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Free Time Benefits Working Memory and Long-Term Memory Differently

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Giving people more time between encoding information elements into working memory improves immediate (i.e., working memory) and delayed (i.e., long-term memory) retrieval. This free-time benefit is often assumed to arise from processes that counteract forgetting of the just encoded item in working memory, suggesting that time has a retroactive effect. Contrary to these predictions, a few studies showed that free time between two items in a serial recall task benefits only the subsequent (to-be-encoded) items, yielding a proactive benefit in working memory. Here, we investigate whether working memory and long-term memory benefit from free time in the same way. In three experiments, we show that free time benefits the to-be-encoded items in working memory (proactive effect) with only a local retroactive effect for recently encoded items, whereas it mainly benefits already encoded items in long-term memory (retroactive benefit). These results challenge a single explanation of the free-time benefit for memory retention across short and long intervals.

Public Significance Statement

Humans rely on two complementary memory systems: a capacity-limited working memory that temporarily maintains task-relevant information and a long-term memory that supports the storage of all our experiences and knowledge. When learning new information, we might invest more or less time on each information. Here we show that time influences working and long-term memory in different ways. When more time is provided during study, working memory benefits primarily for items that come after the additional time, whereas long-term memory benefits mainly for items that have already been studied. These findings demonstrate that the time during learning episodes shapes how information is retained across different memory systems. Extra time helps working memory prepare for information that comes next, whereas long-term memory uses that time to strengthen information that was just learned. This work suggests that strategically introducing time during studying can differentially support short-term performance and long-term retention.

Keywords: serial recall, free recall, elaboration, consolidation, resource replenishment

Giving people more time during encoding information in a working memory (WM) task improves both immediate (i.e., WM) and delayed (i.e., long-term memory, LTM) memory performance (see Mizrak & Oberauer, 2021, 2024; Oberauer, 2022b, for working memory and Camos & Portrat, 2015; Hartshorne & Makovski, 2019; Loaiza & Souza, 2024; Souza & Oberauer, 2017, for both). The beneficial effect of free time in WM has been attributed to increased time for the use of maintenance processes or for short-term consolidation. Recently, Mizrak and Oberauer (2021) tested the predictions of these accounts of the free-time benefit on WM. In their paradigm (see Figure 1), a serial recall task was used in which a longer time gap was inserted between the presentation of two items, while all other items were separated by a shorter time gap. This manipulation made it possible to disentangle the effect of the added free time upon the items that were

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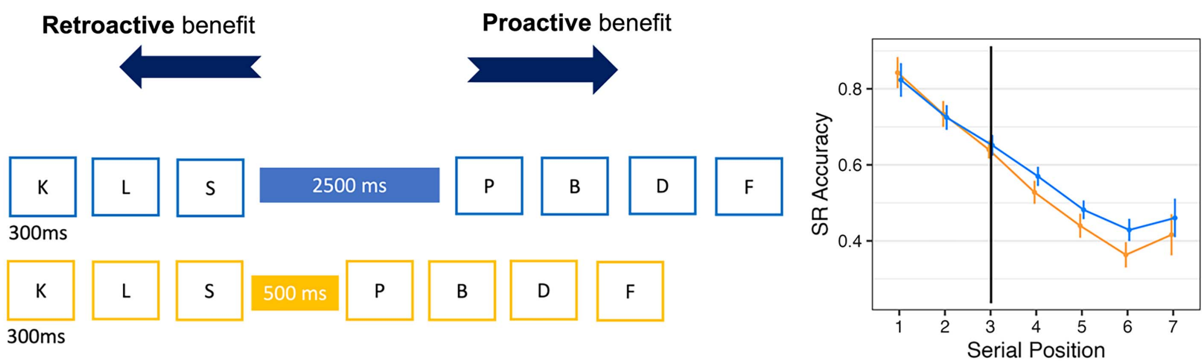
Figure 1

Illustration of Mizrak and Oberauer's (2021) Experimental Design and the Obtained Data



Note. A shorter (orange) or longer (blue) temporal gap—that is, a longer interstimulus interval than the regular ones—was presented in one of the serial positions in a seven-item study list. If the longer free time improved memory for items preceding the gap—in the example, the Items K, L, S—this would produce a global retroactive benefit. If it helped subsequent items—in the example P, B, D, and F—it would produce a global proactive benefit. A local benefit would be observed if only the item immediately before or after the gap improved—in the example, Items S or P. The panel insert on the right shows data from Mizrak and Oberauer (2021) from a study list where the gap was inserted after the third item. There was a global proactive benefit on serial recall accuracy for the longer gap condition (blue line) compared to the shorter gap condition (orange line). SR = serial recall. See the online article for the color version of this figure.

already encoded to WM (i.e., all items before the longer gap) and the items still to be encoded into WM (i.e., items after the longer gap). If time was used to enhance maintenance or consolidation of items that were already in WM, performance for pregap items would improve with longer free time, creating a retroactive benefit. Contrary to this prediction, free time benefited only the postgap items, creating a proactive benefit. To account for this data, Mizrak and Oberauer suggested that free time might be used to replenish a limited encoding resource, which can be used for stronger encoding of subsequently presented items (Popov & Reder, 2020).

So far, it is unclear whether WM and LTM benefit from free time in the same way. In the present study, we tested the free-time benefit for recall from WM in an immediate serial recall task and for recall from LTM with a delayed recall test of the same information. Our aim was to examine if the free-time benefit observed in a WM task translates into more durable traces in LTM. To do so, we used the same paradigm as Mizrak and Oberauer (2021) combining it with an LTM test such as the one used in Souza and Oberauer (2017). We manipulated interitem durations in a serial recall task, adding more free time to one of the interstimulus intervals (ISIs) in a list, creating a deviant ISI (henceforth gap). The gap could be longer (e.g., 4,500 ms) or shorter (e.g., 900 ms), while all other ISIs in the same list remained at 100 ms.

We addressed two questions about the beneficial effect of free time in immediate and delayed recall. First, we asked whether the free-time benefit was proactive, retroactive, or both. For that, we compared memory performance between shorter and longer free-time conditions for items before and after the gap.

Second, we investigated whether the beneficial effect of free time is global or local. A local effect would be specific to the items surrounding the gap (appearing before or after), whereas a global effect would be general, impacting all items before or after the gap. As we discuss below, answering these two questions is diagnostic to distinguish between different mechanisms that explain the free-time effect.

Explanations of the Free-Time Benefit

We consider four sets of mechanisms that can explain why longer free time during a WM task could improve WM and LTM memory for the memoranda studied in the WM task: (a) Free time is used for attending to the last encoded item, thereby *consolidating* it into WM and LTM; (b) during free time, maintenance processes are applied to all items currently in WM; (c) free time increases the temporal distinctiveness between items; and (d) encoding consumes a limited WM resource, and during free time the *encoding resource is replenished*, enabling stronger encoding of subsequently presented information which should strengthen its WM and LTM representation. We will elaborate on the predictions of these three sets of accounts below.

Short-Term Consolidation

Short-term consolidation is the process that strengthens fragile traces, thereby establishing them firmly in WM (Cotton & Ricker, 2022). It is commonly assumed to apply only to the last-encoded item during an interitem interval. Moreover, it relies on a limited processing resource, so that most theorists assume that only one item is consolidated at any time (see Ricker et al., 2018, for a review). This conceptualization implies that in any free-time interval, only the immediately preceding item is consolidated. Short-term consolidation can be assumed to be interruptible by subsequent items such that consolidation of an item stops as soon as the next item is presented (Consolidation 1). Alternatively, it can be assumed to proceed in a resource-greedy fashion such that completion of ongoing consolidation processes has priority over starting new ones (Consolidation 2).

If each item is consolidated only until interrupted by the onset of the next item (Consolidation 1), longer free time would enable longer consolidation of the just encoded item. This would lead to a local retroactive benefit of consolidation. Ricker and Hardman (2017) have proposed an alternative hypothesis: Short-term consolidation is a ballistic process that, once started, runs to completion (Consolidation 2). When not enough time is given for consolidation to be completed, consolidation of the next item is postponed and thereby curtailed. Increased free time avoids that postponement and thereby improves memory for the subsequent item, predicting a proactive benefit for this item. In a series of visual WM experiments, Ricker and Hardman obtained evidence for such a local, proactive effect.

The work of Ricker and Hardman (2017) speaks in favor of Consolidation 2. Oberauer (2022b) observed that free-time benefits increased throughout the serial position in a serial recall task. Simulations showed that a form of Consolidation 2 mechanism is consistent with these results. Therefore, we consider Consolidation 2 as a more probable candidate mechanism in the present study than Consolidation 1 for explaining the free-time benefit in WM tests. Consolidation 2 predicts a proactive benefit because longer free time means that there is less competition among subsequently encoded items for consolidation in memory. Depending on how exclusive that competition is (i.e., a strict bottleneck as in Ricker & Hardman, 2017, or resource sharing as in Oberauer, 2022b), the effect can be more global or local.

What can we expect from short-term consolidation for the delayed recall test? Short-term consolidation is conceptualized as establishing a representation in WM. Cotton and Ricker (2021) suggested that short-term consolidation would also lead to stronger traces in LTM. They demonstrated that requiring participants to encode and maintain one item in WM improved its delayed recognition compared to a perceptual condition in which all information was available (reducing WM demands). This benefit of short-term consolidation might relate to the involvement of attention in the consolidation process. Previous research suggested that formation of episodic LTM traces strongly depends on how long attention is devoted to memoranda (Hannula, 2018). Therefore, if free time is used for short-term consolidation, we can expect that it has comparable effects on immediate and delayed recall.

Maintenance Processes in WM

When interitem time is increased, participants also have more time to apply different maintenance strategies on the items already encoded into WM, such as refreshing, articulatory rehearsal, or elaboration.

Refreshing can be described as directing attention to items that are in WM, going over each of them in a cycle (Barrouillet et al., 2011; Camos et al., 2018). Some authors have suggested that increased refreshing opportunities in WM helps the formation of LTM traces (Abadie & Camos, 2019; Camos & Portrat, 2015). Although several studies have shown that attending to an item in WM improves its recall commensurate with the frequency of refreshing (Atkinson et al., 2022; Souza et al., 2015; Souza & Oberauer, 2017), there is little evidence that people spontaneously apply a deliberate refreshing strategy on WM items (Bartsch et al., 2022; Loaiza & Lavilla, 2021; Oberauer & Souza, 2020; Vergauwe et al., 2018).

Other strategies include articulatory rehearsal (Tan & Ward, 2008) and elaboration (Bartsch et al., 2018). In articulatory rehearsal, to-be-remembered information is repeated verbally during its maintenance. In elaboration, representations of to-be-remembered stimuli are enriched by associating them with LTM knowledge (Craik & Tulving, 1975). Because all these processes are applied to information already in WM, their use predicts a retroactive benefit of free time. Tan and Ward (2008) observed that with longer free time between presentation of items, participants rehearsed more items. As free time yielded better memory, these authors proposed that rehearsal was the reason for the improved performance. This proposal was questioned by subsequent studies that increased the amount of rehearsal through instruction but did not improve WM performance (Souza & Oberauer, 2018, 2020). Additionally, free-time benefits were observed even under articulatory suppression, which rules out rehearsal as a sufficient explanation of the effect (Oberauer, 2022b). These findings indicate that articulatory rehearsal is unlikely to explain the free-time benefit in WM. Likewise, there is little evidence that articulatory rehearsal is beneficial to recall from LTM (Camos & Portrat, 2015; Greene, 1987; Loaiza & McCabe, 2013).

One candidate maintenance strategy that could help LTM acquisition of words studied is elaboration. However, elaboration is unlikely to explain the effect of free time on WM. Although previous research showed a correlation between self-reported elaborative strategies and performance in WM tasks (Bailey et al., 2008, 2011; Dunlosky & Kane, 2007; Kaakinen & Hyönä, 2007), experimental studies that have instructed the use of elaboration observed no discernible benefit of elaboration in tests of WM. At the same time, instructed elaboration improved delayed recall of the same information in surprise tests (Bartsch et al., 2018, 2019, 2022; Bartsch & Oberauer, 2021). These results point to elaboration being beneficial to LTM but not to WM. Accordingly, elaboration is a potential candidate explanation for free-time effects in LTM but not in WM.

Temporal Distinctiveness

According to temporal distinctiveness theories of memory, all events are encoded into memory by associating them to a temporal context that gradually changes over time (Brown et al., 2000, 2007). When event representations are retrieved through temporal retrieval cues, they are more accessible when their temporal context is more distinct from the context of other, potentially interfering events. A longer free-time gap between two list items increases their temporal distinctiveness, and that should reduce the degree to which they interfere with each other. Therefore, if the free-time benefit arises from increased temporal distinctiveness, it should be symmetrically pro- and retroactive. The gain in temporal distinctiveness affects predominantly the items immediately preceding and following the longer gap, and therefore the benefit should be local.

There is some evidence that temporal distinctiveness improves memory for long lists tested through free recall (Brown et al., 2006; though see Grenfell-Essam et al., 2019, for contrary findings). For immediate serial recall of lists in forward order, there is consistent evidence that temporal distinctiveness plays no role (Lewandowsky et al., 2006; Nimmo & Lewandowsky, 2006; Parmentier et al., 2006; Peteranderl & Oberauer, 2018). Therefore, we consider temporal distinctiveness a plausible explanation of free-time benefits in LTM, but it is unlikely to explain the free-time benefit in WM, which has been demonstrated mostly with immediate forward serial recall tests.

Replenishing Encoding Resources

The encoding resource account proposes that encoding into episodic LTM is limited by a resource that is partially depleted by each encoding event and gradually replenishes over time (Popov & Reder, 2020; Reder et al., 2007, 2016; Shen et al., 2018). First discussed in Reder et al. (2007), the account was modeled in the source of activation confusion modeling framework and was later modified by Popov and Reder (2020). According to the model, encoding items that are more difficult requires more resources than encoding easier items. Popov and Reder applied this idea to the frequency effect in word recall. They suggested that high-frequency words need less resources to be encoded into LTM compared to low-frequency words. As a consequence, words presented after high-frequency words benefit from less depleted resource than words presented after low-frequency words. They tested and confirmed the prediction of a proactive effect of word frequency on memory through a reanalysis of multiple free recall data sets: Words following high-frequency words in the list were remembered better than words following low-frequency words.

Popov and Reder (2020) observed the proactive benefit of high-frequency words also in immediate serial recall, suggesting that the encoding resource is relevant also for tests of WM. Therefore, based on the encoding-resource hypothesis, we expect similar effects of free time for WM and LTM.

The Present Study and Predictions From the Different Mechanisms

The question of interest in the present study is whether the effects of free time are the same for WM and LTM and hence whether they can be explained by the same general mechanism. Although previous studies documented free-time benefits for both WM and LTM, they did not implement critical tests to distinguish between the alternative mechanistic explanations outlined above, namely, whether they relate to consolidation, maintenance strategies, or the recovery of a depleted resource. In the present study, we employed a design similar to the one of Mizrak and Oberauer (2021) to distinguish between retroactive versus proactive effects, on the one hand, and local versus global effects, on the other hand. Table 1 summarizes the predictions of the different mechanisms regarding a proactive or retroactive effect and a global or local effect.

Based on the mechanisms discussed previously and summarized in Table 1, we have the following predictions: (a) If free time is used to replenish an encoding resource, its beneficial effect must be proactive, improving both WM and LTM for subsequently given stimuli. (b) Elaboration predicts a retroactive effect, but research has shown that it only benefits LTM. Hence, the observation of a retroactive effect only in LTM but not WM will be consistent with this strategy use. (c) Refreshing should improve both WM and LTM, causing a global retroactive benefit for both. The same prediction holds for articulatory rehearsal, though previous research suggests that it has no beneficial effect on WM and LTM. (d) Short-term consolidation is likely to be ballistic (Consolidation 2) and hence should generate a local proactive benefit both for WM and—indirectly through the allocation of attention—for LTM.

Figure 2 shows the predictions generated by simple computational models implementing the mechanisms. The models are the same as reported in Oberauer (2022b); details can be found in the Appendix. Each panel shows the predicted memory strength across serial positions assuming a manipulation of the gap after the third item. The predictions are the same for immediate (WM) and for delayed (LTM) tests of memory, except for temporal distinctiveness, because temporal distinctiveness depends on the time between encoding and retrieval of an item which is much longer for delayed recall. The consequence of this long delay is that the comparatively small manipulation of the gap duration has a negligible effect on temporal distinctiveness at delayed recall, resulting in the predicted null effect shown in Figure 2.

In three experiments, we varied the durations of interitem time in lists of words. In Experiment 1, interitem times were predictable and were either consistently short or long across the whole list, there was either a longer free-time interval (i.e., a gap) in the middle of the list, or free time was given after all list items' presentation. We predicted that only time given during study list presentation should be helpful, as time after the list cannot have a proactive benefit for immediate recall. In this experiment, we wanted to (a) replicate the benefit of longer free interitem times for both immediate and delayed recall, (b) show that the benefit only happens when the free time was given during the study list presentation, and (c) examine which items benefit from the free time given (e.g., preceding vs. subsequent). In Experiment 1, a gap was introduced only midway through the list in a predictable manner. Predictability of a longer gap could affect how participants used this gap, influencing the use of strategies. In Experiment 2, we varied the position of the gap within the list, making the experiment more similar to the design of Mizrak and Oberauer (2021). Finally, in Experiment 3, participants encoded the memory list, and we randomly varied whether an immediate or delayed serial recall test followed it. This allowed us to test the effects of free time in WM and LTM with the same retrieval requirements.

Table 1
Summary of the Predictions From Different Mechanisms for the Free-Time Effect

Time benefit	Proactive	Retroactive
Global	Encoding resource	Cumulative maintenance processes
Local	Consolidation 2	Consolidation 1
		Maintenance processes of single items

Note. Different mechanisms that can be applied during free time and accounts that predict how free time affects working memory and long-term memory.

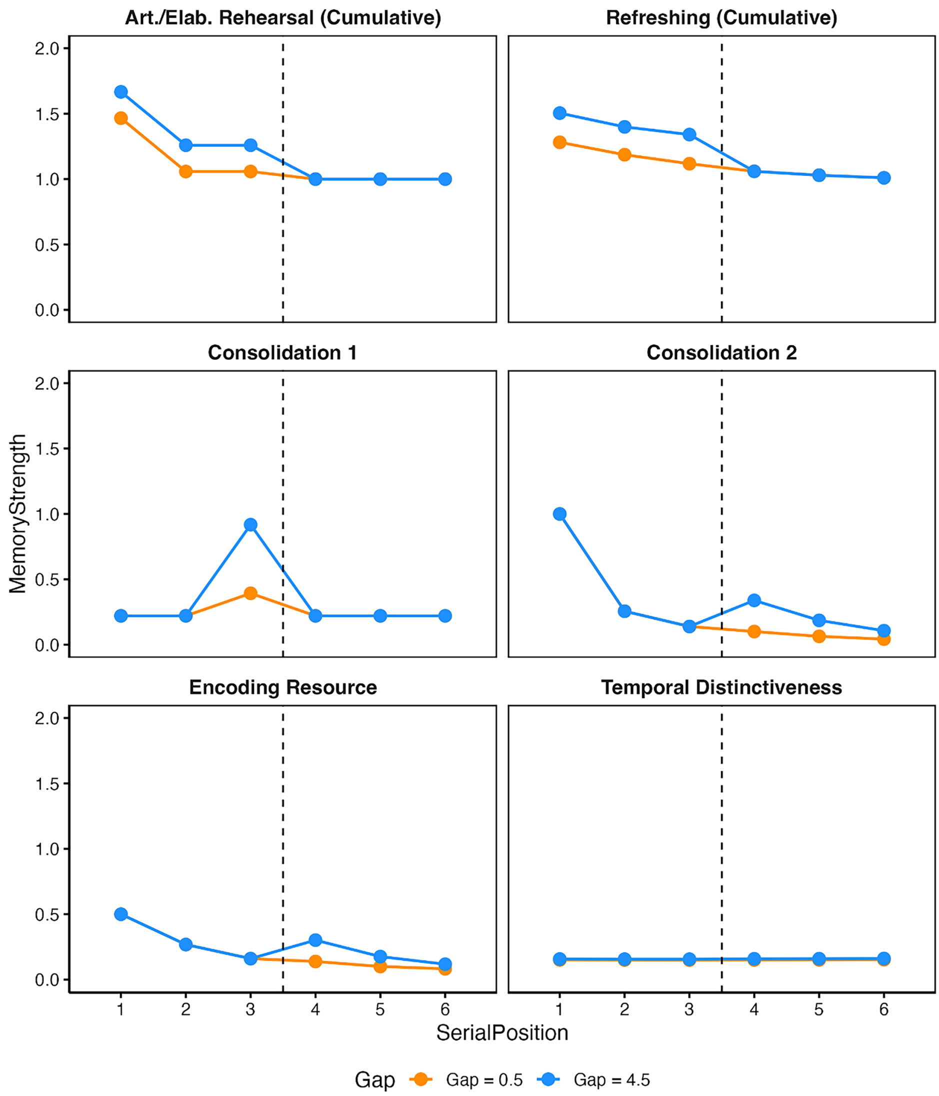
Experiment 1

Method

Participants

Seventy-seven young adults (students from the University of Zurich) participated in Experiment 1. We advertised the study on mailing lists and the University of Zurich website. Inclusion criteria were being between 18 and 35 years old and a native speaker of German. The experiment was programmed in lab.js (Henninger et al., 2024) and ran online. Interested participants contacted us via email and received the link to the experiment. The experiment lasted 50 min, and participants were reimbursed with course credit or 15 Swiss Francs per hour for their time. Data from one participant

Figure 2
Predictions From the Different Mechanisms for the Delayed Recall Data of the Single-Gap Paradigm Used in Experiments 1–3



Note. Predictions are the same for immediate and delayed recall performance for all mechanisms except from the temporal distinctiveness. Art. = articulatory; Elab. = elaboratory. See the online article for the color version of this figure.

were not saved in the server due to technical issues, and data from six participants were excluded due to unusually low performance in the immediate or the delayed recall task (i.e., proportion correct across all conditions below 0.1). The final analysis included 71 participants.

Number of participants was predetermined for all experiments based on experience with previous studies from our lab using similar within-subjects experimental designs. We aimed for collecting data from a minimum of 50 participants for each experiment. As we analyzed the data with Bayesian methods, we planned to increase the sample size in case of ambiguous results (Rouder, 2014). We increased data for both experiments after the first batch of 50 participants, increasing sample size by 50% after our initial results (Experiment 1 from 50 to 77, Experiment 2 from 56 to 88).

In all studies, participants completed an online informed consent form and were debriefed at the end. The experimental protocol did not require special approval from the Institutional Review Board, as it was deemed ethically safe after completion of a self-assessment ethics checklist.

Materials and Procedure

The words used in the immediate recall task were selected from a pool of 1,000 German nouns, three to six letters long (drawn from the dlexdb.de lexical database). In the beginning of the experiment, 180 words were randomly sampled from this pool without replacement for each participant. These 180 words were randomly assigned to study lists for each condition. The stimuli used in the filler task were colored circles. Colors were randomly sampled from the CIELAB color space ($L = 70$, $a = 20$, $b = 38$, and radius = 60).

The experiment consisted of five blocks of five trials each, resulting in 25 trials. In each block, participants completed three tasks: immediate serial recall task, a filler task (i.e., a color recall task), and a delayed free recall task. Each task and condition are described in detail below. The experimental conditions from Experiment 1 are illustrated in Figure 3.

The experimental manipulation was the duration of the interval inserted after the words in the list. We varied one of two intervals: (a) the interval between the words, that is, the ISI, or (b) the interval after the study list was completed (i.e., after the sixth word), referred to as the retention interval (RI). The regular ISI was 100 ms, and the regular RI was 1,000 ms. There were five conditions as illustrated in Figure 3:

1. *Short-fixed:* Each ISI was 100 ms, followed by a 1,000-ms RI;
2. *Long-fixed:* Each ISI was 2,500 ms (+1,000-ms RI);
3. *Short-3*: 800 ms was inserted after the third word in addition to the regular ISI, creating a short gap; remaining ISIs = 100 ms; RI = 1,000 ms;
4. *Long-3*: 4,400 ms was inserted after the third word in addition to the regular ISI time, creating a longer gap; remaining ISIs = 100 ms; RI = 1,000 ms;
5. *Long-6*: 3,500 ms was added to the regular retention interval (i.e., 1,000 ms), providing a total free time of 4,500 ms, which is equivalent to the free time in the long-3 condition (i.e., 4,400 ms + 100 ms ISI).

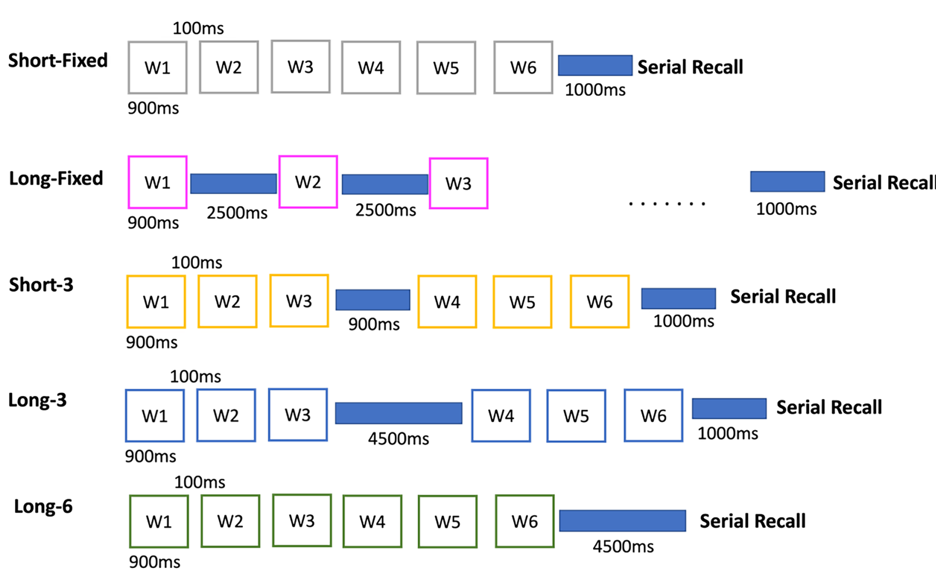
The short-fixed condition serves as a baseline for most conditions: (a) Its contrast to the long-fixed condition allows us to assess the general benefit of free time during encoding; (b) its contrast to the long-6 condition indicates the effect of free time after list encoding; (c) its contrast to the short-3 condition permits the examination of grouping effects (Ryan, 1969a, 1969b), given that the gap in the middle of the sequence creates two subgroups (the first and second halves). Finally, the contrast of the short-3 versus the long-3 conditions allows for the assessment of free-time effects for items before and after the gap, unconfounded by grouping effects.

The long-gap duration of 4,500 ms was chosen for two reasons: (a) to have similar amounts of free time after the third item for both long-fixed (i.e., 5,000 ms of free time was given until the presentation of the fourth item) and long-3 conditions (i.e., 4,700 ms of free time was given until the presentation of the fourth item) and (b) to give enough time for maintenance processes to be applied to words. In comparison to our previous study that used letters as memoranda (i.e., Mizrak & Oberauer, 2021), we implemented an increase of 80% in the amount of free time in the long- and short-gap conditions (from 500–2,500 ms to 900–4,500 ms, respectively) to allow for more time to process the words.

Each block consisted of five trials of the same condition (e.g., one block with five trials of the long-fixed condition). The order of the blocks was assigned to the participants in the beginning of the experiment from an array of block orders. This array was made using a 5 × 5 Latin square in which each condition number occurred exactly once in each row and exactly once in each column. Each set of five successive participants received the block orders given by the five rows of the Latin square ensuring the counterbalancing of the conditions.

Figure 3

Illustration of a Study List Presentation for Each Condition in the Working Memory Task for Experiment 1



Note. W = word. See the online article for the color version of this figure.

Task 1: Immediate Serial Recall of Words. In this task, participants studied a sequence of six words and were asked to recall them in the order of their presentation after a brief RI. For all conditions, each trial began with a fixation cross presented for 1,000 ms, followed by the study list words. Each word was presented centrally onscreen for 900 ms, followed by an ISI of variable duration (depending on the condition) during which the screen was blank. After the last word, a brief RI followed (1,000 ms for all conditions except the long-6 condition), and then participants were prompted to recall the words from that trial. Participants were instructed to type the words they recalled for a given position from one to six. The serial position was presented next to a box where they typed in their response. After each response, they pressed the return key and continued with the recall of the next word.

Task 2: Filler Task. Participants completed an unrelated WM task that took 3 min on average. This task was used to create a delay between the WM task and the delayed recall test that took place in the third phase. In this task, participants studied six colored circles sequentially on random positions on the screen, and at test, they were cued with a color in the middle of the screen and were asked to choose the position in which this color was presented in the study list. They were tested with all the colors presented during the study list. Participants completed five trials in total for the filler task after each block. The results of this task are not of interest here and will, therefore, not be reported.

Task 3: Delayed Free Recall Test

At the end of the block, participants were asked to recall all the words they had seen in the block they just completed. In each block, they studied 30 words across five immediate serial recall trials. In this last phase, they were instructed to type in as many words as they remembered from this block. They could type in the words they recalled in boxes presented in a table grid (in light blue) with five rows of six columns for the 30 words they were asked to recall. Participants were allowed to recall words in any order.

The top, left-most cell was highlighted by showing it in black, and the first typed word appeared therein. When participants pressed the Enter key, the next cell in that column was highlighted, and the second typed word was presented therein, and so on, until all cells were highlighted. When participants could not recall more words, they were instructed to simply press Enter repeatedly to leave the subsequently highlighted cells empty. When the delayed free recall test was finished, participants were instructed that a new block would start with a new set of words for immediate recall.

Data Analysis

We estimated Bayesian linear mixed-effects models using the brm function from the brms package (Version 2.20.4; P. Bürkner, 2018) implemented in the R programming environment (Version 4.3.1; R Core Team, 2023). All analyses were performed on the accuracy of responses for each serial position (i.e., 1 s and 0 s) assuming a Bernoulli distribution and a logistic link function.

We computed Bayes factors (BFs) using the bridge sampler method by Gronau et al. (2018) to gauge the level of support for both the null and alternative hypotheses. For each hypothesis, this involved comparing the full model with all fixed and random effects against a model in which the fixed effect for the factor under scrutiny was removed (as suggested by Singmann et al., 2023). This approach avoids the use of inclusion BFs in which the evidence for each model term is not clearly attributable to one statistical model (cf. Hinne et al., 2020) and also avoids the necessity of first performing a model selection procedure to identify the best model (the full model is by definition the most flexible model therefore the least biased; see also Doorn et al., 2020). Because our data contained repeated measures (i.e., all participants completed all conditions in all experiments), the full model always included random slopes for each fixed effect which represented the maximal random effect structure justified by the design (Barr et al., 2013; Oberauer, 2022a).

Results reported below are often given in the form of BF_{10}, indicating the strength of evidence for a particular focal model, Model 1, against a comparison model, Model 0. Model 1 was always the full model (i.e., all fixed effects). The value of BF_{10} indicates how much more likely Model 1 is over Model 0. If the value of BF_{10} is greater than 1, this indicates evidence for the alternative model (i.e., Model 1 over Model 0). If the value of BF_{10} is less than 1, this indicates evidence for the simpler model (i.e., Model 0 over Model 1). In the latter case, we report BF_{01} instead, which is given by $BF_{01} = 1/BF_{10}$ so that BF_{01} values larger than 1 indicate evidence for the simpler model. BFs should not be interpreted as p values, as they provide continuous evidence in support of one model over the other. Although there are no decision cutoffs on the BF scale, the following interpretative guideline has been proposed: BFs smaller than 3 are considered weak evidence, BFs between 3 and 10 are considered substantial evidence, and BFs larger than 10 are considered strong evidence in favor of the winning model (Kass & Raftery, 1995).

For the fixed-effect regression coefficients that were of primary interest here, we used student-t priors with 3 degrees of freedom and a scale of 0.5 (for categorical fixed-effect coefficients, we used $+1/-1$ contrast codes). For the fixed-effect intercept, we used a logistic prior with a scale of 1 and a location of 0 which implied a noninformative prior on the response (i.e., probability) scale. For random effects, we used nonnegative weakly informative priors (half-student-t prior with 3 degrees of freedom and a scaling parameter of 2).

For Experiment 1 immediate and delayed recall analyses, the fixed effects were the condition (i.e., conditions of interest for each comparison) and the list part (i.e., first part = Serial Positions 1–3 and the second part of the list = Serial Positions 4–6).

Results

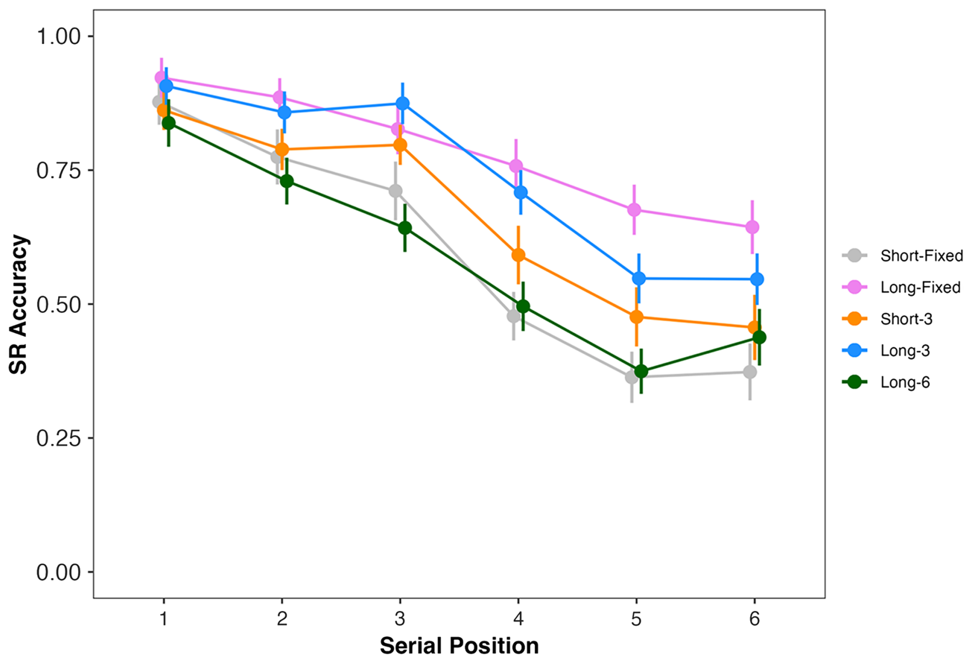
We wanted to compare the effect of free time on items before and after the gap in the short-3 and long-3 conditions to gauge retroactive and proactive benefits of free time, respectively. To do so, we divided the lists into two halves: the first part (Serial Positions 1–3) and the second part (Serial Positions 4–6). This way, we could compare all the lists with each other and examine the benefit of time on the first part and second part of the list.

Immediate Serial Recall

Figure 4 shows immediate recall for each serial position across the five conditions. Table 2 shows the BFs for all fixed effects and their interactions for each analysis. For all analyses, we focused on the main effect of the condition contrast and the interaction of condition and list part. The main effect of list part simply reflects the difference

Figure 4

Serial Recall (SR) Accuracy as a Function of Serial Position for All Conditions in Experiment 1



Note. Error bars represent within-subjects 95% confidence interval. See the online article for the color version of this figure.

in performance over serial position, and it is not of relevance for our research questions.

Fixed Free Time During List Presentation. First, we examined the benefit of a fixed amount of free time added after each list item during encoding. For this analysis, we only included the short-fixed versus long-fixed condition. Our analysis showed a strong benefit of free time in both the first and the second part of the list ($BF_{10} > 1,000$ for the main effect of condition). This benefit was bigger in the second part of the list than the first part ($BF_{10} = 13.2$ for the model including the interaction), replicating the interaction of free time with serial position (Oberauer, 2022b).

Free Time After List Presentation. We hypothesized that free time would only benefit memory if it was given during list presentation, but not after the end of the list. To test this, we compared the long-6 condition, in which free time was only given at the end of the list, to the short-fixed condition. There was evidence for an interaction between condition and list part ($BF_{10} = 19.2$). While the short-fixed condition had slightly better accuracy for the first part of the list, this pattern seems to be the opposite for the second list part, specifically for Item 6. Overall, these results suggest that adding free time after the study list has a local retroactive benefit.

Proactive and Retroactive Effects of the Free-Time Gap. The comparison of the long-3 and short-3 conditions allows us to assess the benefit of free time for specific list items. This analysis can indicate if benefits are retroactive, proactive, or both. There was strong evidence for the free-time benefit ($BF_{10} > 100$ for the main effect of condition).

Table 2

Bayes Factors (BFs) of the Main Effects and Interaction in the Analysis of the Immediate Serial Recall Data of Experiment 1

Effect	Conditions compared	BF_{10}	BF_{01}
Time during list presentation	Short-fixed vs. long-fixed	724.2×10^{8}	
List part (1–3 vs. 4–6)		6.15×10^{23}	
Interaction		13.2	
Time after list presentation	Short-fixed vs. long-6		3.63
List part		6.2×10^{23}	
Interaction		19.2	
Free-time gap	Short-3 vs. long-3	270.11	
List part		14.3×10^{21}	
Interaction			3.92
Temporal grouping	Short-fixed vs. short-3	13.15	
List part		10.99×10^{25}	
Interaction			1.30

The long-3 condition yielded better performance than the short-3 condition for both preceding and subsequent items, and there was evidence against the interaction of free time with list part (BF_{01} = 3.92). To conclude, we observed both proactive and retroactive benefits of free time.

Temporal Grouping Effects. We expected both the short-3 and long-3 conditions to benefit from temporal grouping due to the midlist gap creating two subgroups within the study list. Whereas the long-3 condition should benefit from both temporal grouping and longer free time, the short-3 condition should benefit mainly from temporal grouping. To examine temporal grouping benefits, we compared the short-3 condition to the fixed-short condition, which revealed better performance for short-3 condition for both list halves (BF_{10} = 13 for the main effect of condition; with ambiguous evidence against the interaction with list part, BF_{01} = 1.3). This indicates the presence of temporal grouping benefits in WM showing symmetric improvement of both list halves due to the short temporal gap.

Delayed Free Recall

Figure 5 presents delayed free recall accuracy separately for the first and second halves of the list in the five conditions. We added a covariate to each analysis which was the immediate recall status of the items. If a word was recalled during immediate serial recall task (i.e., regardless of its position), the recall status was coded as 1; otherwise, it was 0. This covariate is meant to capture the effect of retrieval practice during the WM task, insofar as retrieval practice strengthens LTM more when retrieval is successful. We tested whether the covariate had an effect or not for each analysis (see BFs for the covariate for each analysis in Table 3). We performed the same comparisons across conditions that we did for immediate recall performance. For all analyses, the effect of WM retrieval success was strongly supported; hence, we maintained this covariate in the model.

Free Time During List Presentation. The long-fixed condition yielded better LTM recall than the short-fixed condition (BF_{10} > 10,000), and there was weak evidence against the interaction with list part (BF_{01} = 3.16), implying approximately equal beneficial effects of free time for both the first and the second list halves. Hence, in line with the WM results, free time during encoding improved the LTM retention of all encoded words.

Free Time After List Presentation. The long-6 condition did not differ from the short-fixed condition (BF_{01} = 5.73 evidence against the main effect of free time; BF_{01} = 3.26 evidence against interaction). Hence, free time after the memory list was not beneficial to LTM.

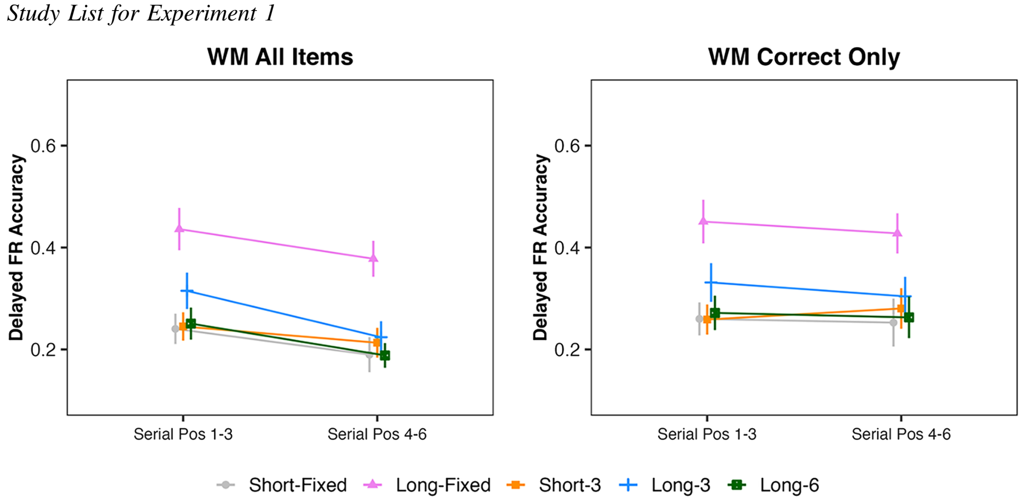
Proactive and Retroactive Effects of the Free-Time Gap. The proactive free-time benefit observed for the immediate recall in the long-3 condition was no longer present for delayed recall. The long-3 and short-3 conditions produced similar delayed recall for postgap items (see Figure 5). Evidence on the main effect of free time was ambiguous (BF_{01} = 1.73), and so was the evidence pertaining to the interaction with list part (BF_{10} = 2.01).

Temporal Grouping Effect. There was no benefit of temporal grouping on delayed free recall: The short-3 and short-fixed conditions did not differ. Hence, unlike WM, temporal grouping did not benefit LTM.

Discussion

Experiment 1 examined the effects of free time on WM (i.e., immediate recall) and LTM (i.e., delayed recall) under conditions that allowed us to assess proactive versus retroactive benefits. The crucial comparison was between the short-3 versus the long-3 conditions that vary in free time while controlling for temporal grouping. For WM, free time produced retroactive and proactive benefits. For LTM, free time was beneficial overall, as shown by better memory in the long-

Figure 5
Delayed Free Recall (FR) Accuracy as a Function of Condition for the First Part and Second Part of the Study List for Experiment 1



Note. This data included only the words recalled correctly in the first task (i.e., serial recall task). Error bars represent within-subjects 95% confidence interval. WM All Items: Analysis on the items regardless of their WM recall status. WM Correct Only: Analysis of items that were recalled correctly during WM task. WM = working memory. See the online article for the color version of this figure.

Table 3

Bayes Factors (BFs) of the Main Effects and Interaction in the Analysis of the Delayed Free Recall Data of Experiment 1

Effect	Conditions compared	BF_{10}	BF_{01}
Immediate recall (covariate)		18×10^{32}	
Time during list presentation	Short-fixed vs. long-fixed	35.6×10^{6}	
List part (1–3 vs. 4–6)			7.00
Interaction			3.16
Immediate recall (covariate)		68.8×10^{31}	
Time after list presentation	Short-fixed vs. long-6		5.73
List part			6.76
Interaction			3.26
Immediate recall (covariate)		57.9×10^{38}	
Free-time gap	Short-3 vs. long-3		1.73
List part			4.86
Interaction		2.01	
Immediate recall (covariate)		11.2×10^{32}	
Temporal grouping	Short-fixed vs. short-3		4.43
List part			6.29
Interaction			4.00

Note. Immediate recall (covariate) is the recall status of the items during the immediate recall test (i.e., either 0 or 1, 1 if an item was correctly recalled regardless of its position).

fixed than the short-fixed condition. However, increasing free time of a single gap yielded only a weak benefit, and although numerically the benefit was larger for the first part of the list, there was ambiguous evidence for an interaction. One additional finding was that temporal grouping effects were observed only for WM but not LTM. A similar observation has been reported by Guitard et al. (2022).

These results point to differences between the effect of free time in WM and LTM. They also diverge in some regards from our previous published study in which only proactive benefits were observed in a WM task with letters (Mizrak & Oberauer, 2021). We reasoned that one critical difference between these studies is related to how the temporal gap was implemented: It was fixed in the current experiment but varied across serial positions in our previous study. We conducted Experiment 2 to further examine the difference between free-time effects in WM and LTM with an improved design that reduced free-time predictability.

Experiment 2

In Experiment 2, we varied the position of the longer gap within the memory list to reduce the usefulness of applying a specific strategy during the midlist long gap. To do so, we adapted the same experimental design as Mizrak and Oberauer (2021) using words instead of letters. Based on their findings, we predicted a global proactive free-time benefit in WM. We examined whether this effect extended to the delayed free recall of the words.

Method

Participants

Eighty-eight young adults (students from the University of Zurich) participated online in Experiment 2. This experiment took place over two sessions. Each session took between 40 and 50 min. Participants were reimbursed with course credit or 15 Swiss Francs per hour for their time. Data from eight participants were excluded due to unusually low performance in the delayed recall task (i.e., average delayed free recall accuracy below 0.1). Data from three participants were excluded due to an error in data saving. The final analysis included 77 participants.

Materials and Procedure

Experiment 2 used the same materials and procedure as Experiment 1. In this version, we focused on the deviant ISI manipulation, that is, the additional free time provided in the gap. We only included the short- and long-gap conditions, with one difference: The gap was not at a fixed position but rather varied unpredictably across lists. In each trial, the gap could be inserted in any of the five ISI positions. For instance, in one trial, the second ISI could be longer than all others. In another trial, the fourth ISI could be longer. In total, there were 10 conditions: Two Deviant Gap Durations (short vs. long) × Five ISI Positions. Figure 6 illustrates an example trial for the long and short conditions. In each trial, there was a deviant ISI—either short (900 ms) or long (4,500 ms)—at one interitem position. Both created a temporal gap against the background of the remaining standard ISIs, which were all 100 ms.

The experiment consisted of two sessions. This was done to increase the number of trials per condition. Each session consisted of five blocks. Each block consisted of five trials of the same ISI duration condition (e.g., one block of five trials with the long deviant condition). The ISI position varied across trials within a block. There was one trial per ISI position condition in each block. Each block had a different ISI duration manipulation. If one block was a short-deviant condition, the next one was a long-deviant condition. This was counterbalanced across participants and across sessions. Each block was followed by a 3-min period of the same filler task used in Experiment 1, and a free recall test of all 30 words from that block, as in Experiment 1.

Results

In Experiment 2, we varied the position of the free-time gap to prevent participants from strategizing on how they used the free

Figure 6

Illustration of a Study List Presentation for Each Condition in the Working Memory Task for Experiment 2

Note. Blue bars represent unfilled time. Regular interstimulus time was 100 ms. Gap interstimulus intervals are shown below the blue bars within study list presentation. In this example, the gap is in the second interstimulus interval position. On different trials, it could be at any of the five interstimulus interval positions. W = word. See the online article for the color version of this figure.

time. Here, we will focus on the effect of free time as a function of the list position of the presented items relative to the gap (i.e., lag distance between an item and the gap on that trial). By doing so, we can analyze the impact of free time on preceding and subsequent items separately. The lag is calculated as the signed distance of an item from the position of the gap in the list. For instance, if the gap was between the third and fourth item, the third item would be at lag −1 and the fourth item would be at lag +1. We excluded Serial Positions 1 and 6 from this analysis. Serial Position 1 could only be a preceding item, hence only contributing to negative lags, whereas Serial Position 6 could only be a subsequent item, hence only contributing positive lags. This is similar to the analysis strategy employed by Mizrak and Oberauer (2021). After this exclusion, there were eight lags: −4, −3, −2, −1, +1, +2, +3, +4. Negative lags include items preceding the gap, and positive lags include items after the gap. Hence, the sign of the lag is used to distinguish retroactive and proactive effects. This coding allowed us to examine effects across all possible combinations of item positions and gap positions in a list at once. For example, a lag of +2 would include (a) an item at Serial Position 4 when the gap was between Items 2 and 3 and (b) an item at Serial Position 5 when the gap was between Items 3 and 4. Memory performance for lag +2 is calculated by averaging across serial recall performance for these items in the appropriate gap-position conditions.

To examine the proactive and retroactive effects of free time on immediate and delayed memory performance, we compared the effect of short and long free time on the negative and positive lags averaged across the absolute value of the lag. The interaction of free-time duration with lag sign tells us whether the effect of free time was more retroactive or more proactive. Additionally, the free-time benefit could be specific to the items just following or preceding the gap (local effect) or it can be across all lags (global effect). To test this, we defined a contrast on the absolute lag number, comparing lags 1 and −1 to all the other lags (i.e., absolute lag number 1 vs. >1).

Immediate Serial Recall

We first look at how free time improved items studied in the WM task (i.e., immediate serial recall). As can be seen in Figure 7, accuracy for positive lags was higher for the long free-time condition compared to the short one (blue > orange), showing a global proactive benefit. We also observe a local retroactive benefit of time on lag −1. Our first analysis included all three variables: time (short vs. long), absolute lag number (1 vs. 2–3–4), and lag sign (negative vs. positive). This analysis showed some evidence against a three-way interaction but evidence for the time and lag number interaction, as well as the lag number and lag sign interaction (see BFs for these effects in Table 4). The time and lag number interaction reflect the time benefit being stronger on the items in proximity to the gap (−1 and +1), indicating a local benefit (see Figure 7).

To examine more closely whether the beneficial effects were global or local for negative and positive lags, we ran separate analyses to examine the proactive and retroactive benefits. This analysis included two variables: lag number and free time. An interaction between the lag number and free time indicates a local benefit. There was evidence for an interaction between lag number and free time for negative lags ($BF_{10} = 16.92$), suggesting an effect of lag number indicating local retroactive benefit.[1] There was evidence against an interaction for positive lags ($BF_{01} = 5.81$), suggesting a global proactive benefit. There was strong evidence for the overall benefit of free time on negative lags ($BF_{10} = 45$) and on positive lags ($BF_{10} >$ 10,000 evidence for the main effect of free time).

Delayed Free Recall

We performed the same analyses for the delayed free recall performance (see Table 4). Figure 8 shows that the free-time benefit seems to be specific to negative lags only (i.e., a retroactive benefit). This was supported by evidence for the interaction between free time and lag sign ($BF_{10} = 16.2$), indicating a selective retroactive benefit of free time on delayed free recall performance, replicating Experiment 1. We did separate analyses on the preceding and subsequent items testing the free time and lag number (see Table 5). These analyses showed a benefit of time for preceding items ($BF_{10} = 3.62$) and evidence against a benefit for subsequent items ($BF_{01} = 3.12$).

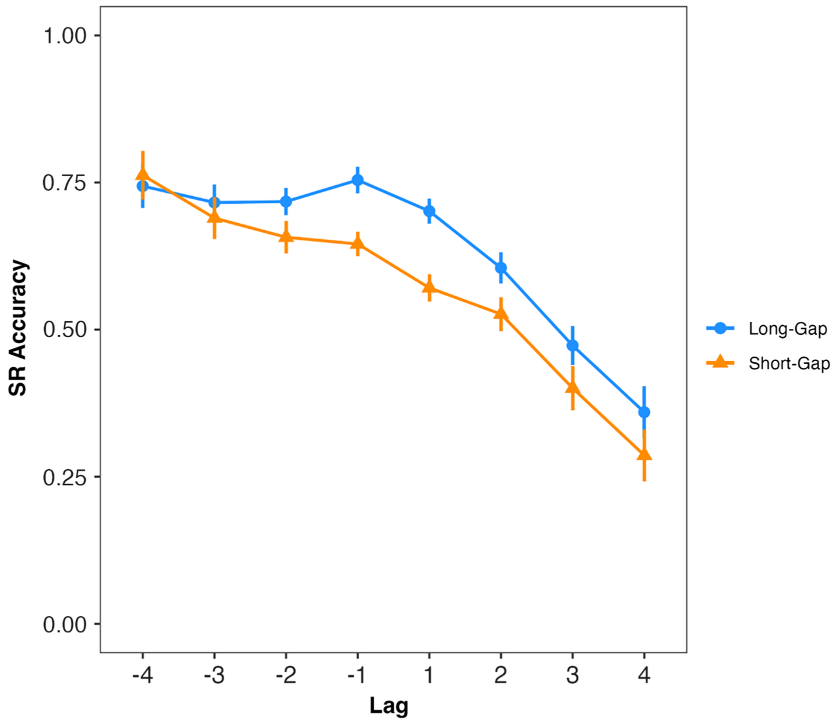
Discussion

Results from Experiment 2 provided more conclusive evidence for a global, purely retroactive benefit of time on the delayed free

[1] Although this interaction suggests that the retroactive benefit is strongest for lag −1, we also observe a visible difference between long- and short-gap condition at lag −2 ($BF_{10} = 8$).

Figure 7

Proportion of Correct Responses on the Immediate Serial Recall (SR) Task for Items Preceding the Free Time Gap and Subsequent Items as a Function of Free Time Duration Experiment 2



Note. Error bars denote 95% within-subjects confidence intervals. Negative lags = preceding items; positive lags = subsequent items. See the online article for the color version of this figure.

recall performance, a pattern that was ambiguously supported in Experiment 1. For WM, we replicated the global proactive benefit observed in Experiment 1. The retroactive benefit of time, however, was more local in Experiment 2 than in Experiment 1. These findings collectively indicate that LTM and WM benefit from time in different ways. However, this difference could be due to the way we tested LTM in our task: serial recall for WM but free recall for LTM, with LTM tests always occurring after an immediate test. The next experiment tested WM and LTM under equal testing conditions.

Table 4

Bayes Factors (BFs) of All the Main Effects and Interactions in the Analysis of the Immediate Serial Recall and Delayed Free Recall Data of Experiment 2

	Immediate serial recall		Delayed free recall	
Effect	BF_{10}	BF_{01}	BF_{10}	BF_{01}
Time	8.1×10^{16}			8.31
Lag number	15.17×10^{12}			4.1
Lag sign	6.58×10^{16}			11.66
Time × Lag Number	658.05			5.88
Time × Lag Sign		4.82	16.2	
Lag Number × Lag Sign	22.9×10^{12}			1.74
Time × Lag Number × Lag Sign		3.15		3.14
Immediate recall (covariate)[a]			1.22	

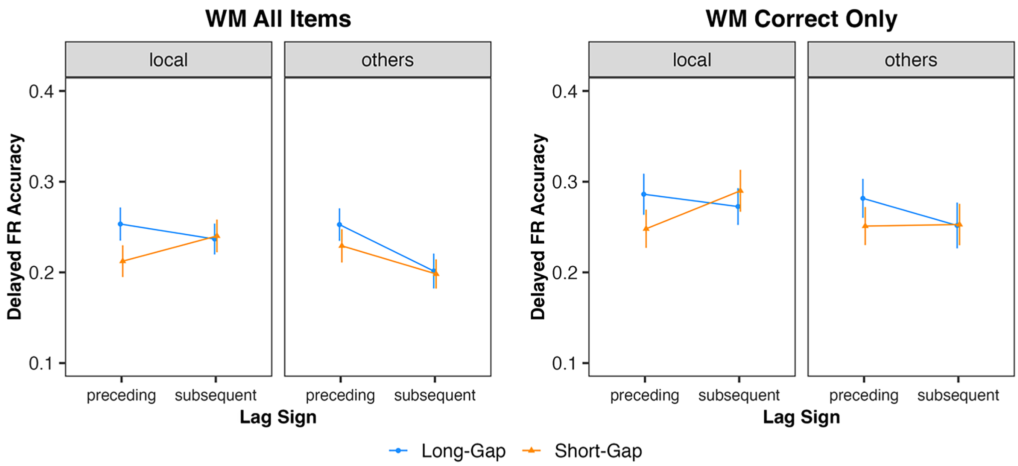
[a] The covariate was included only in the analysis of the delayed free recall data.

Experiment 3

In the previous experiments, the LTM test required participants to freely recall all items memorized during the WM trials. This means that WM and LTM tests differed in two ways: (a) type of test (serial recall requiring item-position memory; free recall requiring only item memory) and (b) LTM recall always occurring after a WM test. These differences might explain their differential sensitivities to free-time effects. Hence, in Experiment 3, we aimed to test the benefit of time by (a) making the recall procedure similar for WM and LTM and (b) eliminating the dependency between WM and LTM. The study list presentation and the gap manipulations were the same as in Experiment 2. The only difference was the delayed recall procedure. After list presentation, participants either did an immediate serial recall task or a delayed serial recall task following a 1-min filler task. This was randomly chosen; therefore, participants did not know whether the test would be immediate or delayed, which made each trial's encoding processes the same.

Figure 8

Proportion of Correct Responses on the Delayed Free Recall (FR) in Experiment 2



Note. Error bars denote 95% within-subjects confidence intervals. Local items are the items neighboring the gap (lag −1 or +1), and others are the items that are more distant relative to the gap (lags −4, −3, −2 or +2, +3, +4). WM All Items: Analysis on the items regardless of their WM recall status. WM Correct Only: Analysis of items that were recalled correctly during WM task. WM = working memory. See the online article for the color version of this figure.

Method

Participants

One hundred seven young adults (students from the University of Zurich) were recruited online in Experiment 3. The experiment took place over two sessions. Each session took 50–60 min. Participants were reimbursed with course credit or 20 Swiss Francs per hour for their time. Only 88 participants completed both sessions. Out of this 88, data from 15 participants were excluded due to unusually low performance in either the delayed task (i.e., average delayed recall accuracy below 0.1; 13 participants) or the filler task (i.e., average sorting accuracy below 0.5; seven participants). The final analysis included 73 participants.

Table 5

Bayes Factors (BFs) for the Separate Analysis of Proactive and Retroactive Effects of Time for the Immediate Serial Recall Data and Delayed Free Recall Data in Experiment 2

Effect	Immediate serial recall		Delayed free recall	
	BF_{10}	BF_{01}	BF_{10}	BF_{01}
Time (retroactive)	45.17		3.62	
Lag number	1.03			10.5
Time × Lag Number	16.92			4.84
Immediate recall (covariate)[a]			17.1×10^{42}	
Time (proactive)	24.7×10^{4}			3.12
Lag number	6.19×10^{28}		1.05	
Time × Lag Number		5.81		5.30
Immediate recall (covariate)[a]			9.1×10^{71}	

[a] The covariate was entered only in the analysis of the delayed free recall data.

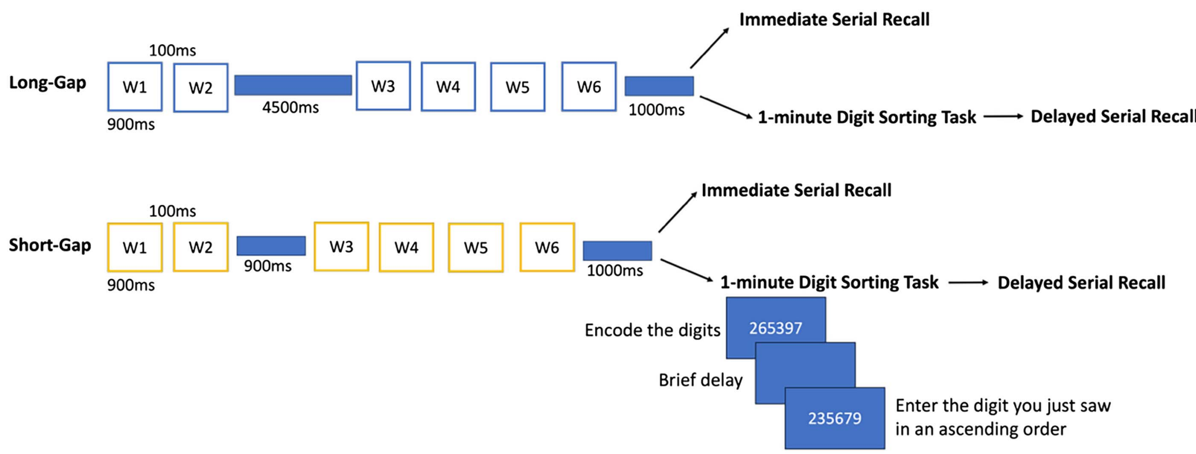
Materials and Procedure

Experiment 3 used the same materials and procedure as Experiment 2. The conditions were the same. There were 10 conditions: Two Deviant Gap Durations (short vs. long) × Five ISI Positions. The testing procedure was different than Experiment 2. After the presentation of a six-word study list on each trial, participants performed either immediate or delayed serial recall which aimed to measure their WM and LTM separately. If participants performed an immediate serial recall task, they started recalling the words after a brief delay (1 s) following the study list. If they performed a delayed serial recall task, they first completed a 1-min filler task before their memory was tested. On each trial of the filler task, participants were shown a random six-digit list (e.g., 784361) for 1.5 s. After the digit list disappeared, participants were tasked with entering the presented digits in ascending order (e.g., 134678) into a response box and pressing ENTER to start the next trial of the filler task. Participants completed the digit sorting trials at their own pace. Therefore, each filler task had a different number of trials of digit sorting, but all of them lasted for a minute. We aimed to measure LTM in the delayed serial recall task. The filler task, which includes processing and storage components, should prevent maintenance of the study list of words in WM. Figure 9 illustrates the procedure in Experiment 3.

Each session consisted of five blocks. Each block consisted of 10 trials of the same ISI duration condition (e.g., one block of 10 trials with a long gap). The ISI positions and the test type were varied across trials within a block. There was one trial per ISI position condition and test type in each block. Each block had a different ISI duration manipulation. If one block was a short-deviant condition, the next one was a long-deviant condition. This was counterbalanced across participants and across sessions.

Figure 9

Illustration of a Study List Presentation for Each Test Condition for Experiment 3



Note. After encoding, participants performed a serial recall task either immediately or after a minute of digit sorting task (i.e., delayed serial recall test). W = word. See the online article for the color version of this figure.

Results

We tested whether time has proactive and retroactive effects locally and globally on immediate or delayed serial recall performance. To do so, we ran separate analyses to examine these effects for immediate and delayed test performance. These analyses included three variables: lag sign (preceding vs. subsequent items), lag number (1 vs. >1; local vs. global), and free time (long vs. short). Results are shown in Table 6. There was evidence for a three-way interaction between time, lag number, and lag sign for immediate serial recall memory (BF_{10} = 4.62), whereas there was evidence against an interaction for delayed serial recall memory (BF_{01} = 3.78). This difference indicates that the retroactive time benefit in WM was local, whereas it was global for LTM (see Figure 10: Compare lag −1 vs. lags −2, −3, and −4).

To examine these results better, we ran separate analyses for preceding and subsequent items for both immediate and delayed test performance. These analyses included two variables: lag number (1 vs. >1; local vs. global) and free time (long vs. short). We observed a global proactive benefit for both immediate and delayed test performance (evidence for an effect of condition for immediate: $BF_{10} = 36 \times 10^4$, for delayed: $BF_{10} = 14 \times 10^5$ with evidence against an interaction for immediate: BF_{10} = 5.2, for delayed BF_{10} = 3.2). We observed a local retroactive benefit for immediate performance (evidence for an effect of condition for immediate: BF_{10} = 7,000 and evidence for an interaction: BF_{10} = 32). The retroactive benefit for delayed performance was global although the retroactive benefit seems to be the strongest for lag −1 as the evidence for an interaction was weak (evidence for an effect of condition for immediate: $BF_{10} = 13 \times 10^4$ and evidence for an interaction: BF_{10} = 1.5).

Table 6

Bayes Factors (BFs) for All the Main Effects and Interactions in the Analysis of the Immediate and Delayed Serial Recall Data of Experiment 3

	Immediate		Delayed	
Effect	BF_{10}	BF_{01}	BF_{10}	BF_{01}
Time	4×10^7		10×10^8	
Lag number	5.28×10^{11}		12×10^7	
Lag sign	10×10^{13}		20×10^7	
Time × Lag Number	1.88		2.48	
Time × Lag Sign		1.92		5.27
Lag Number × Lag Sign	17×10^{12}		20×10^{10}	
Time × Lag Number × Lag Sign	4.62			3.78

Discussion

Results from Experiment 3 showed both retroactive and proactive time benefits for LTM. In Experiments 1 and 2, only a retroactive benefit was observed, but LTM was tested at the end of each block with free recall. When we closely aligned the memory tests in WM and LTM, we revealed a proactive time benefit for LTM similar to the one observed for WM. This result suggests that in serial recall tasks (immediate or delayed), providing free time benefits the encoding of the list position or order of the following items.

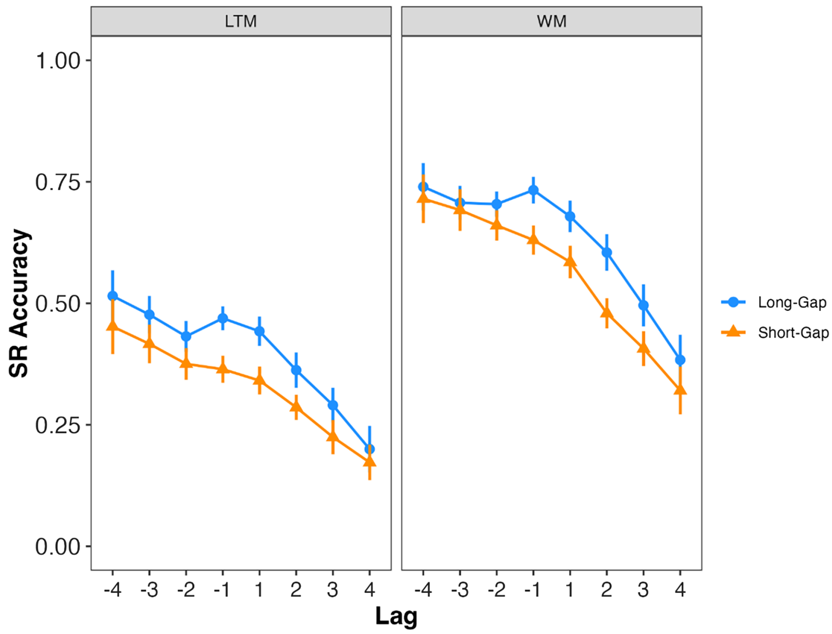
Differences between LTM and WM remained, however, regarding the extent of the retroactive benefit of time, which was local for WM but global for LTM. As we stated in the introduction, global retroactive benefits are better explained by maintenance strategies, whereas local effects are also consistent with Consolidation 1.

Transparency and Openness

All materials including scripts for programming the experiments and scripts for data analysis as well as the anonymized data are available on the Open Science Framework (https://osf.io/uzkx9/). The experiments were programmed using the free and open online experiment builder lab.js (Henninger et al., 2024). Data analyses and plotting were conducted using R (R Core Team, 2023) and the R-packages tidyverse (Wickham et al., 2019), rstan (Stan Development Team, 2023), brms (P.-C. Bürkner, 2017), and afex (Singmann et al., 2025).

Figure 10

Proportion of Correct Responses on the Immediate Serial Recall and Delayed Serial Recall Task for Preceding and Subsequent Items as a Function of Free-Time Duration in Experiment 3



Note. Error bars denote 95% within-subjects confidence intervals. LTM (delayed serial recall) = long-term memory, WM (immediate serial recall) = working memory. See the online article for the color version of this figure.

General Discussion

We examined the effect of increasing the free time given to study items on immediate and delayed memory performance. Table 7 summarizes the main findings observed across our three studies. Free time helps both WM and LTM albeit in different ways: Benefits tend to be locally retroactive and globally proactive for WM, whereas for LTM, free time had global retroactive benefits. Additionally, proactive benefits were not observed in delayed free recall but were present for delayed serial recall, suggesting that time has a proactive benefit on memory for serial order. We will discuss each of these findings in turn.

Benefits of Free Time on Immediate Serial Recall

In Experiments 2 and 3, we replicate the findings by Mizrak and Oberauer (2021) of a global proactive time benefit in WM, generalizing that observation from consonants to words. We also observed a strong benefit for the single item preceding the gap, indicative of a local retroactive benefit (the benefit was sometimes observed for lag −2 but was the strongest for lag −1), which was not observed with consonants in the Mizrak and Oberauer study. A recent study (Lu et al., 2024) observed a strong local retroactive benefit with consonants when the short gap was reduced to 100 ms and an even stronger retroactive benefit, leaning to be global, with words. They replicated the global proactive benefit for both words and consonants. In the present Experiment 1, we observed a global retroactive benefit (in addition to the common proactive one) with words. This experiment differs from all others summarized here by having the gap at a fixed list position.

Overall, these findings indicate that in immediate serial recall of verbal materials, free time has a consistent global proactive benefit. In addition, it sometimes has a retroactive benefit that is mostly

Table 7

Summary of the Main Findings Across Experiments 1–3

	Immediate serial recall		Delayed serial recall		Delayed free recall	
Experiment	Retroactive	Proactive	Retroactive	Proactive	Retroactive	Proactive
1	Global	Global			Global[a]	None
2	Local	Global			Global	None
3	Local	Global	Global	Global		

[a] In Experiment 1, the evidence supporting the global retroactive effect was ambiguous.

local, with the spread of the benefit depending on the predictability of the gap, the duration of the short-gap interval, and the type of study list material.

In line with the predictions detailed in Table 1, the pattern observed for WM can be attributed to two processes. The global proactive benefit can be explained by the encoding resource mechanism or Consolidation 2 (shared resource version), whereas the local retroactive benefit can be explained by Consolidation 1 (i.e., consolidation that is interrupted by the next item). The retroactive benefit seems to differ between experiments using different timings and different types of materials. For the most part, the benefit was rather local, which we reasoned before could be explained by Consolidation 1. According to Consolidation 1, if time given to consolidate an item is insufficient, consolidation will be stopped by the presentation of the next item, leaving the item's consolidation unfinished. With a longer gap, the likelihood of complete consolidation of the item right before the gap increases, leading to a local retroactive benefit of free time. Lu et al.'s (2024) study supports this explanation. In an experiment using lists of consonants, they manipulated the shorter gap duration between 100 ms, 500 ms, and 1,000 ms, keeping the longer gap duration the same. Whereas they found a strong local retroactive benefit relative to a 100-ms shorter gap duration, they did not find any retroactive benefit relative to a 500-ms or 1,000-ms shorter gap duration. This is the predicted result if consolidation of a letter takes between 100 and 500 ms: When the short gap is only 100 ms, the immediately preceding letter (lag = −1) is not fully consolidated, and replacing it by a longer gap yields a benefit for that item. When the short gap is 500 or 1,000 ms, the preceding letter is always consolidated and therefore does not benefit from a longer gap.

Words could plausibly take longer to consolidate than letters. Lu et al. (2024) found a retroactive benefit of free time with word lists with short gaps of 500 ms and long gaps of 2,500 ms. If consolidation of a word takes longer than 500 ms, then the word preceding the gap is more fully consolidated with a long than a short gap, leading to a local retroactive benefit. In the present study, the shorter gap duration was only 900 ms, which might still not have been sufficient to fully consolidate a word. These results suggest that when the shorter gap duration does not cover the consolidation time of the preceding item, there is a local retroactive benefit for that item in the longer gap condition because during the longer gap, the preceding item's consolidation can be completed.

Another possibility is that maintenance processes such as rehearsal contributed to the retroactive benefit. To explain why the retroactive benefit is largely local, we would have to assume that rehearsal is not cumulative—starting with the first presented item—but rather focused on the last one or two items preceding a given gap. The 900 ms of the short-gap duration might not have been sufficient to rehearse a single item, whereas the 4,500 ms of the long-gap duration could have sufficed to rehearse the last one or two items, causing either a strong local retroactive benefit and sometimes a retroactive benefit expanding to lag −2. Although we have not observed such strong effects with consonants, it is possible that articulatory rehearsal is more effective for words. However, when Souza and Oberauer (2018) examined articulatory rehearsal's effectiveness as a strategy on immediate serial recall performance of words, they found evidence against it. Therefore, we find rehearsal as an explanation of the retroactive benefit we observed in WM unlikely.

Consolidation Versus Resource Replenishment Accounts of Proactive Effects

We considered a version of Consolidation 2 in which several consolidation processes can run in parallel, sharing a processing resource, and each process runs to completion. This variant has shown promise in explaining the results of Oberauer (2022b), who included it in a set of simple computational models of processes that could explain the free-time benefit. When we applied these models to the gap paradigm, we found that the resource-sharing version of Consolidation 2 is a strong contender for explaining the proactive benefits of free time in WM (see Figure 2). The same is true for the assumption of an encoding resource that gradually replenishes during free time (Popov & Reder, 2020; Mizrak & Oberauer, 2021).

Consolidation 2 shares some properties with the hypothetical encoding resource such as depending on a limited resource that is bound only temporarily. With Consolidation 2, part of the processing resource is freed up when consolidation processes are completed; the encoding resource is replenished simply by time passing. The difference between these assumptions is very subtle, and for the present experiments their predictions are indistinguishable. Perhaps there is no need to choose between them. What our data and previous studies such as Mizrak and Oberauer (2021) show is that proactive benefits in WM are best explained with a process relying on a limited resource that is needed for establishing representations in WM and is gradually released during free time. Note that Consolidations 1 and 2 combined can explain both the strong local retroactive benefit and global proactive benefit in WM and LTM. Consolidations 1 and 2 could exist together in a mixture model: In some trials (or even for some individual items), the onset of the next item interrupts consolidation of the preceding item (Consolidation 1), and in others, it does not, leading to Consolidation 2.

Benefits of Time on Delayed Free Recall and Delayed Serial Recall

Proactive Benefits

Based on Popov and Reder's (2020) findings and theory, we would expect improved acquisition of episodic LTM with more free time before the items are presented. However, we did not observe that in the delayed free recall tests (Experiments 1 and 2). In prior studies where participants learned a long list of words and were asked to freely recall the words they had just studied, the duration of the ISI before the item affected the recall of the item (Popov et al., 2021). This finding suggested a proactive benefit of free time for episodic LTM. However, in Experiments 1 and 2, although immediate memory performance for the items following the gap improved (showing proactive benefits), delayed free recall of these items did not.

There are a few differences between our task and the tasks with free recall of long lists for which Popov and Reder (2020) found a proactive benefit of free time. In the WM task of Experiment 2, participants needed to form and use item-context bindings (i.e., each word was to be bound to a specific position within the list of the current trial to enable memory for the serial order of the words). In the delayed task, only item memory was needed (i.e., memory for which words have been presented in the most recent block, regardless of their position within a list, or the position of a list within the block). It is possible that due to our experimental design, participants invested the hypothetical encoding resource predominantly into the formation of memory representations needed for successful immediate serial recall, such as bindings between items and their ordinal list positions, and not into the formation of representations needed for delayed free recall. Longer free time during the gap serves to partially replenish the encoding resource, thereby providing an advantage to the encoding of item-position bindings of items following the gap. That explains why there was a proactive benefit of free time on immediate serial recall but not on delayed free recall. This explanation receives support from the observation that once we tested LTM with a serial recall test in Experiment 3, we found a proactive benefit also for delayed serial recall.

This explanation rests on the assumption that immediate serial recall and delayed free recall rely on different information in memory. Against that assumption, there is a wealth of research showing that serial recall and free recall rely largely on the same representations and processes (Grenfell-Essam & Ward, 2012; Spurgeon et al., 2014; Ward et al., 2010). In particular, in free recall, participants still tend to recall the items in forward order; they just follow that order less strictly than in serial recall (Bhatarah et al., 2008). Hence, both serial and free recall rely on information about items' list positions, differing only in the degree to which they depend on that information. That said, in Experiments 1 and 2, we did not test LTM through free recall of a single list but of all words distributed over multiple lists from the preceding WM tests. It is not clear to what extent that test relies on information about items' positions within their original lists. On balance, the assumption that free time serves to replenish an encoding resource that is invested primarily into encoding item-position bindings remains viable.

Retroactive Benefits

There are two possibilities that can explain the global retroactive benefit of time in LTM in contrast to the more local effect observed in WM. One is that participants used the free time to elaborate on the previously presented words and this helps LTM more than WM. Alternatively, LTM traces need longer time to be built than WM representations. Therefore, more time after the presented items could be used to establish stronger LTM traces for those items. Below, we will evaluate these possibilities.

Elaboration helps enrich representations of to-be-remembered stimuli by associating them with prior knowledge. For instance, through elaboration, the meaning of the item can be linked to a network of semantic associations that exist in LTM (Craik & Tulving, 1975; Greene, 1987). Although a few studies indicated that elaboration could help both WM and LTM (Bailey et al., 2011), these studies did not directly manipulate the use of elaboration. Recent studies directly manipulated elaboration through instruction and tested its effect on both WM and LTM using an immediate/delayed paradigm similar to ours. These studies showed that elaboration improved LTM performance but not WM performance (Bartsch et al., 2018, 2019, 2022; Bartsch & Oberauer, 2021; Loaiza & Lavilla, 2021). These findings support the possibility that the retroactive benefit observed in LTM is due to elaboration. Future studies could directly test the role of elaboration for the global retroactive benefit in LTM by using materials that cannot be elaborated. With these materials, there should be no global retroactive benefit of free time.

Alternatively, if two separate WM and LTM traces are created during the study list presentation, the time required to fully consolidate WM and LTM traces might be different. Consolidation is the process by which a robust item representation is created after encoding for storage in memory. In WM, consolidation time is thought to be relatively short, estimated to take between 0.5 and 1.5 s after encoding an item (Jolicoeur & Dell'Acqua, 1998; Nieuwenstein & Wyble, 2014). However, for building LTM traces, consolidation time could be longer (Cotton & Ricker, 2021). In this case, the time presented after an item could be used for consolidating a LTM trace for this item which would benefit the item presented before the free time, resulting in a local retroactive benefit of free time (assuming Consolidation 1, which is interrupted by presentation of the next item). However, the retroactive benefit we observed was global. In contrast to consolidation, elaboration can be applied to all the items before the free time. Therefore, it is more likely that elaboration leads to the global retroactive benefit we observed.

Constraints on Generality

The data reported here are based on three experiments with healthy young adults (ages 18–35), recruited primarily from the University of Zurich participant pool. All participants were native speakers of German, and all tasks involved the encoding of short visually presented German nouns in controlled online experimental settings. Memory was assessed through immediate serial recall and delayed recall tasks using the same verbal stimuli.

Previously, the time benefit was shown for words (abstract and concrete), letters, digits, and visual materials before in previous experiments from our lab (Mizrak & Oberauer, 2021; Oberauer, 2022b; Souza & Oberauer, 2017) and studies outside of our lab (Lu et al., 2024; Ricker & Hardman, 2017). We expect the results to generalize to situations in which participants are asked to study and recall verbal materials, and we have no reason to expect otherwise for visual materials.

This study and Mizrak and Oberauer's (2021) study were done with University of Zurich participant pool, and it was online. However, we have replicated Mizrak and Oberauer's study in online settings with Prolific participants in multiple experiments (see preprint in Mizrak & Oberauer, 2024). Additionally, previous studies from our lab yielded similar results when the experiment was done in the lab. We have no indication that the findings depend on other specific characteristics of the participants or the experimental context. Therefore, we think the results should generalize to other populations than University of Zurich students and to both online and in-person settings.

Finally, we expect that the present results will be reproducible with participants drawn from similar subject pools of young adults (ages 18–35). There are studies showing time benefits in older adults (Loaiza & Lavilla, 2021). However, the direction of the time benefit was not tested in older adults before. Nevertheless, the benefits we have shown here do not depend on any cognitive ability specific to younger adults. We expect the direction of the benefit and differences between working memory and long-term memory to also generalize to healthy older adults population.

Conclusion

Increasing free time during a study list improved both immediate serial recall (i.e., testing WM) and delayed recall performance (i.e., testing LTM). The time benefit was global proactive with local retroactive benefits for WM. For LTM, we consistently observed global retroactive effects. The observation of a proactive benefit on LTM depended on the task. These findings indicate that WM and LTM benefit from time in different ways. Our results suggest that WM benefits from free time to consolidate the last presented item (generating a local retroactive effect) and replenishment of an encoding resource that is used for item-context bindings, generating a global proactive benefit. LTM benefits from time through elaborative strategies that lead to a global retroactive effect, and when item-context bindings are relevant, free time also yields a global proactive benefit.

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Appendix

Simulations of Six Explanations of the Free-Time Benefit

The simulations shown in Figure 2 were generated by a simple model that describes how six hypothetical mechanisms that could explain the free-time effect affect the memory strength of items in different list positions, given the time parameters of the experiments reported in this article.

Articulatory or Elaboratory Rehearsal

Upon encoding, each item i receives an initial memory strength value $M(i) = 1$. During each ISI following encoding of an item, the items encoded up to that point are rehearsed in a cumulative fashion, that is, rehearsal starts with the first item and proceeds in forward order until the end of the ISI. We first computed the expected number of rehearsals that can be carried out during the ISI, assuming a rehearsal duration of $t_r = 300$ ms per item, as $n_r = \mathrm{ISI}(i)/t_r$, rounding down to the next integer. The number of rehearsals is divided equally among all items encoded up to the current position p, with priority to the earlier list items because they are rehearsed first in a cumulative rehearsal schedule. Then we translated the number of rehearsals of each item, $n_r(i, p)$, into an increment of the item's memory strength by

$$M(i) = M(i) + (1 - \exp(-Rt_r n_r(i, p))), \tag{A1}$$

where R is the rate of strengthening through rehearsal, set to 0.2. During each ISI, all items encoded up to the current position have their memory strength incremented in this way. The model does not assume decay or any other form of memory loss. In the context of theories assuming memory loss, the strength increment by rehearsal can be interpreted as the net gain of strength from the combined effects of rehearsal and memory loss.

Refreshing

We simulated the effect of refreshing in the same way as that of articulatory or elaborative rehearsal, except that the refreshing duration was set to $t_r = 50$ ms.

Consolidation 1 (Interrupted)

Memory strength is assumed to grow as a function of consolidation time t_c, with a consolidation rate $C = 0.5$.

$$M(i) = (1 - \exp(-C \cdot t_c(i))). \tag{A2}$$

Because consolidation of each item is interrupted by the onset of the next item, the $t_c(i) = \mathrm{ISI}(i)$.

Consolidation 2 (Ballistic)

As consolidation is ballistic, every item's consolidation runs to completion. Therefore, the resulting memory strength only depends on the efficiency of consolidation, which depends on the proportion of the central processing resource assigned to the item's consolidation process. This proportion depends in turn on the number of consolidation processes running in parallel when item i is consolidated.

For the first item, which is consolidated without competition, we set the consolidation strength c_i to the proportion of the central processing resource recruited by each consolidation process, p_c (here we set $p_c = 0.5$). For every item $i > 1$, we first computed the probability that each previously encoded item's consolidation process is still ongoing. We assumed that the consolidation durations are Gamma distributed with shape $\alpha = 2$ and rate $\beta = 0.5$. This duration is independent of the resource share assigned to a consolidation process. This assumption is necessary to render Consolidation 2 a viable explanation for the free-time benefit. The alternative would be to assume that each consolidation process continues until the consolidated item receives a certain memory strength; consolidation would then take longer when fueled with a smaller resource share but result in the same memory strength. With this scenario, all memory strengths would be equal regardless of ISI if enough time is allowed after list presentation to complete all consolidation processes, so that with a sufficiently long retention interval memory performance for every ISI would converge to the same high level.

The probability of consolidation processes of previous items, $C(j)$, still ongoing, is 1 minus the cumulative Gamma distribution evaluated at the duration for which item j is already in memory at the onset of item i:

$$P(C(j) = 1) = 1 - G(t_i - t_j; \alpha, \beta), \tag{A3}$$

with t_j for the time at which item j was presented and t_i as the time at which the current item i is presented. The differences between these times are the sum of the ISIs separating i and j in the list. Next, we computed the probability distribution over possible numbers N_c of consolidation processes still ongoing, with N_c ranging from 0 to $i - 1$:

$$p(N_c = n) = PB(n, \mathbf{P}). \tag{A4}$$

Here, PB is the Poisson–Binomial distribution, and $\mathbf{P}$ the vector of probabilities of consolidation processes still ongoing for items 1 to $i - 1$.

The memory strength assigned to item i is the proportion of the central processing resource that is devoted to the consolidation of

(*Appendix continues*)

that item. We implemented Consolidation 2 as a resource-greedy process: Every consolidation process recruits a proportion p_c of the still available processing resource. Hence, if no other consolidation process is still ongoing, consolidation of item i receives p_c of the processing resource; if one other consolidation process is still ongoing, consolidation of item i receives $p_c(1-p_c)$ of the processing resource, and so on. Generally, the strength of consolidation of item i is a function of the number of still ongoing consolidation processes:

$$c_i = p_c(1 - p_c)^{N_c}. \quad \text{(A5)}$$

We can compute the expected memory strength of item i as the weighted sum of their consolidation strengths for every possible N_c, weighted by the probability of that N_c.

$$M(i) = \sum_{n=0}^{i-1} P(N_c = n) p_c (1 - p_c)^n. \quad \text{(A6)}$$

Temporal Distinctiveness

We computed the temporal distinctiveness of each item according to scale-invariant memory, perception, and learning (Brown et al., 2007). First, we calculate for each item j the time between presentation of item j and the time at which the person tries to retrieve some item i (which could be item j or another one). This time—the item's temporal distance from the present—is the sum of the ISI values following j and all subsequently presented items, and the time for recalling preceding items:

$$t_j = \sum_{i=j}^{N} ISI(i) + t_{\text{delay}}, \quad \text{(A7)}$$

with N for the list length and td for the delay between the end of list presentation and test. Because we consider temporal distinctiveness as an explanation for free-time effects in delayed recall only, we set the delay to 180 s (the delay used in the present Experiments 1 and 2).

The temporal similarity of item i to each other item j is computed from the difference of their temporal distances from the present on a log-transformed mental time line:

$$S_{i,j} = \exp(-c|\log(t_i) - \log(t_j)|). \quad \text{(A8)}$$

The memory strength of item i is that item's temporal distinctiveness, which is the inverse of its summed similarity to all items in memory:

$$M(i) = \frac{1}{\sum S(i,j)}. \quad \text{(A9)}$$

The temporal distinctiveness of items in the current list—especially those at the beginning of the list—also depends on their temporal separation from the preceding list. Therefore, we also computed the temporal similarity of each item in the current list to the preceding list, assuming an intertrial interval of 5 s. For simplicity, this similarity enters as a single value into the sum.

Encoding Resource

We formalized the depletion and replenishment of the encoding resource in the same way as in Mizrak and Oberauer (2021). The encoding resource R starts at its maximal value of 1 before encoding the first item, $R(1) = 1$. Encoding of each item i recruits a constant proportion p_r of the currently available resource ($p_r = 0.5$), and the memory strength is set to the resource amount devoted to the item's encoding:

$$\begin{aligned} M(i) &= p_r R(i) \\ R(i)^* &= (1 - p_r) R(i). \end{aligned} \quad \text{(A10)}$$

After being depleted to the level $R(i)^*$, the resource is replenished in the subsequent ISI by an exponential growth toward an asymptote of 1, with rate r_e, which we set to 0.15.

$$R(i+1) = R(i)^* + (1 - R(i)^*)(1 - \exp(-r_e ISI(i))). \quad \text{(A11)}$$

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