12 s for memory recovery to occur, but still showed no effect. At this point the case against memory recovery begins to appear fairly strong, but it is possible that memory recovery may occur, albeit only under very specific conditions.

Experiment 3

In our final experiment we attempted to produce memory recovery by closely mimicking the method which had shown memory recovery in previous work (White, 2012). Some differences may remain between our work and previous work, but if so one would be hard pressed to give a theoretical explanation of why our method should not be expected to produce memory recovery, while the work of White (2012) should produce such a result.

Method

Participants—31 students from the University of Missouri (19 female, on average 19 years of age) completed the experiment in exchange for partial course credit. All participants had normal or corrected-to-normal vision and were native speakers of English.

Materials—The materials were the same as those used in Experiment 2, except that in this experiment we used the full 200 word set described in the previous experiment.

Design—In comparison to our first 2 experiments several changes were made for the present experiment. A 32-s Retention interval condition was added, resulting in a total of 5 Retention Interval Durations. We now used 4 levels of our Cognitive Load manipulation within the same experiment: Low, High, Switch after 8 s (Switch8), and Switch after 16 s (Switch16). Retention Interval Duration and Cognitive Load were now fully crossed, resulting in 20 different types of trials. It should be noted that in only 3 of these trial types did a switch in the cognitive load actually occur, specifically, in the 16-s Retention Interval with a Switch after 8 s, the 32-s Retention Interval with a Switch after 8 s, and the 32-s Retention Interval with a Switch after 16 s. All other Switch trials were replications of the High Load trials of the same retention interval duration because the retention interval was not long enough for a switch to occur. For the purpose of analysis at each individual Retention Interval Duration we averaged together High Load trials and Switch Load trials when the retention interval was too short to allow for a switch. This was done because these trials were identical to one another and this method improves the estimation of true performance levels.

Procedure—Several changes from the procedure of our previous experiments were made. Trials were no longer participant initiated. Instead, each trial began immediately after the response period which was now 6 s in duration. The experimenter now sat behind a screen in

the same room as the participant, rather than beside the participant throughout the experiment. Responses were typed on the computer keyboard rather than spoken out loud.

There were only 2 practice trials in Experiment 3. There were 5 blocks of 20 experimental trials. Each block consisted of 1 trial of each of the 20 trial types which resulted from fully crossing the 5 Retention Interval Durations with the 4 Cognitive Load conditions.

Results

Mean performance levels for all conditions are presented in Figure 4. The pattern of results in Experiment 3 looks very similar to those of Experiments 1 and 2. Performance declined as a function of both Retention Interval Duration and Cognitive Load. When the CL was switched from high load to low load, performance did not decline as much as when the CL stayed high throughout the entire retention interval. Despite the improved accuracy when the CL was eased, accuracy did not recover, but instead continued to decrease at a slower rate, or leveled off. There is one occurrence of an increase in accuracy after a switch occurred, namely the difference between the 16-s High condition and the 32-s Switch conditions. This very small difference is an increase in proportion correct of roughly .02 over a period of 16 s of eased load (or an increase of .00125 in proportion correct per second), well within the standard error of the mean of the relevant conditions. Unsurprisingly, this tiny possible increase was not supported statistically.

To examine the overall effects of Retention Interval Duration and Cognitive Load we conducted a Bayes Factor ANOVA on proportion correct with these manipulations as factors, excluding all trials on which a switch occurred. This analysis demonstrated an effect of Retention Interval Duration, (means: 2s=0.88, 4s=0.76, 8s=0.66, 16s=0.61, 32s=0.58), $F(4,120)=39.64$, $p<.001$, $\eta_p^2=0.57$, with a Bayes factor of more than 10^{21} to 1. An effect of Cognitive Load was also observed, (means: Low=0.75, High=0.65), $F(1,30)=22.21$, $p<.001$, $\eta_p^2=0.43$, with a Bayes factor of more than 6,500 to 1. The two main effects also interacted, $F(4,120)=6.97$, $p<.001$, $\eta_p^2=0.19$, with a Bayes factor of 24 in favor of this effect. The statistics are clear; accuracy decreased with a longer retention interval and with a greater level of load. When the cognitive load was greater there was a greater effect of retention interval duration under the conditions of this experiment. All of this is as in Experiments 1 and 2.

As in our previous experiments, no recovery is evident when the CL was decreased (see Figure 4). Mean performance levels show that the eased load in the switch conditions never led to more than a very minimal increase in performance as compared to accuracy at the time-point before the load was eased. More often performance continued to decrease after the switch, as in our previous experiments (means: 8s-High=0.61, 16s-Switch8=0.58, 32s-Switch8=0.55, and 16s-High=0.53, 32s-Switch16=0.55). To examine the statistical support against recovery after the CL was eased we conducted several Bayes Factor t-tests on proportion correct for comparisons relevant to determining loss in the switch condition. The most important test is the comparison of accuracy between the 16-s High condition and the 32-s Switch16 condition, as mean accuracy did show a minimal increase after the switch. This comparison was examined with a one-tailed Bayes Factor t-test of proportion correct comparing whether accuracy was greater in the 32-s Switch16 condition as compared to the

16-s High condition. Results indicate that there was no increase in accuracy after the load was eased, $t(30)=0.60$, $p>.2$, $d=0.11$, with a Bayes factor of 2.35 in favor of no effect. The other two switch conditions provided even stronger evidence against memory recovery when load is eased. The same test comparing whether accuracy was greater in the 16-s Switch8 condition as compared to the 8-s High condition gave strong support against recovery, $t(30)=-0.84$, $p>.7$, $d=-0.15$, with a Bayes factor of 6.45 in favor of a null result. Comparing the 32-s Switch8 condition and the 8-s High condition produced a similar result, $t(30)=-0.96$, $p>.8$, $d=-0.17$, with a Bayes factor of 6.86 in favor of a null result. In all, the statistical evidence strongly supports a lack of recovery when the cognitive load was eased.

Discussion

Even under conditions very close to those which gave positive results in past work (White, 2012) we were not able to produce any meaningful short-term memory recovery. In one condition there was a very small increase in accuracy, an increase in proportion correct of about .00125 per second over a total of 16 s. This tiny increase is well within the standard error of the means for the relevant conditions. It is certainly not dramatic or meaningful recovery. Given that this was the only relevant comparison which showed any numerical increase in our studies, out of a total of eight individual comparisons which should have shown memory recovery if it exists, the clear conclusion must be against memory recovery in our experiments. Our Bayes factor analysis supports this conclusion, with all Bayes factors indicating positive evidence in favor of no effect.

General Discussion

The results of our experiments are clear: There is no recovery of memory due to decreasing the CL during a retention interval. Instead, a decrease in secondary task demand leads to either a cessation of forgetting or continued forgetting at a slow rate. The present results are replicated across all three experiments with a clean and consistent pattern. Although it would have been more spectacular could we claim to have demonstrated memory recovery, the present results are important for theories of short-term memory precisely because of the absence of such an effect.

Impact on the Debate over the Existence of Decay

In the last decade, the CL effect has been the strongest argument used in favor of time-based memory decay as a central element in short-term memory performance (Barrouillet et al., 2004; Barrouillet & Camos, 2012; Oberauer & Lewandowsky, 2011). Some authors have argued against this conclusion by proposing that memory decay coupled with attention-based refreshing is not needed to explain the CL effect because it can also be explained with an interference and repair approach (Lewandowsky et al., 2009; Oberauer & Kliegl, 2006). This repair approach naturally predicts memory recovery when cognitive load is eased during a retention interval. The data we report here refute this claim and the accompanying theory by providing strong evidence against memory recovery.

While our data are consistent with a decay approach to forgetting, they do not provide direct evidence in support of decay. Strong support for decay can be found elsewhere (Barrouillet

& Camos, 2012; Ricker & Cowan, 2010, 2014; Ricker et al., 2014a; Ricker, Vergauwe, & Cowan, 2014). Instead, the present work contributes to the argument in favor of decay by removing one of the strongest alternative explanations of CL effects.

To be clear, our data do not rule out all interference-only approaches to forgetting. Some new models have begun to incorporate memory maintenance mechanisms based on interference removal rather than memory trace repair directly. In the SOB-CS model (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012) interference removal can only occur for the most recent interfering item. This more restricted memory maintenance mechanism is not capable of fixing past damage done to memory by interfering representations and so would not lead to predictions of memory recovery. In this way the present data are still consistent with an interference approach that includes a structural prohibition on fixing any forgetting which occurred further in the past than the immediately preceding event. In theory a similar sort of repair approach could be proposed, but these models would have to sacrifice much of their flexibility and intuitive appeal to do so. It could also be that we did not test memory performance under the proper conditions needed to observe memory recovery, but we would be hard pressed to explain why this is the case. There is no reason of which we are aware that a repair theory would predict memory recovery under other short-term memory conditions, but not in those of the present work.

To some, it may appear that the present results can also be interpreted as arising from temporal distinctiveness effects. Temporal distinctiveness theories argue that memory recall is determined by how difficult it is to retrieve the target item from long-term memory. Retrieval difficulty is in turn determined by the temporal distinctiveness of the target item, how separated in time it is from other similar items that could be mistakenly retrieved in place of the target item. The application of this idea to the present work would be that the easy task involves fewer representations than the hard task and so creates a less crowded temporal context than does the hard task. Thus, easing the CL could lead to a more temporally distinct memory target as compared to maintaining a hard load throughout.

We see several problems with this account. Although past work using serial recall has sometimes produced results in line with temporal distinctiveness predictions (Brown, Neath, & Chater, 2007; Loess & Waugh, 1967; Turvey, Brick, & Osborn, 1970; Unsworth, Heitz, & Parks, 2008), these works often contradict one another as to how distinctiveness should function and other recent work has produced strong evidence against temporal distinctness accounts (Barrouillet et al., 2012; Lewandowsky, Duncan, & Brown, 2004; Oberauer & Lewandowsky, 2008; Ricker et al., 2014a). In addition, it is not likely that our distractor task representations (consisting of numbers) would be mistakenly retrieved for response in our memory task (consisting of non-numeric word representations), as would be necessary for a temporal distinctiveness approach to hold explanatory value in the present work.

The explanation of the retention duration effects observed here as arising from temporal distinctiveness is also extremely unlikely. Ricker et al. (2014a) demonstrated directly that temporal distinctiveness cannot explain retention duration effects in a verbal memory task very similar to that used in the current work. Instead, we prefer a decay approach to time-based forgetting which incorporates proactive interference through the use of temporal

context as described by Ricker et al., (2014a). This interpretation is more satisfying intuitively, as it does not assume that participants would mistake a numerical distracter representation for the target noun, and is more consistent with a wide variety of research.

Relationship to Previous Findings

There are at least two previous studies with enough similarity to our own method to warrant discussion. Dillon and Reid (1969, Experiment 4) provide some evidence against recovery by demonstrating that requiring performance of an easy distracting task following a hard distracting task does not lead to improved memory performance. Given that the study was not designed to test for memory recovery effects in the context of modern theories of short-term memory performance, strong conclusion cannot be drawn but our data generally agree with findings from this previous work. On the other hand White (2012) found that memory recovery did occur using a method very similar to our own. We have tried to find a reason for this contradiction, but there appear to be no theoretically important differences between our Experiment 3 and the work of White that can account for the divergence in results. The reason that White's findings are in conflict with our findings is ultimately unknown. What is clear is that we cannot produce any evidence that forgotten short-term memories are recovered when cognitive loads are eased. Quite the opposite, our work demonstrates strong evidence against memory recovery during short-term memory performance.

Our data also differ from what is predicted by the standard decay and refreshing account of CL. The Time-Based Resource-Sharing theory of CL predicts that there should not be an effect of retention interval duration on forgetting when the CL is kept constant (Barrouillet & Camos, 2012). Here we find that this is not entirely true; longer retention intervals generally led to decreased performance. This rate of forgetting becomes smaller and may level off at longer retention times, possibly due to maintenance and forgetting processes reaching equilibrium, as predicted by CL theories. The finding that, given a constant cognitive load, longer retention intervals result in lower performance has been reported in other works as well (McKeown & Mercer, 2012; Morey & Bieler, 2013; Ricker & Cowan, 2010, 2014; Ricker et al., 2014a; Ricker et al., 2014b; Vergauwe, Camos, & Barrouillet, 2014) and needs further investigation. It is consistent with the plausible notion that an occasional flaw or lapse in the refreshing process could result in the inactivation of some stimuli, which then could not be recovered for recall in the trial.

There was also a strong interaction observed between Cognitive Load and Retention Interval Duration such that the higher CL led to a greater effect of Retention Interval Duration. This is in conflict with our previous findings that the effects of CL and retention duration are independent (Ricker & Cowan, 2010; Vergauwe et al., 2014). Perhaps we observed this interaction here, but not in previous work, because the high-load task used in the present study was extremely difficult to complete in the allotted amount of time. According to the decay-based CL theories, loss over time would be taken as an indication that the CL was so high that participants were unable to use refreshing well enough to quickly reach a stable equilibrium at which decay and refreshing exactly counteract one another.

Concluding Remarks

The current work invalidates repair-based arguments against decay approaches to forgetting. This is of critical importance, given that an entire class of theories relies on time-based forgetting as a mechanism of short-term forgetting (Baddeley, 2003; Barrouillet, Portrat, & Camos, 2011; Cowan, 1995; Ricker et al., 2014b; Vergauwe et al., 2014). The above findings present a strong challenge to models that rely on a repair mechanism that reconstructs memory items after distractor-based interference, as these models should predict recovery of memory when the CL is eased. This prediction is in clear conflict with our findings. Despite the flaws of the repair-based models there is still room for interference models which use more limited maintenance mechanisms such as restricted distractor removal. Although the promise of memory recovery under eased load would be a great boon to learning and memory, it does not appear to exist.

Acknowledgements

Thanks to Geoff White for generously sharing the details of his methodology with us, including his stimulus set. Thanks also to Pierre Barrouillet for directing us to important previous research on our topic of interest. Funding for this project was provided by NIMH Grant #1F31MH094050 to Ricker, by Swiss National Science Foundation Grant # PA00P1_139604 to Vergauwe, and by NICHD Grant #2R01HD021338 to Cowan. The content is solely the responsibility of the authors and does not necessarily represent the official views of the funding agencies.

References

- Baddeley AD. Working memory: looking back and looking forward. *Nature Reviews: Neuroscience*. 2003; 4:829–839.
- Barrouillet P, Bernardin S, Camos V. Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*. 2004; 133:83–100. doi: 10.1037/0096-3445.133.1.83. [PubMed: 14979753]
- Barrouillet P, Camos V. As time goes by: Temporal constraints in working memory. *Current Directions in Psychological Science*. 2012; 21:413–419. doi:10.1177/0963721412459513.
- Barrouillet P, De Paepe A, Langerock N. Time causes forgetting from working memory. *Psychonomic Bulletin & Review*. 2012; 19:87–92. doi: 10.3758/s13423-011-0192-8. [PubMed: 22184034]
- Barrouillet P, Portrat S, Camos V. On the law relating processing to storage in working memory. *Psychological Review*. 2011; 118:175–192. [PubMed: 21480738]
- Cowan, N. *Attention and memory: An integrated framework*. Oxford University Press; Oxford, England: 1995.
- Dillon RF, Reid LS. Short-term memory as a function of information processing during the retention interval. *Journal of Experimental Psychology*. 1969; 81:261–269. doi:10.1037/h0027769.
- Edwards W, Lindman H, Savage LJ. Bayesian statistical inference for psychological research. *Psychological Review*. 1963; 70:193–242. doi:10.1037/h0044139.
- Fearnley S. MRC Psycholinguistic Database search program. *Behavior Research Methods, Instruments, & Computers*. 1997; 29:291–295. doi:10.3758/BF03204829.
- Harris MJ, Rosenthal R. Mediation of interpersonal expectancy effects: 31 meta-analyses. *Psychological Bulletin*. 1985; 97:363–386. doi:10.1037/0033.
- Lewandowsky S, Oberauer K, Brown GDA. No temporal decay in verbal short term memory. *Trends in Cognitive Science*. 2009; 13:120–126. doi:10.1016/j.tics.2008.12.
- McKeown D, Mercer T. Short-term forgetting without interference. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2012; 38:1057–1068. doi:10.1037/a0027749.
- Morey CC, Bieler M. Visual short-term memory always requires general attention. *Psychonomic Bulletin & Review*. 2013; 20:163–170. doi: 10.3758/s13423-012-0312-z. [PubMed: 23002024]

- Morey, RD.; Rouder, JN. BayesFactor: Computation of Bayes factors for simple designs. R package version 0.8.8. 2012. <http://CRAN.R-project.org/package=BayesFactor>
- Oberauer K, Kliegl R. A formal model of capacity limits in working memory. *Journal of Memory and Language*. 2006; 55:601–626. doi:10.1016/j.jml.2006.08.009.
- Oberauer K, Lewandowsky S. Modeling working memory: A computational implementation of the Time-Based Resource-Sharing theory. *Psychonomic Bulletin & Review*. 2011; 18:10–45. doi: 10.3758/s13423-010-0020-6. [PubMed: 21327362]
- Oberauer K, Lewandowsky S, Farrell S, Jarrold C, Greaves M. Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review*. 2012; 19:779–819. doi: 10.3758/s13423-012-0272-4. [PubMed: 22715024]
- Portrat S, Barrouillet P, Camos V. Time-related decay or interference-based forgetting in working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2008; 34:1561–1564. doi: 10.1037/a0013356.
- Ricker TJ, Cowan N. Loss of visual working memory within seconds: The combined use of refreshable and non-refreshable features. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2010; 36:1355–1368. doi:10.1037/a0020356.
- Ricker TJ, Cowan N. Differences between presentation methods in working memory procedures: A matter of working memory consolidation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2014; 40:417–428. doi:10.1037/a0034301.
- Ricker TJ, Spiegel LR, Cowan N. Time-based loss in visual short-term memory is from trace decay, not temporal distinctiveness. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2014a
- Ricker TJ, Vergauwe E, Cowan N. Decay theory of immediate memory: From Brown (1958) to today (2014). *Quarterly Journal of Experimental Psychology*. 2014b
- Rouder JN, Morey RD, Speckman PL, Province JM. Default Bayes factors for ANOVA designs. *Journal of Mathematical Psychology*. 2012; 56:356–374. doi:10.1016/j.jmp.2012.08.001.
- Rouder JN, Speckman PL, Sun D, Morey RD, Iverson G. Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*. 2009; 16:225–237. doi:10.3758/PBR.16.2.225. [PubMed: 19293088]
- Souza AS, Oberauer K. Time-based forgetting in visual working memory reflects temporal distinctiveness, not decay. *Psychonomic Bulletin & Review*. 2014 Online ahead of print. doi: 10.3758/s13423-014-0652-z.
- Turvey MT, Brick P, Osborn J. Proactive interference in short-term memory as a function of prior-item retention interval. *Quarterly Journal of Experimental Psychology*. 1970; 22:142–147. doi: 10.1080/00335557043000078.
- Vergauwe E, Barrouillet P, Camos V. Do mental processes share a domain-general resource? *Psychological Science*. 2010; 21:384–390. doi:10.1177/0956797610361340. [PubMed: 20424075]
- Vergauwe E, Camos V, Barrouillet P. The impact of storage on processing: How is information maintained in working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2014 Online ahead of print. doi:10.1037/a0035779.
- Wagenmakers EJ. A practical solution to the pervasive problems of p values. *Psychonomic Bulletin & Review*. 2007; 14:779–804. doi:10.3758/BF03194105. [PubMed: 18087943]
- White KG. Dissociation of short-term forgetting from the passage of time. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2012; 38:255–259. doi:10.1037/a0025197.

Figure 1.
An example of a single experimental trial.

Figure 2.

Proportion correct in Experiment 1 as a function of the length of the retention interval and cognitive load. *Switch load* refers to a switch from high to low load half-way through the retention interval. Error bars represent standard error of the mean.

Figure 3.

Proportion correct in Experiment 2 as a function of the length of the retention interval and cognitive load. *Switch load* refers to a switch from high to low load after 4 s. Error bars represent standard error of the mean.

Figure 4.

Proportion correct in Experiment 3 as a function of the length of the retention interval and cognitive load. *Switch* conditions refer to a switch from high to low load at a specified time point during the retention interval. Error bars represent standard error of the mean.