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BENEFITS OF DISTRACTION FOR SHORT-TERM AND LONG-TERM MEMORY

Doctoral dissertation

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Warszawa 2024

ABSTRACT

Our everyday lives are abundant with various distractions that affect our cognitive functioning in a number of different ways. Although our memory performance is more often than not harmed by the factors such as environmental noise, recent studies demonstrate that in certain conditions distraction can be actually beneficial for our memory. This project's goal was to delineate conditions under which the usual detrimental effect of distraction on memory is reversed and to provide a systematic answer regarding the sources of this phenomenon. In a total of seven experiments utilizing two different research paradigms, a thorough examination of the effects of distraction similar to the information to be remembered was conducted and consequently the roots of the benefit of such distraction in short-term and long-term memory tests were elucidated. The novel theoretical framework underpinned by the empirical findings of this project sheds a new light on the mechanisms of distraction processing and provides a unifying explanation to the short-term and long-term memory phenomena.

STRESZCZENIE

Życie każdego człowieka obfituje w sytuacje w których nie jest on w stanie optymalnie funkcjonować poznawczo ze względu na rozpraszające jego uwagę czynniki środowiskowe. Co prawda w zdecydowanej większości sytuacji gdzie jesteśmy poddani dystrakcji negatywnie wpływa na naszą pamięć, nowe badania naukowe sugerują, że w określonych warunkach dystrakcja taka jest w stanie wspierać nasze procesy pamięciowe. Celem tego projektu było określenie jakie dokładnie są to warunki oraz przedstawienie systematycznej odpowiedzi na pytanie co leży u źródła zjawiska poprawy pamięci dzięki dystrakcji. Na przestrzeni siedmiu eksperymentów wykorzystujących dwa różne paradygmaty badawcze, gruntownie przebadano wpływ dystrakcji podobnej do materiału do zapamiętania na skuteczność zapamiętywania, co pozwoliło określić przyczyny pozytywnego wpływu dystrakcji na pamięć krótko- i długotrwałą. Wyniki badań pozwoliły zbudować nowatorską teorię która jest w stanie wytłumaczyć równocześnie zjawiska z zakresu pamięci krótko- i długotrwałej.

INTRODUCTION

If mere retention of memories and knowledge were to be the only function of human memory, this system would not be more useful to us than a vacuum cleaner for an individual striving for cleaning up a forest. A device capable only of absorbing matter would undoubtably quickly run out of processing and storing power faced with abundance of nature, not mentioning the fact that it would surely devour lots of objects that should be left alone to continue their existence in the wilderness. Similarly, to work efficiently memory requires mechanisms that facilitate selection of valuable information that should be recorded and differentiating it from data that should be discarded due to being deemed to be useless or otherwise unwanted. If memory were to be just passive storage for information, it would not be as effective as it is in retrieving relevant data when we need it for our present purposes. Thus, mechanisms allowing for filtering important data from environmental noise are crucial to our everyday cognitive functioning as well as to understanding how memory works in general.

One of the most impactful findings from studies of selective processing is that even though memory is indeed capable of attending to and consequently encoding relevant information while generally ignoring concurrent non-relevant stimuli, yet this system cannot completely shield itself from unwanted information (e.g. Hughes & Marsh, 2020; Jones & Macken, 1993; Röer et al., 2015). In other words, unless one completely shuts their eyes and ears, both relevant and non-relevant information will reach their memory and will be processed by it. This fact has profound consequences. It implies that when one is faced with external distraction while trying to memorize target information, the contents of the distracting information—the distractors—will be processed by the same preliminary memory mechanisms that process the contents of the target information. In other words, targets and distractors will be competing for the same resources (e.g. attention or capacity) and/or can interfere with each other within this buffer system. This explains a phenomenon widely present in our everyday lives, namely the greater ease of remembering information when we can afford to do so while not being distracted by environmental factors (Ellermeier & Zimmer, 1997; Jones et al., 1997).

The detrimental effect of distraction can be easily obtained in laboratory conditions and it has been demonstrated in a variety of tasks designed to study various mechanisms of memory. For instance, it has been shown that distraction harms memory when it is being presented simultaneously with the target presentation (e.g. Hanczakowski et al., 2018; Marsh et al., 2015), and when it is inserted in-between consecutive memoranda (e.g. Altmann et al., 2014; Turner & Engle, 1989). Although traditionally these two instances have been treated as different experimental situations, the former one being called distraction and the latter interruption, they both demonstrate that even when one is determined to completely ignore extraneous information, more often than not one still performs worse than in the absence of these stimuli.

Of note, detrimental effects of distraction have been observed in both immediate and delayed memory tests, which are traditionally assumed to gauge the workings of working memory (WM) and long-term memory (LTM), respectively. However, the relationship between the effects of distraction on immediate and delayed tests is not clear. First, as mentioned above, these two types of tests are treated as markers of different memory systems, thus theoretical frameworks for describing the processes underpinning distraction effects are often incompatible. Second, a recent surge of interest in interactions between WM and LTM has brought to light findings that demonstrate dissociations between distraction effects on performance in immediate and delayed memory tests. For example, as illustrated by the McCabe effect (Loaiza et al., 2011; McCabe, 2008), we know that although in the short term performance is better when we compare a simple span task, which uses no distraction, to a complex-span task, which utilizes distraction in between the presented memoranda, in the long term this effect is reversed, with higher performance in the delayed test for the items presented in the complex-span rather than simple span task.

The McCabe effect, or, more specifically, its long-term component, brings to light yet another unexpected finding regarding the effects of distraction, namely that there are some conditions that may alleviate the negative effect of distraction, even to the point that they render distraction beneficial rather than harmful. Other examples of similar no-distraction costs or distraction-related benefits can also be found in the literature. For example, Marsh and colleagues (Marsh, Sörqvist, et al., 2015) demonstrated that when distraction promotes an increase in main task engagement, the negative impact of distraction is significantly mitigated.

Curiously, a growing number of studies highlight the fact that similarity between distraction and to-be-remembered information is one of the factors that modulates the pattern of distractibility by external stimuli. For instance, Oberauer (2009b; Oberauer, Farrell, et al., 2012) demonstrated that if targets and distractors in a complex-span procedure are semantically or phonologically similar, performance is better than for dissimilar target-distractor ensembles, and thus the overall distraction is mitigated. Similar results have been obtained in LTM studies, wherein, using the auditory distraction paradigm, Hanczakowski et al. (2017) showed that targets from semantically related target-distractor pairs were recalled better than targets from unrelated, leading to the elimination of the distraction effect altogether for related auditory distractors.

As the studies demonstrating limits of distractibility for WM and LTM started emerging, our grasp of the mechanisms driving distraction effects in general seems to be dwindling. Currently it is not entirely clear when, and—more importantly—why memory performance can be entirely shielded from distraction or can even benefit from it. Moreover, although the beneficial effects of distraction have been obtained in WM and LTM paradigms, we do not know whether these effects are due to the same mechanism(s). Rather, the current theoretical explanations of these phenomena propose mechanisms that are specific to their respective fields of research. Yet, the conditions under which the effect can be found in these two fields are strikingly similar: when targets and distractors are related to each other, the memory for targets is enhanced, at least compared to unrelated distractors. Hence, if there was a proof that this effect emerges for both WM and LTM tests simultaneously, an Occam's Razor would deem a single-mechanism distraction theory preferable, if it was readily available. Moreover, as such theory would imply that related-distraction effects should not be task-specific, observing benefits of related distraction in conditions not examined before, yet having potential to be prone for its influence, would render a single-mechanism stance even stronger.

Testing the contentions delineated above was the main goal of my doctoral research. More specifically, I aimed at: (1) examining whether the benefits of distraction can be observed in immediate and delayed memory tests using a single learning procedure; (2) if that were the case, then proposing a theory explaining this fact by a single memory mechanism that is not specific neither to WM nor to LTM; and finally (3) testing if the effect predicted by this theory will emerge when both WM and LTM (or arguably non-specific memory in general) need to be engaged in a single task.

To this end, I have planned, conducted, and published two series of experiments. In the first project, I focused on providing empirical evidence for the claim that short-term and long-term benefits of related distraction stem from the same learning conditions and thus are most likely driven by a common mechanism. The second project applied insights from the first one to a new study subject to examine if performance in a different task engaging both WM and LTM mechanisms would be able to benefit from the related-distraction effect. Below I present a brief overview of the methodology and results of those two projects.

Study #1: Elaboration by Superposition: From Interference in Working Memory to Encoding in Long-term Memory (Piątkowski et al., 2023)

To establish whether effects of related distraction found independently in WM and LTM studies can be attributed to the same mechanism, a series of five experiments was conducted. In each experiment a single learning procedure was used, in which participants had to study a series of nouns (targets), and perform two tests for the those targets. In Experiments 1a-3, in each learning trial the targets (e.g., "ruby") were interspersed with distracting stimuli, some of which were semantically related to the preceding target (e.g., "diamond", "sapphire"; this was the *related* condition) and some were unrelated to the targets (e.g., "ivy", "magnolia"; the *unrelated* condition).

The targets were studied in a complex-span procedure, where after each target presentation a secondary task had to be performed. Following Oberauer's studies that demonstrated the distraction-relatedness effect in WM (Oberauer, 2009b; Oberauer, Farrell, et al., 2012), here the secondary task was to read aloud, but otherwise to ignore, the words presented on the screen in between the targets. The relatedness of targets and distractors was manipulated via category membership; in the related condition, to-be-uttered distractors were drawn from the same semantic category as the preceding target (e.g., "gemstones" if the target was "diamond"), and in the unrelated condition, distractors were from a category different than that of the last target (e.g., "plants").

After each trial of four targets, each followed by four distractors, a serial recall test was employed right after the presentation of the last item. The novelty of this design was that each block of four such trials was followed by a category-cued recall test. Here category labels (e.g., "gemstones") were displayed and participants were to respond with the target from one of the last four trials that matched the presented category. Hence, in this design two dependent variables were measured: performance in the immediate serial recall test (reflecting WM efficiency) and in the delayed cued-recall test (reflecting LTM efficiency).

Each experiment followed this general outline, thus allowing for replicating results from the first study while testing additional predictions. For instance, Experiment 1b was conducted to ensure that the relatedness effect found in the delayed tests of Experiment 1a was not due to carryover from the preceding immediate tests. Here, half of the trials, both related and unrelated, were not followed by an immediate test, which was substituted for a filler task. Results from this experiment, in conjunction with a conditional analysis (on successful recall in an immediate test) of the cued-recall results of Experiment 1a, proved that the results in the two memory tests were independent from each other, in a sense that recalling the item in the first test did not drive the relatedness effect in the second one. In other words, carryover effects from previous tests were found not to be a viable explanation of the relatedness effect.

Experiments 2 and 3 were conducted to establish boundary conditions of the relatedness effect. They were designed to examine if temporal proximity of the related targets and distractors was sufficient for the relatedness effect to occur, or rather, as predicted by interference-by-superposition theory for the WM (Oberauer, 2009b; Oberauer, Farrell, et al., 2012), the target needs to by directly followed by the related distractors for the relatedness effect to occur.

Experiment 4 introduced a baseline condition to examine if the benefit of related distraction is due to distractors actually enhancing memory efficiency or it is due to the detrimental effect of distraction itself being alleviated in the related condition. Hence, similar to the studies on the McCabe effect, here performance in the complex-span task (with related and unrelated distractors) was compared to performance in the simple-span task wherein no distractors are presented.

Overall, this line of studies clearly demonstrated that when a target is presented alongside related distractors, performance is better than when the distractors are unrelated to the target. However, for this effect to emerge, both in WM and in LTM, the target needs to be directly followed by the distractors. Finally, this effect manifests itself in an attenuation of the negative effect of distraction on WM performance, but also—interestingly—it seems to be leading to LTM augmentation. This is the first time that the relatedness effect has been independently obtained for both immediate and delayed memory tests with a single learning procedure. Based on these findings, we have proposed a theory of elaboration-by-superposition, which I will return to in the Discussion.

Study #2: Forgetting during interruptions: The role of goal similarity (Piątkowski et al., 2024)

As the first line of studies established empirically that relatedness can be beneficial to memory in general, the second part of the project homed in on the effects of similar distraction in a task that engages both short-term and long-term memory at once. Furthermore, here the problem of the influence of distraction on memory was looked upon from a wider perspective of memory-in-action, or in other words, task-performing research. The main task in these experiments required learning a set of decision rules that were to be performed in a given order with occasional interruptions that required halting the main task and performing a secondary task. Thus, this procedure required first encoding into and then retrieving from long-term memory a set of decision rules to be performed, maintaining in working memory information relating to which operation should be performed next, and holding this information during the interruption period or trying to retrieve it from the LTM if it was lost during the interruption.

A sequential-decision making paradigm introduced by Altmann et al. (2014) was adapted for the study, in which a number of decisions are to be made in a specific order denoted by an acronym. The tasks in this series of experiments consisted of decisions regarding visual stimuli presented on the screen, like deciding whether the letter presented on the screen is close or far from the beginning of the alphabet, or whether presented digit is greater or lower than five. Each decision required pressing one of two keys which were unique for this decision (e.g., “O” for far [**O**dległa in Polish] or “B” for near [**B**liska in Polish] from the beginning of the alphabet). Each decision was represented by a single letter (e.g., “O” for the “near or far” decision) and the letters were combined into a single word MILONGA that determined the order of the consecutive operations to be conducted.

The crucial part of the experiments were the interruption periods. From time to time, the MILONGA task was stopped, and participants had to perform a secondary task. Of most interest was the relationship between the material processed during the interruption task and adjacent steps of the main task. We manipulated what type of item was to be processed during the secondary task: items matching the operation preceding the interruption (an analog of the related condition from the first line of studies) or a mismatching item (analogous to the unrelated conditions). Thus, distractor-target similarity was operationalized as matching or mismatching letters/operations processed across the interrupted and interrupting tasks.

In the first experiment, in the secondary task participants had to process letters corresponding to the letters denoting operations. For example, if the procedure stopped after task O and before task N from the MILONGA sequence, participants could be asked in the interrupting task to search for the letter “O” in a visual array (the *pre-interruption* condition), for the letter “N” (the *post-interruption* condition), for the letter “M” (the *random* condition, in which the to-be-processed letter was from the MILONGA acronym, but was not the letter that came just before or after the interruption), or for the letter “F” (the *other* condition, in which the letter was from outside MILONGA). In the second experiment the interruption tasks consisted of performing the same or different operations than the neighboring ones: the O operation (the *pre-interruption* condition), the N operation (the *post-interruption* condition), or an operation denoted by any other letter from the MILONGA acronym (the *random* condition).

Here, similarly to the complex-span studies, conditions with disrupting materials related to the closest steps in the interrupted procedure turned out to be the ones with performance higher than those in which disruption was dissimilar. The effect of related distraction was manifested in the rate of post-interruption errors, with interruptions matching adjacent steps leading to fewer errors when the main task needed to be resumed. Thus, the relatedness effect was conceptually replicated here.

CONCLUSIONS

Studies that constitute the body of my PhD work, although somewhat differing in their methodologies, have led to the same conclusion. They provided systematic evidence for the beneficial effect of related distraction on performance in explicit memory tests (study 1) and in tasks requiring memory maintenance (study 2). Furthermore, the project as a whole gave robust evidence for the existence of the relatedness effect in tasks traditionally viewed as markers of WM and LTM performance, and it did so using within-participant experimental designs, as well as directly comparing different memory measures for the same learned materials. Notably, this effect has been demonstrated in experimental conditions traditionally associated with different fields of memory research, that is distraction and interruption studies. More specifically, it has been established that the benefit of distraction can be obtained both when distraction is presented while the main task is being performed and when the task needs to be halted altogether to process the distraction.

As the similarity between information that is focal for the present task and the distracting external stimuli was a central subject of investigation, it is important to consider how similarity was operationalized in the conducted experiments. Consider that the effect of relatedness was obtained when targets and distractors belonged to the same semantic category (study 1), were represented by the same symbol (study 2, Experiment 1), and required performing the same task, but in different contexts (study 2, Experiment 2). Thus, the studies conclusively demonstrated that the benefit of related distraction is far from being specific to a given paradigm, and that the similarity of the targets and distractors is a question worth investigating further as the effect observed here might be generalizable to vastly different experimental contexts.

Henceforth, through thorough and systematic examination my work has shed new light on the interactions between distraction and focal information in short-term and long-term memory tasks. Crucially, not only did it confirm previous findings, but it also allowed for constructing a theoretical framework to understand the results to date as different emanations of a single cognitive mechanism. Below, our results are discussed in a broader context of the current theoretical discussion on the mechanisms engaged in processing distraction to illustrate the importance of the presented work for the advancement of our understanding of memory as a whole.

DISCUSSION

The main finding of my studies might also seem to be the most counterintuitive one. After all, to date, the vast majority of distraction studies established that processing two or more similar items at once leads to memory loss rather than to its enhancement compared to distraction-free processing.

For instance, classic findings concerning WM capacity are that fewer items can be held in the short-term storage if they all are presented in the same modality (e.g., verbal or visual) than when they are of different modalities (Baddeley & Hitch, 1974; Turner & Engle, 1989). Also, a number of LTM studies point to the fact that distraction similar to the target information harms memory performance more than dissimilar one (e.g., Marsh et al., 2008). Considering these facts, it is important to note that these findings might be in contrast to what I have found in my PhD research, but are not contradictory; in fact, my findings can be considered complimentary to the current state of knowledge. Critically, my arguments are based on already existing theoretical explanations of observed beneficial effects of similarity in memory. Thus, the novelty of my research lays not in a sole demonstration of how similarity of distraction can modulate distractibility, but in providing a framework for understanding the impact of related distraction as a general memory phenomenon rather than a domain-specific mechanism. This is a major step forward in distraction research, as up to this point the growing amount of evidence for the similar benefit of related distraction on long-term and short-term memory performance could not be comprehensively explained without the need of evoking various mechanisms for different learning conditions.

Consider, for instance, the case of distraction benefits in the immediate serial recall test. From the perspective of the WM research, the influence of related distraction has been comprehensively explained by the SOB-CS model (Oberauer, Lewandowsky, et al., 2012). This model posits that representations of serially presented items are encoded along representations of their serial positions, and representations of the serial positions are updated with the presentations of new *target* items. From this it follows that distractors, which do not update the representations of the positions, are encoded along with the representation of the last target's position, albeit with lesser strength. Hence, as related distractors share a number of features with a similar target, these shared features are selectively enhanced in their bindings with representations of serial position. Consequently, when position is used as a retrieval cue in the serial recall test, the target whose features were bound stronger to the position's representation is easier to be retrieved than a target that has not been presented with related distractors. This does not, however. explain why, when serial position is *not* used as a retrieval cue, as it happens in the majority of delayed memory tests, relatedness effect still occurs in LTM studies.

Interestingly, the LTM research solution to the problem of the related-distraction benefit has also emphasized the importance of strengthening specific features of the target by distraction. Here it has been assumed that even involuntary processing of related distractors can highlight those features that are shared between the target and distractors (Hanczakowski et al., 2017). This should not universally enhance memory of the target, but rather it should help to retrieve it from memory when a retrieval cue accentuates the features that have been elaborated by the related distraction. This neatly explains why targets presented with the members of the same category as the distractors were easier to recall in the delayed category-cued recall test where positional cues were absent. Yet this theory would predict that in the serial recall test, where no semantic cues are present, there should be no effect of related distraction.

The theory that emerged from my PhD research combines solutions from both of these approaches to describe a memory-general mechanism explaining the benefits of related distraction in both immediate as well as delayed tests. Here, the notion of serial positions from the SOB-CS model is generalized and treated as spatio-temporal context, as described for instance in the TCM model (Howard & Kahana, 2002). Instead of static representations updated by the targets' serial positions, the theory assumes a continuously evolving context representation that changes by partially incorporating representations of items encoded at a given time. Hence, as this context would consist of both episodic (flow of time) as well as semantic (imbued representations of presented items) components, it would allow for retrieval of items both for the sake of serial recall as well as cued recall, and it should drive the effect of the related distraction.

Importantly, not only does the theory of elaboration-by-superposition proposed in study 1 facilitate understanding of why related distraction affects WM and LTM in more or less the same way, but it provides a better grasp on how distraction affects memory in general. This can be neatly demonstrated when the study of interruptions (study 2) is analyzed through lenses of this framework. Here participants were subjected to a task that required them to repeatedly go through a sequence of pre-learned tasks while occasionally being interrupted by a secondary task. In order to perform the correct task after the interruption period, participants needed to somehow access the information regarding where in the sequence they were before the interruption and/or what step should be performed when the task is to be recommenced. Ostensibly there are two options explaining how that might be possible. Either this information is kept in WM's short-term storage during the whole interruption period and is readily available when the main task resumes, or the information is lost and thus needs to be retrieved from the LTM. Thus, it is not clear whether the contents of the interrupting task influence memory by interfering with this crucial information through WM processes or rather affect retrieval from LTM. On the other hand, the elaboration-by-superposition account is capable of resolving this question without the need to determine which memory system was engaged. It can be assumed that while the secondary task was being performed, the ever-changing spatio-temporal context was being enriched by the contents of the interrupting task which were either related or unrelated to the information necessary for resuming the main task. In consequence, determining what step should be performed after the interruption was easier in the related condition because the relevant information was being reinforced by similar features of the interruption's contents. This was reflected in the lower error rates in the related conditions in both experiments reported in this study.

The present findings lay ground for future studies that should in the first place provide a precise description of the mechanism by which context retrieved at test drives the relatedness effect. Neural network models on which my thinking builds upon, such as TCM, assume that the process of retrieval is sequential; that is, the context to which a given item was bound is retrieved only after this item is retrieved. Since the elaboration-by-superposition account assumes that related distraction enhances bindings of overlapping features to the current context, it is not clear why this context, which is retrieved only after its target was recalled (Howard & Kahana, 2002; Polyn et al., 2009), should play any role in facilitating retrieval of this specific item.

One way to accommodate the contextual explanation of the relatedness effect into this framework is to assume that retrieval is a two-step process. First, using the semantic cue provided at test (the categorical label), a candidate set of responses is retrieved, with each candidate item retrieving its own context. In the second step, the retrieved contexts averaged together would provide an episodic cue that would help select an item from the candidate set to be produced. This could potentially provide an additional benefit for the targets presented with related distractors, because the candidate set would most probably consist of, among different items, the majority of presented targets and distractors from the cued category. Thus, since targets and distractors from the related conditions would be encoded along contexts very similar to each other, altogether they would bias the final episodic cue formed in the second step to resemble the context of the correct target to a greater extent.

Yet another approach to this problem could assume that the process of redintegration (see Oberauer, Lewandowsky, et al., 2012; Schweickert, 1993)—i.e., a reconstruction of a memory representations based on its degraded but retrieved fragments and leading to correct recall— is a continuous mechanism instead of an instant event. In other words, one could envision that before a retrieved and partially distorted representation is interpreted as one of the items from long-term memory, it automatically retrieves a representation of a context most likely associated with this representation. This retrieved context, in turn, could then help to render item's representation more similar to one of the items stored in memory, completing the self-reinforcing cycle of retrieval. However, if the retrieved context happened not be satisfactorily similar to any of the items (e.g. some threshold of similarity measure would not be reached), a next contextual representation would be retrieved from memory that would help to retrieve even more accurate items representation that could be finally redintegrated and thus recalled. Both solutions delineated above allow target's context to actually influence its retrieval, but to determine the most probable mechanism future modelling work would be necessary.

Certainly not the most obvious, yet definitely the most important finding from this research is that for the relatedness effect to occur, spatio-temporal adjacency of the related distractors to the targets is not sufficient. Apparently, for this effect to occur, the target needs to be directly followed by related distractors. Although this has been already demonstrated and explained in the context of short-term memory paradigms (Oberauer, 2009b; Oberauer, Farrell, et al., 2012), acquiring this effect with a delayed memory test is a novel finding. This claim undoubtedly needs further investigation, but it is important to remember that the elaboration-by-superposition account predicts noticeable attenuation of the relatedness effect when the target is preceded by related distractors, but not necessarily that there would be no effect whatsoever. However, considering the second study from the current project it is not clear whether in fact the relatedness effect was purely due to related distraction following the target. After all, although with related distractors error rates were significantly lower, the error patterns suggest that representation used to guide performance might be more complex than a single letter or operation, possibly consisting of representations of both prior as well as succeeding steps of the procedure. Nevertheless, distractors similar to items and most likely to be held in immediate memory led to enhanced performance, which suggests that relation between related targets and distractors in terms of their temporal proximity might be more complex than proposed here.

Future empirical investigations based on the present findings should focus on establishing boundary conditions of the relatedness effect to determine which types of similarity should bring benefits to memory and which, as demonstrated in majority of studies on similarity to date, are detrimental to performance. One prediction from the present theory is that for the long-term memory tests the effect of the related distraction should emerge predominantly when the test taps those aspects of the memoranda that were elaborated by the distraction (Hanczakowski et al., 2017; Zawadzka et al., 2021). In other words, when related distractors elaborate categorical information about the target, the beneficial effect of distraction should primarily be present in category-cued recall test, but not necessarily on the free-recall test that lacks the categorical cues that guide retrieval.

Finally, worth mentioning is the fact that my PhD research contributes to scientific discourse wider than the one on the impact of distraction on memory. Distraction is usually considered as a factor that contributes to the loss of information from working memory, but the reason for this occurring is not universally agreed upon. The time-based resource-sharing (TBRS) theory (Barrouillet et al., 2004, 2007; Camos et al., 2009) assumes that distraction is detrimental to WM performance because it hinders the process of maintaining information in the short-term store (either via rehearsal or refreshing; see Camos et al., 2009, 2018). Thus, distraction is harmful as much as it captures attention during the retention interval. However, the opponents of this view claim that what renders distraction detrimental to WM is the fact that it interferes with the representations held in the short-term store (e.g. Lewandowsky & Oberauer, 2009; Nairne, 1990; Oberauer & Lewandowsky, 2008). Thus, to simplify, according to the TBRS model it is the *quantity* of distraction to be engaged with in a given unit of time that drives the loss of memory, but the interference stance assumes that it is the *quality* of the distracting stimuli that is responsible for the representation fading. As shown in studies by Oberauer (Oberauer, 2009b; Oberauer, Farrell, et al., 2012), even though such interference is usually harmful, in some special cases, when particular items' features of the targets and distractors are overlapping, a phenomenon dubbed interference-by-superposition might occur and enhance target memory. This finding has been directly replicated in study 1 of this project, and—crucially—study 2 demonstrated this effect in a new experimental environment. Both studies demonstrated that while in both related and unrelated conditions distractors were presented for the same amount of time, related distractors still were enhancing memory performance, thus clearly it was the content of the distraction and not merely its amount that contributed to its impact.

Yet, the implications of this research go even beyond the dispute on the WM mechanism of information loss. After all, the benefits of distraction have been detected not only in immediate memory tests, but in delayed ones as well. Moreover, the proposed mechanism responsible for this fact does not need to differentiate between short-term and long-term memory stores. Therefore, I argue that this project can be used as an argument in a heated debate whether distinction between WM and LTM is necessary to understand how memory works.

The current status quo of separating these two systems that emerged in the 1960s (e.g., Atkinson & Shiffrin, 1968; Murdock, 1967; Waugh & Norman, 1965) was adopted based on a prevailing belief that due to fundamental differences in how different mnemonic materials are processed, an ensemble of specialized systems needs to be assumed to explain how memory operates in general. Importantly, this belief was supported by the data obtained from neurologically impaired patients (e.g., Saffran & Marin, 1975; Vallar & Baddeley, 1984) that demonstrated selective attenuation of cognitive functions assumed to be specific to short-term or long-term memory. Furthermore, an influential model of working memory introduced by Baddeley (1986; 2000; Baddeley & Hitch, 1974) proved to be extremely useful for explaining and predicting data from immediate memory tests, which gave the WM-LTM distinction even more credibility. Although nowadays this model is by and large treated as outdated (for a recent critique see Langerock et al., 2014), the notion of a phonological loop has been widely acknowledged and thus still makes a strong case for the existence of a system distinct from LTM. Yet, on the other hand, a growing number of researchers postulate that there is no need to consider WM and LTM as separate systems (e.g., Brown et al., 2007; Nairne, 1991, 2002; Surprenant & Neath, 2008). For instance, a prominent class of theories, called embedded processes models (Cowan, 1999; Oberauer, 2009a; see also Unsworth & Engle, 2007) propose to treat WM as an activated part of LTM with its capacity limited by the amount of attentional resources that are necessary for maintaining items' high level of activation.

The theory of elaboration-by-superposition posits that the relatedness effect observed both in immediate and delayed memory tests can be viewed simply as different instantiations of using spatio-temporal context as a retrieval cue at test. No short-term maintenance mechanism is required by this theory, as it assumes that target-distraction interactions are based on interference of their distributed representations. When temporally adjacent targets and distractors are similar enough, through the process of interference-by-superposition the features of the target that overlap with the features of distractors are more strongly bound to the present state of the context. Hence, as this context, in the form of position markers, is used as a retrieval cue in an immediate serial recall test, it facilitates retrieval of the targets presented with related distractors. In the case of a delayed category-cued recall test, this enriched context facilitates target retrieval arguably because it is retrieved automatically with a candidate target, thus indirectly providing an episodic cue that helps to distinguish the target from other items matching the presented semantic (category) cue. Since the context of the target presented with related distractors is imbued more strongly with the features of the target, it serves as better retrieval cue as well.

The above analysis leads to a conclusion that context-based retrieval is a sufficient mechanism to explain the discussed distraction-related phenomena in both immediate and delayed tests, rendering a short-term versus long-term memory distinction obsolete. It is worth noticing that similar reasoning to the one presented above is common among proponents of the unitary memory system. For instance, as stated by Surprenant and Neath (2008, p. 16): "According to a dual-store theorist, STM is the explanatory concept for why you can remember only a limited number of items coded in a phonological format for a short period of time whereas LTM is the explanatory concept for why you can remember a large (infinite?) number of items coded in a semantic format for a long period of time (forever?). If we deleted reference to the two stores, we could still explain the same findings: if you process items phonologically, you can remember only a few items for a short period of time but if you process items semantically, you can remember a far larger number for far longer.".

To conclude, the present research project demonstrated that the beneficial effect of similar distraction is a phenomenon not specific to either experimental task, memory test nor even a mnemonic system. Thus, it provides crucial insights into the mechanisms by which distraction affects the contents of our memory. Moreover, based on previous as well as present findings, it outlines a framework compatible with a number of existing models, such as SOB-CS or TCM, that unifies effects obtained in immediate and delayed tests by attributing them to a common denominator, that is context-based encoding and retrieval.

REFERENCES

Altmann, E. M., Trafton, J. G., & Hambrick, D. Z. (2014). Momentary interruptions can derail the train of thought. *Journal of Experimental Psychology: General*, *143*(1), 215–226.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *Psychology of learning and motivation* (Vol. 2, pp. 89–195). Academic Press.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417–423.

Baddeley, A. D. (1986). *Working memory*. Oxford University Press.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In *Psychology of learning and motivation* (Vol. 8, pp. 47–89). Academic Press.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, *133*(1), 83–100. https://doi.org/10.1037/0096-3445.133.1.83

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(3), 570–585. https://doi.org/10.1037/0278-7393.33.3.570

Brown, G. D., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review*, *114*(3), 539.

Camos, V., Johnson, M., Loaiza, V., Portrat, S., Souza, A., & Vergauwe, E. (2018). What is attentional refreshing in working memory? *Annals of the New York Academy of Sciences*, *1424*(1), 19–32. https://doi.org/10.1111/nyas.13616

Camos, V., Lagner, P., & Barrouillet, P. (2009). Two maintenance mechanisms of verbal information in working memory. *Journal of Memory and Language*, *61*(3), 457–469.

Cowan, N. (1999). An embedded-processes model of working memory. *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*, *20*(506), 1013–1019.

Ellermeier, W., & Zimmer, K. (1997). Individual differences in susceptibility to the "irrelevant speech effect." *The Journal of the Acoustical Society of America*, *102*(4), 2191–2199.

Hanczakowski, M., Beaman, C. P., & Jones, D. M. (2017). When distraction benefits memory through semantic similarity. *Journal of Memory and Language*, *94*, 61–74. https://doi.org/10.1016/j.jml.2016.11.005

Hanczakowski, M., Beaman, C. P., & Jones, D. M. (2018). Learning through clamor: The allocation and perception of study time in noise. *Journal of Experimental Psychology: General*, *147*(7), 1005–1022.

Howard, M. W., & Kahana, M. J. (2002). A distributed representation of temporal context. *Journal of Mathematical Psychology*, *46*(3), 269–299.

Hughes, R. W., & Marsh, J. E. (2020). When is forewarned forearmed? Predicting auditory distraction in short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(3), 427–442.

Jones, D. M., & Macken, W. J. (1993). Irrelevant tones produce an irrelevant speech effect: Implications for phonological coding in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*(2), 369–381.

Jones, D. M., Macken, W. J., & Mosdell, N. A. (1997). The role of habituation in the disruption of recall performance by irrelevant sound. *British Journal of Psychology*, *88*(4), 549–564. https://doi.org/10.1111/j.2044-8295.1997.tb02657.x

Langerock, N., Vergauwe, E., & Barrouillet, P. (2014). The maintenance of cross-domain associations in the episodic buffer. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(4), 1096.

Lewandowsky, S., & Oberauer, K. (2009). No evidence for temporal decay in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(6), 1545–1551. https://doi.org/10.1037/a0017010

Loaiza, V. M., McCabe, D. P., Youngblood, J. L., Rose, N. S., & Myerson, J. (2011). The influence of levels of processing on recall from working memory and delayed recall tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(5), 1258–1263. https://doi.org/10.1037/a0023923

Marsh, J. E., Hughes, R. W., & Jones, D. M. (2008). Auditory distraction in semantic memory: A process-based approach. *Journal of Memory and Language*, *58*(3), 682–700.

Marsh, J. E., Hughes, R. W., Sörqvist, P., Beaman, C. P., & Jones, D. M. (2015). Erroneous and veridical recall are not two sides of the same coin: Evidence from semantic distraction in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(6), 1728–1740.

Marsh, J. E., Sörqvist, P., & Hughes, R. W. (2015). Dynamic cognitive control of irrelevant sound: Increased task engagement attenuates semantic auditory distraction. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(5), 1462–1474.

McCabe, D. P. (2008). The role of covert retrieval in working memory span tasks: Evidence from delayed recall tests. *Journal of Memory and Language*, *58*(2), 480–494. https://doi.org/10.1016/j.jml.2007.04.004

Murdock, B. B. (1967). Recent developments in short-term memory. *British Journal of Psychology*, *58*(3–4), 421–433. https://doi.org/10.1111/j.2044-8295.1967.tb01099.x

Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, *18*(3), 251–269. https://doi.org/10.3758/BF03213879

Nairne, J. S. (1991). Positional uncertainty in long-term memory. *Memory & Cognition*, *19*(4), 332–340. https://doi.org/10.3758/BF03197136

Nairne, J. S. (2002). Remembering Over the Short-Term: The Case Against the Standard Model. *Annual Review of Psychology*, *53*(1), 53–81. https://doi.org/10.1146/annurev.psych.53.100901.135131

Oberauer, K. (2009a). Design for a working memory. In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 51, pp. 45–100). Academic Press.

Oberauer, K. (2009b). Interference between storage and processing in working memory: Feature overwriting, not similarity-based competition. *Memory & Cognition*, *37*(3), 346–357. https://doi.org/10.3758/MC.37.3.346

Oberauer, K., Farrell, S., Jarrold, C., Pasiecznik, K., & Greaves, M. (2012). Interference between maintenance and processing in working memory: The effect of item–distractor similarity in complex span. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(3), 665–685. https://doi.org/10.1037/a0026337

Oberauer, K., & Lewandowsky, S. (2008). Forgetting in immediate serial recall: Decay, temporal distinctiveness, or interference? *Psychological Review*, *115*(3), 544–576.

Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review*, *19*(5), 779–819. https://doi.org/10.3758/s13423-012-0272-4

Piątkowski, K., Beaman, C. P., Jones, D. M., Zawadzka, K., & Hanczakowski, M. (2024). Forgetting during interruptions: The role of goal similarity. *Journal of Cognitive Psychology*, 1–16. https://doi.org/10.1080/20445911.2024.2313570

Piątkowski, K., von Bastian, C. C., Zawadzka, K., & Hanczakowski, M. (2023). Elaboration by superposition: From interference in working memory to encoding in long-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *49*(3), 371–388.

Polyn, S. M., Norman, K. A., & Kahana, M. J. (2009). A context maintenance and retrieval model of organizational processes in free recall. *Psychological Review*, *116*(1), 129–156. https://doi.org/10.1037/a0014420

Röer, J. P., Bell, R., & Buchner, A. (2015). Specific foreknowledge reduces auditory distraction by irrelevant speech. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(3), 692–702.

Saffran, E. M., & Marin, O. S. (1975). Immediate memory for word lists and sentences in a patient with deficient auditory short-term memory. *Brain and Language*, *2*, 420–433.

Schweickert, R. (1993). A multinomial processing tree model for degradation and redintegration in immediate recall. *Memory & Cognition*, *21*(2), 168–175.

Surprenant, A. E. M., & Neath, I. A. N. (2008). The nine lives of short-term memory. In *Interactions between short-term and long-term memory in the verbal domain* (pp. 28–55). Psychology Press. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203938966-8/nine-lives-short-term-memory-aime%C3%A2-surprenant-ian-neath

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*(2), 127–154.

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*(1), 104–132. https://doi.org/10.1037/0033-295X.114.1.104

Vallar, G., & Baddeley, A. D. (1984). Fractionation of working memory: Neuropsychological evidence for a phonological short-term store. *Journal of Verbal Learning and Verbal Behavior*, *23*(2), 151–161.

Waugh, N. C., & Norman, D. A. (1965). Primary memory. *Psychological Review*, *72*(2), 89–104. https://doi.org/10.1037/h0021797

Zawadzka, K., Baloro, S., Wells, J., Wilding, E. L., & Hanczakowski, M. (2021). On the memory benefits of repeated study with variable tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. https://doi.org/10.1037/xlm0001013

AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology:
Learning, Memory, and Cognition

ISSN: 0278-7393

2023, Vol. 49, No. 3, 371–388
https://doi.org/10.1037/xlm0001188

Elaboration by Superposition: From Interference in Working Memory to Encoding in Long-Term Memory

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Distraction embedded in working memory tasks leads to impaired performance. This impairment is mitigated when targets and distractors that follow them share common features—a signature effect of interference by superposition. Here we propose that target-distractor similarity modulates not only forgetting from working memory but also encoding into long-term memory. In five experiments, we test this elaboration-by-superposition hypothesis, demonstrating that semantic relatedness between targets and distractors benefits delayed category-cued recall performance (Experiments 1a and 1b), which is not due to carry-over effects from working memory testing (Experiment 2). Just as in the case of working memory, this long-term memory effect is reduced when distractors precede targets (Experiment 3). Finally, we show that while high target-distractor similarity reduces forgetting from working memory, it produces net benefits for long-term memory performance (Experiment 4). Together, the results suggest that common mechanisms underlie encoding into working and long-term memory, and that bindings between features of spatiotemporal context and features of to-be-remembered items play a crucial role.

Keywords: working memory, long-term memory, distraction, cued recall, elaboration

Working memory (WM) is a system that serves to keep a limited amount of information in an active state so that it can be manipulated and used in ongoing activities. For instance, retaining prices of several items to calculate their total value, or holding someone's phone number in memory while engaged in a conversation are typical functions of the WM system. The defining feature of WM is its limited capacity, by which WM performance drops rapidly when a relatively small number of to-be-maintained items is exceeded. By contrast, long-term memory (LTM) is characterized by in principle unlimited capacity for storing new information, which can be accessed after prolonged delays. This capacity distinction between WM and LTM determines the research agenda for researchers investigating these two theoretical constructs. WM researchers are often interested in the reasons for which information is lost from WM, postulating mechanisms like decay or interference to account for rapid forgetting. LTM researchers typically assume that information is not lost, although it may become inaccessible (Tulving & Pearlstone, 1966), and often concentrate their efforts on establishing how information is encoded into LTM in the first place (e.g., Craik & Tulving, 1975; Hunt & Einstein, 1981; Naveh-Benjamin & Brubaker, 2019). In the present study, we present an attempt to link these two perspectives, showing how a mechanism postulated to account for forgetting from WM is responsible for determining the type of information encoded into LTM. The mechanism of forgetting from WM which we put under scrutiny here is one of interference by superposition (Oberauer, 2009; Oberauer et al., 2016; Oberauer, Farrell, et al., 2012). The mechanism by which changes are introduced into LTM representations is often termed elaboration (Craik & Watkins, 1973; Greene, 1987). Thus, the current study constitutes a proof of concept for a mechanism of *elaboration by superposition*.

The tool of choice for investigating WM is a complex-span task, which requires both maintaining items for a subsequent serial-recall test and processing distraction inserted in between study items (Daneman & Carpenter, 1980). Much discussion has been devoted to the issue of why exactly distraction causes forgetting from WM, with studies assigning this phenomenon to decay—fading of memory representations due to passage of time when attention is devoted to processing distraction (e.g., Barrouillet et al., 2004, 2007; Lilienthal et al., 2014; Page & Norris, 1998; Ricker et al., 2020; Soemer, 2019; Towse et al., 2000; Vergauwe et al., 2009)—or interference resulting from storing new information when distractors enter WM (e.g., Lewandowsky et al., 2010; Lewandowsky & Oberauer, 2008, 2009;

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We thank Ewa Butowska, Karolina Lukasik, Paulina Pietrak, and Oliwia Zaborowska for their assistance with data collection.

This work was supported by the National Science Center Grant 2017/27/B/HS6/02001 awarded to Maciej Hanczakowski, and by Grant PPN/PPO/2018/1/00103 from the National Agency for Academic Exchange awarded to Katarzyna Zawadzka. All data are available at https://osf.io/jemzs.

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Nairne, 1990; Oberauer et al., 2004; Oberauer & Kliegl, 2006; Saito & Miyake, 2004). Independent of whether one accepts a role of decay in forgetting from WM, the role of interference remains uncontested. Indeed, proponents of WM models incorporating a decay mechanism have argued that decay may actually make memory representations more vulnerable to interference (e.g., Barrouillet et al., 2007; Portrat et al., 2008). The current state of research on WM assigns the limits of maintaining items in WM in the face of ongoing distraction at least partially to the fact that processing distractors means that distractors are themselves encoded into WM, interfering with representations already maintained in this system.

When interference is considered as a mechanism by which distraction causes forgetting from WM, one key point concerns the similarity between the to-be-remembered targets and to-be-ignored distractors. Arguably, for distractors to interfere with target memory there has to be some similarity between the two. And, indeed, studies have repeatedly found that distractors from the same domain (e.g., words or digits) as targets cause more forgetting from WM than distractors from a different domain (e.g., Bayliss et al., 2003; Conlin et al., 2005; Turner & Engle, 1989). However, there is also an exception to this general pattern of the effect of item-distractor similarity. Oberauer (2009) showed that when targets and distractors come from the same domain, WM performance can actually benefit from distractors that are similar to the to-be-remembered target. This counterintuitive pattern, to which we will turn in more detail now, is predicted by one of the leading models of WM, the Serial Order in a Box-Complex Span model (SOB-CS; Oberauer, Lewandowsky, et al., 2012). It also provides support for a particular mechanism of interference implemented in this model—interference by superposition.[1]

In the study by Oberauer (2009), participants performed a series of trials of the complex-span task. In this task, four to-be-remembered target words were consecutively displayed, each followed by four words that participants were asked to read aloud but otherwise ignore for the purpose of performing the WM task. Each target on a given trial was taken from a different semantic category. In the related-distraction condition, the to-be-read distractors that followed the targets were taken from the same semantic category as the target word, whereas they were from a different semantic category than any of the targets on a given trial in the unrelated-distraction condition. Each trial of this complex-span task concluded with participants attempting to serially recall the presented targets. The results revealed better serial-recall performance in the related- than in the unrelated-distraction condition, confirming that the similarity of distractors to their respective targets can mitigate the interference these distractors generally cause in WM. A similar pattern of results was also documented by Oberauer, Farrell, et al. (2012) in a study that manipulated phonetic rather than semantic target-distractor similarity in a task requiring memorizing nonwords.

The patterns observed by Oberauer (2009) and Oberauer, Farrell, et al. (2012) were predicted by the SOB-CS model, which specifies how distractors encoded into WM interfere with maintenance of target items (see Oberauer, Lewandowsky, et al., 2012, for a full specification). Briefly, in this model it is assumed that items have distributed representations consisting of a number of features. These features are bound during study with position cues, also represented as bundles of features. Interference occurs because targets and distractors immediately following them are bound to the same position cues. In this model, new position-distractor bindings are superimposed on position-target bindings, distorting them and, thereby, causing interference. However, when the target and the following distractors share common features (e.g., their semantic category), the overall distortion of position-target bindings is less severe because superposition strengthens the bindings between shared features and the common position cue. This net result of less severe distortion for related distractors can be observed in a serial-recall task, where using position cues to serially retrieve targets results in accessing the original position-target bindings (see Figure 1 in Oberauer, Farrell, et al., 2012, for a visualization of the superposition mechanism).

So far, the studies on target-distractor similarity have been concerned with testing predictions of the SOB-CS model and they were limited to assessing performance in variants of serial-recall tasks tapping WM. The novel question asked here is how superposition affects LTM performance. Going back to SOB-CS, this model assumes that serial-recall performance is determined by bindings between items and their positions within a study list. The idea of position cues that encode the place of a particular item within a study list is common in conceptual work on WM (Burgess & Hitch, 1999; Kowialiewski et al., 2021; Oberauer, Lewandowsky, et al., 2012). However, modeling of LTM often substitutes position cues for context cues—the overall contents of the mind that accompany the presentation of an item and which include details about the environment and also thoughts elicited by processing the item itself (Howard & Kahana, 2002). Recent work by Logan (2021; see also Logan & Cox, 2021) underscores that position cues in models of WM may in fact be an example of a broader class of context cues as defined in conceptual frameworks of LTM (see Howard & Kahana, 2002). This stance follows from previous work on WM in which the role of context cues has been implicated, accounting in particular for the patterns of errors in the immediate serialrecall task (Unsworth & Engle, 2006). The postulated identity of position and context cues has important consequences for mechanisms operating across WM and LTM. If position cues used to describe the operations of the WM system are the same as context cues used to describe the operations of the LTM system, then mechanisms that build on position cues in WM should affect LTM performance, also in tests that are context dependent but that do not require strict serial reproduction of study items.

Returning to interference by superposition, reduced interference caused by distractors that follow related targets is assumed in SOB-CS to reflect a superposition of bindings between overlapping features of related targets and their distractors on the one hand and a common position cue on the other (Oberauer, Lewandowsky, et al., 2012). Thus, in the complex-span task used by Oberauer (2009), if the word EMERALD is followed by four other instances of gemstone, as opposed to instances of a different category (e.g., fish), participants' ability to remember EMERALD in its actual position within the study list is enhanced. However, if this position cue is taken to constitute context as understood in the

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[1] Interference by superposition should not be confused with another mechanism, one of interference by confusion: an observation that retrieval becomes less effective when a cue is associated with more competing memory representations (Watkins & Watkins, 1975). In our studies, we took care to eliminate any influence of interference by confusion—as described in the Method section of Experiment 1a—and we do not consider this mechanism here. Whenever we refer to interference throughout this article, it should be taken to denote interference by superposition as implemented in the SOB-CS model (Oberauer, Lewandowsky, et al., 2012).

models of LTM, then it follows that presenting related distractors should strengthen bindings between overlapping item-distractor features and context that is then used to access items at the time of contextually cued retrieval from LTM. Thus, the word EMERALD, when followed by related distractors, should be easier to recall within the context of a given study list, not only at its particular position within this list. In other words, related distractors would serve to elaborate episodic, contextually bound representation of a target by rendering the particular features that are shared by these distractors and the immediately preceding target more prominent. Testing this prediction of the parallel effects in WM and LTM of using related distractors is the main empirical aim of the present work.

The chances to detect the putative aftereffects of superposition of feature and context bindings should be increased in a test of LTM in which performance is dependent on accessing these particular bindings. Such a test requires cuing with both context and specific features shared across targets and distractors. All explicit tests of episodic LTM, that is tests that require accessing a particular contextual representation, are necessarily dependent on contextual bindings (e.g., Davis et al., 2008; Schwartz et al., 2005). However, not all tests can be assumed to benefit from stronger episodic representations of particular features common to targets and related distractors. For example, when EMERALD is followed by distractors such as *diamond* or *ruby*, the bindings between context and features describing EMERALD as a gemstone should be strengthened. If a subsequent test used the word *green* as a cue, this would fail to match the particular features strongly bound to the context by virtue of using related distraction, reducing our chances of observing the effect that we pursue here. Generally, the chances of observing our effect of interest should be greatest with cues that specifically embed the information that superposition helps encode into episodic memory, which in this case is common categorical membership of targets and their distractors—the gemstone label in our example. In other words, what is most auspicious for detecting aftereffects of superposition in this case is a category-cued recall test (see Hanczakowski et al., 2017; Zawadzka et al., 2021, for similar logic). In the present work, we adopt the paradigm developed by Oberauer (2009) and test for effects of target-distractor similarity, implemented in the WM task, for LTM performance. We use category membership as a feature linking targets and their respective distractors in the complex-span task and a test of category-cued recall to reveal the effects of elaboration by superposition of targets and distractors.

We present five experiments designed to reveal the common dynamics across WM and LTM systems. All experiments utilized a variant of the complex-span task and manipulated target-distractor similarity, by which targets were accompanied by distractors that were either taken from the same category as the target itself, or from a different semantic category. For WM performance, we expected to replicate the results of Oberauer (2009) and demonstrate the signature effect of interference by superposition: reduced interference when related (rather than unrelated) distractors follow their respective targets. The novel feature in our design was an LTM test of category-cued recall that was tailored to determine whether related distractors strengthen contextual encoding of features shared across targets and their respective distractors. If superposition of the to-be-remembered targets and distractors determines contextual encoding, then related distractors should strengthen episodic representations of features shared across targets and their respective distractors, leading to better category-cued recall performance compared with a situation in which targets are followed by unrelated distractors. Experiments 1a, 1b, and 2 tested this basic prediction of the mechanism we term elaboration by superposition. Experiment 3 tested an additional specific prediction of the superposition account, by which the discussed effects of superposition on both WM and LTM performance should be observed primarily when related distractors follow rather than precede their respective targets. Experiment 4 included an additional no-distraction condition to demonstrate that target-distractor similarity reduces interference in WM but produces a net benefit to LTM performance.

Experiments 1a and 1b

In Experiments 1a and 1b, we adapted the procedure used previously by Oberauer (2009) for assessing the role of target-distractor similarity for WM performance to examine whether the type of distraction within the WM task also determines LTM performance. Participants performed a series of complex span trials in which four target words, each from a different semantic category, were interspersed with distractors that had to be read aloud by participants. Across trials, distractors were either from the same or a different semantic category as the directly preceding target. Immediate serial recall was used to assess WM performance, in a direct replication of the design used by Oberauer. A category-cued recall test followed a series of four complex-span trials—two from the related and two from the unrelated-distraction condition—to assess LTM performance. We used a category-cued recall task, as previous work indicated that to detect elaborative encoding of semantic features of to-be-remembered words, a test is necessary that taps those particular features (Hanczakowski et al., 2017; Zawadzka et al., 2021).

Experiments 1a and 1b differed in that in Experiment 1a all trials were followed by the immediate serial-recall test, whereas in Experiment 1b immediate serial-recall tests were administered only for half of the trials of the complex-span task, with an arithmetic distractor task administered for the other half. In this way, Experiment 1b assessed whether any effect observed in LTM measure of cued recall could be due to carry-over effects from differences observed in immediate serial recall. If the same effects are observed for trials not followed by immediate serial-recall tests, this would serve to eliminate the explanation based on carry-over effects.

Method

Participants

The sample size was based on Oberauer's (2009, Experiment 2) results for the benefits of semantic relatedness with in-position scoring—an effect size of $d = .66$. A power analysis suggested that to obtain power of .95, 27 participants were required. Thus, 30 undergraduates from the SWPS University participated in Experiment 1a and 32 undergraduates participated in Experiment 1b. All participants received partial course credit. Due to technical problems, two participants in Experiment 1a did not complete the procedure, and so two more participants were tested to replace their data. We attempted to retain the same sample size for all experiments presented here. Demographic data (age, gender) were not collected in this series of experiments. The study was approved by the Research Ethics Committee at the SWPS University.

Materials and Design

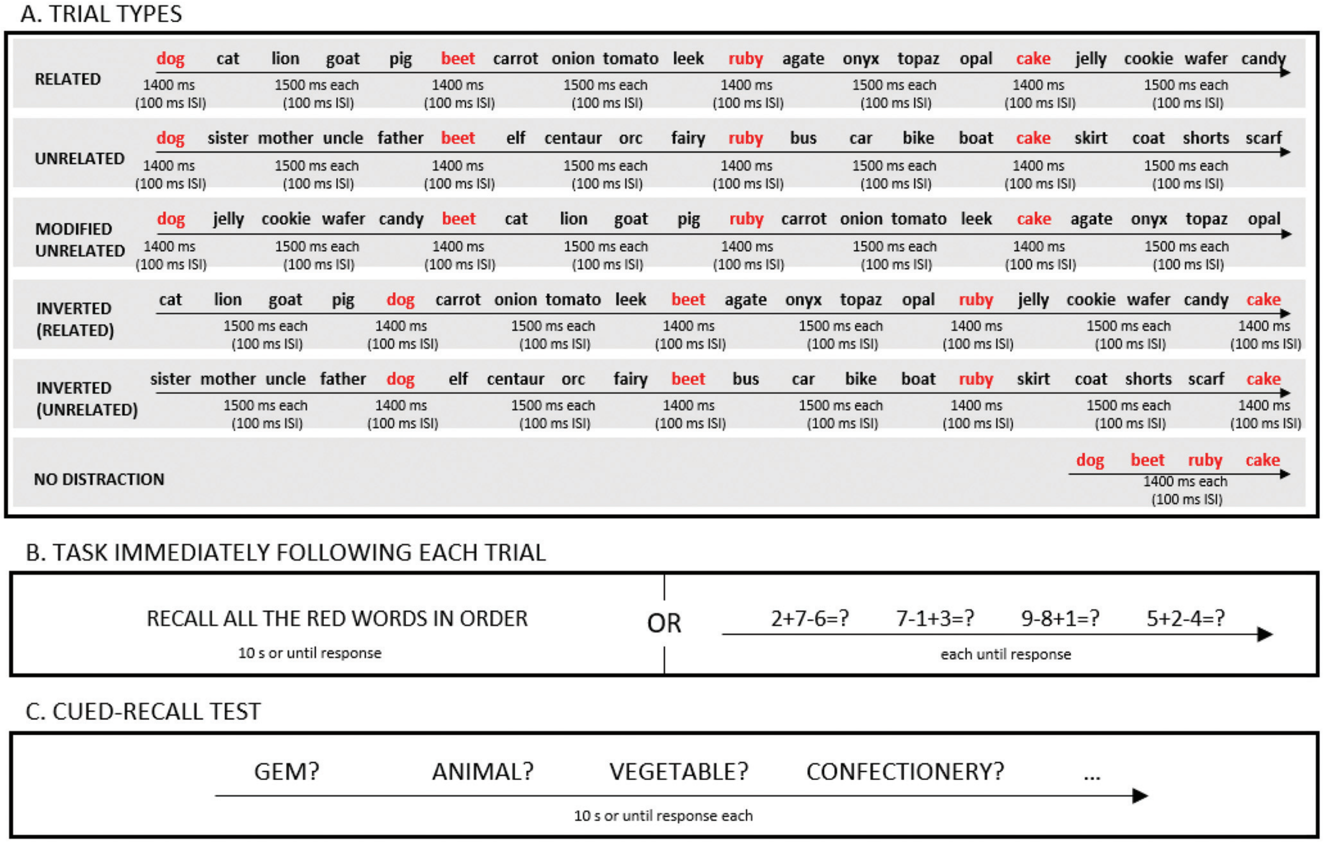
A set of 192 Polish nouns, with 12 instances of 16 categories, was chosen based on an online survey conducted with an independent sample of participants (N = 173). In this survey, participants were given unique category labels (e.g., "fish" or "family member") and were asked to generate exemplars for these categories. From each category, the most often mentioned one-word exemplars were picked to serve as stimuli. Any words that were deemed not appropriate for their category labels (e.g., *dolphin* for "fish") were excluded. In the experiments reported here, words from each category were used both as targets and distractors in the complex-span task, with each word serving once as a target in the entire experimental task but three times as a distractor across various blocks. Category labels were then used as cues for the delayed recall test.

A trial in the complex-span task consisted of four targets, each from a different semantic category, followed by four distractors. A block consisted of four trials and ended with a cued-recall test for all 16 targets (four from each trial). Each target within one block came from a different semantic category, which allowed for using unique category cues on the cued-recall test. The same 16 categories were used across all 12 blocks of the procedure.

There were two types of trials of the complex-span task (see Figure 1). On related-distraction trials, each target was followed by four distractors from the same category (e.g., EMERALD, *topaz*, *amber*, *diamond*, *opal*; the target is capitalized here for illustration purposes as in the actual experiment all items were presented in lowercase). On unrelated-distraction trials, targets were followed by a set of four distractors from a single category that was different from the category of that target (e.g., EMERALD, *larch*, *fir*, *spruce*, *yew*). Within a block, two trials were assigned to the related-distraction condition, and the other two to the unrelated-distraction condition. The order of trials in a given block was random. The assignment of targets to conditions was counterbalanced across participants. For the unrelated-distraction condition, unrelated distractors were repaired across trials within the same block. Thus, if EMERALD, followed by *larch*, *fir*,

Figure 1

Experimental Design of Experiments 1a–4



Note. Panel A shows six types of study trials, with targets presented in red and distractors presented in black: Related trials from Experiments 1a, 1b, 2, and 4; Unrelated trials from Experiments 1a, 1b, and 4; Modified Unrelated trials from Experiment 2; two types of Inverted trials, with related and unrelated distractors, from Experiment 3; and No-distraction trials used in Experiment 4. Panel B presents tasks to be performed immediately after each trial: the immediate serial-recall test used in Experiments 1a, 2, 3, 4, and for half of Experiment 1b trials (left), and the filler task used for the other half of Experiment 1b trials (right). Panel C depicts the delayed category-cued recall test that was administered after a block of four trials in each experiment. See the online article for the color version of this figure.

spruce, and *yew*, was one of the targets in one of the unrelated trials, then the distractors *topaz*, *amber*, *diamond*, and *opal* would follow one of the other targets within the same block, chosen randomly. With this design, the number of items associated with each category cue in the test of LTM was equated across related- and unrelated-distraction conditions: one cue was associated with a single target from the WM task and four different distractors that either immediately followed this target in the related-distraction condition, or were used in a different unrelated-distraction trial within the same block. This served to equate the set size of cues across experimental conditions, eliminating any potential effects of interference by confusion.

In Experiment 1a, each trial of the complex-span task ended with a serial-recall test in which participants were asked to reproduce the most recent targets in the same order in which they were presented. In Experiment 1b, for half of the trials within a given block—one trial from the related-distraction condition and one trial from the unrelated-distraction condition, counterbalanced across participants—the immediate serial-recall test was substituted with an arithmetic task. Thus, Experiment 1a had a single independent variable of type of distraction (related vs. unrelated), whereas Experiment 1b used a 2 (distraction: related vs. unrelated) × 2 (immediate serial-recall test: present vs. absent) design. All variables were manipulated within participants.

Procedure

The experiments were conducted online. Throughout the experiment, an experimenter supervised one participant at a time via a video and audio link to ensure that experimental instructions were followed. The experiment began with a training session wherein participants were accustomed with the complex-span task in a single trial of study and serial recall. Participants then performed 12 blocks of four trials each.

On each trial, four target words were presented individually on the screen for 1,400 ms in a red font. Each target was followed by four distractors, displayed individually on the screen for 1,500 ms in a black font, with a 100 ms interstimulus interval. Participants were instructed to read silently and memorize the words displayed in red, and to read aloud but otherwise ignore those displayed in black. All trials in Experiment 1a and half of the trials in Experiment 1b concluded with a serial-recall test in which participants were asked to recall and type in all the targets (red words) from the present trial in the order of their presentation. If participants could not recall a word in a certain position, they were asked to type in “x” in its place. The remaining half of the trials in Experiment 1b concluded with an arithmetic task, where participants were presented with four simple algebraic tasks of addition and subtraction. The average time needed for completing the math task was 17.30 s (*SD* = 8.10).

After completing four trials of the complex-span task, participants were given a cued-recall test. In the cued-recall test, a single category label (e.g., *Gemstone*) was displayed on the screen at a time and participants were asked to recall and type in the word from this category that served as the target in the current block (EMERALD). If a participant failed to type in and accept the answer within 10 s, the procedure automatically advanced to the next cue. The order of presentation of 16 category cues from each block was randomized anew for each participant.

Transparency and Openness

The study was not preregistered. All data are publicly available at https://osf.io/jemzs. All experiments, variables, as well as data exclusions are reported.

Results

Descriptive statistics for all serial- and cued-recall measures are presented in Table 1. Figure 2 depicts aggregate as well as participant-level data.

Experiment 1a

Immediate Serial Recall

Two scoring methods were used to assess performance in the serial-recall task. For correct-in-position scoring, words were counted as correctly recalled only if they were provided in the same output position in which they were presented at study. For item scoring, correctly recalled words were counted as such regardless of their output position. The analysis of performance with correct-in-position scoring revealed a significant difference, $t(29) = 5.53$, $p < .001$, $d = .83$, with higher performance in the related-distraction than in the unrelated-distraction condition. Likewise, the analysis of performance with item scoring revealed higher performance in the related-distraction than in the unrelated-distraction condition, $t(29) = 4.56$, $p < .001$, $d = .84$.

Table 1

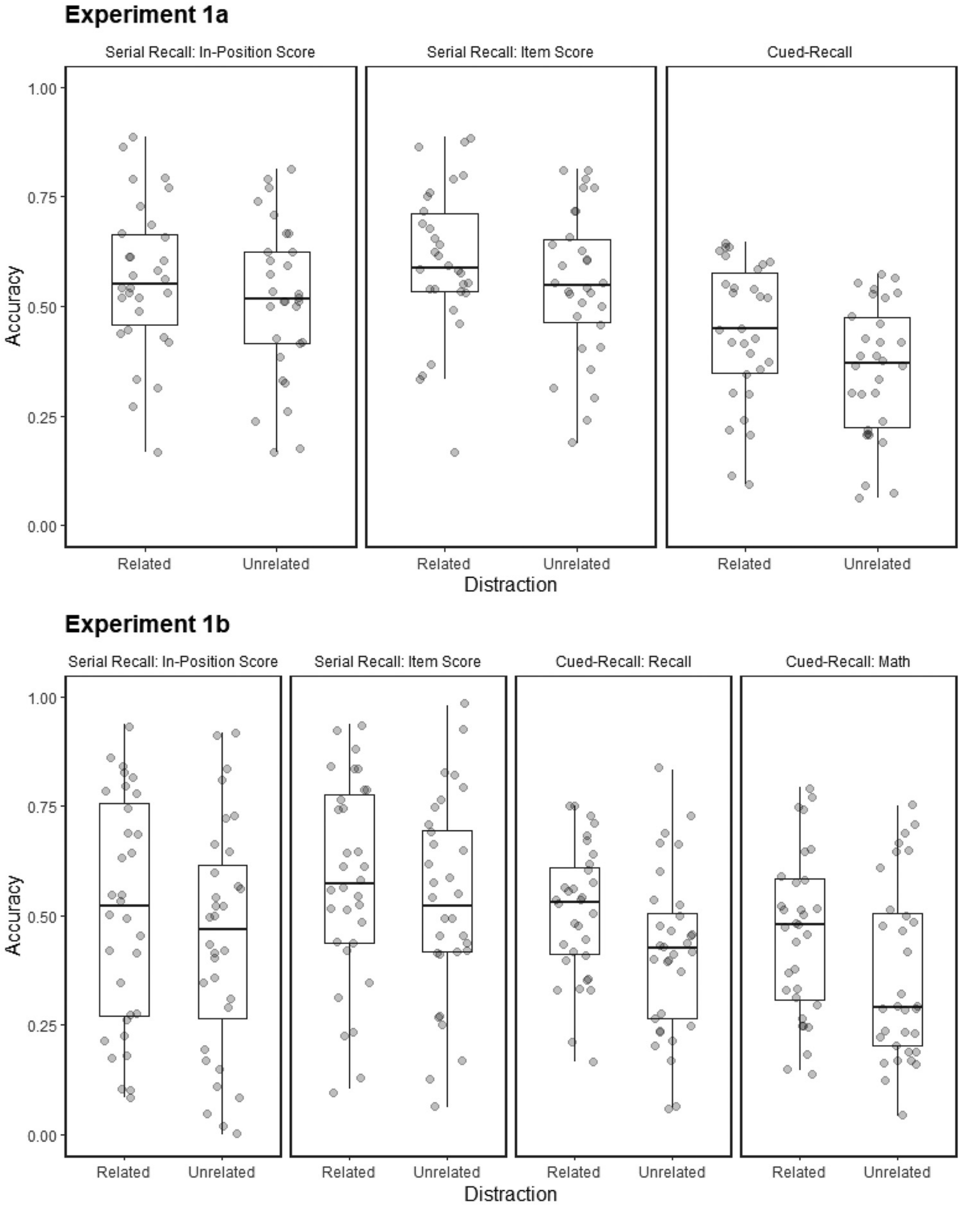
Mean Proportions of Correctly Recalled Items in the WM Serial Recall Task - According to Strict Correct-in-Position Scoring and More Lax Item Scoring - and in the LTM Category-Cued Recall Task in Experiments 1a–4

	Serial recall—in-position scoring			Serial recall—item scoring			Category-cued recall		
Experiment	Related distraction	Unrelated distraction	No distraction	Related distraction	Unrelated distraction	No distraction	Related distraction	Unrelated distraction	No distraction
Experiment 1a	.53 (.20)	.48 (.20)	—	.57 (.19)	.52 (.19)	—	.44 (.16)	.35 (.15)	—
Experiment 1b									
Immediate test present	.51 (.26)	.45 (.26)	—	.58 (.23)	.52 (.25)	—	.51 (.15)	.42 (.19)	—
Immediate test absent	—	—	—	—	—	—	.46 (.18)	.36 (.20)	—
Experiment 2	.75 (.19)	.71 (.20)	—	.78 (.18)	.75 (.18)	—	.59 (.18)	.54 (.18)	—
Experiment 3	.66 (.23)	.65 (.23)	—	.74 (.15)	.72 (.15)	—	.50 (.20)	.48 (.20)	—
Experiment 4	.55 (.21)	.50 (.22)	.87 (.12)	.61 (.19)	.56 (.21)	.90 (.08)	.53 (.17)	.46 (.17)	.28 (.15)

Note. WM = working memory; LTM = long-term memory. The results for Experiment 1b are presented also as a function of whether serial recall was administered or not after list presentation. Standard deviations are given in parentheses.

Figure 2

Immediate Serial Recall and Delayed Category-Cued Recall Performance in Experiments 1a (Top) and 1b (Bottom)



Note. Boxplots represent group-level data and dots depict accuracy scores of individual participants. For both experiments, in-position-, as well as item-scores of serial-recall performance are presented. For Experiment 1b, cued-recall results for items from trials concluded with serial recall ("Cued-Recall: Recall") and from trials concluded with a math filler task ("Cued-Recall: Math") are presented separately.

Delayed Cued Recall

An analysis of category-cued recall performance revealed a significant difference between the experimental conditions, $t(29) = 5.02$, $p < .001$, $d = .92$, with higher performance in the related-distraction than in the unrelated-distraction condition, mirroring the results found in the serial-recall measures.[2]

To ensure that this pattern is not due to carry-over effects from the immediate serial-recall test, we also examined the results of

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[2] In the present design, the cued-recall test followed immediately the last trial of the complex-span task. It is possible that some of the targets in the cued-recall task were actually retrieved from WM, whenever cues for particular words from the last trial of the complex-span task happened to be presented at the beginning of the cued-recall task. To address this issue, we re-analyzed cued-recall data excluding targets that were recalled in the last complex-span trial of each block and that could contaminate our measure of LTM performance. The difference between related- and unrelated-distraction conditions remained significant, $t(29) = 4.34$, $p < .001$, $d = 0.79$.

the delayed cued-recall test conditionalized on whether items were recalled correctly in the immediate serial-recall test. The conditionalized results replicated the difference between related- and unrelated-distraction conditions, $t(29) = 4.04$, $p < .001$, $d = .74$. The specific results for the conditionalized analyses for this and the remaining experiments in this study can be found in the Appendix.

Experiment 1b

Descriptive statistics for all serial-recall and cued-recall measures are presented in Table 1, and aggregated and participant-level data are presented in Figure 2.

Immediate Serial Recall

Here the results were analyzed for half of the trials that concluded with an immediate serial-recall test. The analysis of performance with correct-in-position scoring revealed a significant difference, $t(31) = 2.59$, $p = .015$, $d = .46$, with higher performance in the related-distraction than in the unrelated-distraction condition. Likewise, when item scoring was used, performance was significantly higher in the related- than in the unrelated-distraction condition, $t(31) = 2.72$, $p = .011$, $d = .48$.

Delayed Cued Recall

A 2 (distraction: related vs. unrelated) × 2 (serial recall: present vs. absent) within-participants analysis of variance (ANOVA) was conducted on category-cued recall performance. This analysis revealed a significant main effect of distraction, $F(1, 31) = 33.59$, $MSE = .26$, $p < .001$, $\eta^2 = .22$, which reflected overall higher performance in the related-distraction ($M = .48$, $SD = .15$) than in the unrelated-distraction condition ($M = .39$, $SD = .19$). The main effect of serial recall was also significant, $F(1, 31) = 8.70$, $MSE = .08$, $p = .006$, $\eta^2 = .07$. This reflected higher performance when immediate serial recall was present ($M = .46$, $SD = .16$) than when it was absent ($M = .41$, $SD = .18$). Critically, however, the interaction was not significant, $F < 1$. Because nonsignificant interactions are not straightforwardly interpretable, we also computed a Bayes factor for this analysis, using the default settings in JASP (Wagenmakers et al., 2018), which provided moderate evidence against the interaction, $\text{BF}_{\text{inclusion}} = 0.26$. We also confirmed that the effects of related distraction were reliable both in the condition with an initial serial-recall test, $t(31) = 3.93$, $p < .001$, $d = .70$, and—with an almost identical magnitude of the effect—without it, $t(31) = 3.96$, $p < .001$, $d = .70$.

Discussion

In the first two experiments, we found similar benefits of semantically related distractors embedded in the complex-span task for immediate WM performance and delayed LTM performance. The results for immediate serial recall replicate those reported by Oberauer (2009) and document reduced forgetting from WM when targets and distractors share common features. The WM results confirm that the interference-by-superposition mechanism described by the SOB-CS model (Oberauer, Lewandowsky, et al., 2012) operated in our study. The novel contribution of the present experiments concerns LTM performance, which also revealed benefits of related distraction at study. This effect on cued-recall performance was not due to carry-over effects from immediate testing, as evidenced by both the analysis of conditionalized results in Experiment 1a and the results from the condition without immediate testing in Experiment 1b. These LTM results are consistent with the notion that not only does superposition underlie forgetting from WM, but at the same time it determines the type of information encoded into LTM. This confirms that the operation of the superposition mechanism is not limited to position cues determining performance in tests dependent on serial information, such as serial recall used to assess WM performance, but generalizes to other tests tapping episodic memory representations, such as in this case category-cued recall. By implication, our results suggest that position cues determining serial recall within WM are in fact identical with context cues that determine performance across a variety of tests of episodic memory (see Logan, 2021).

We argue that to observe the benefits of related distraction, semantic and temporal-contextual characteristics of distraction need to be confounded: only when distractors are presented in the same contexts as their respective targets, can contextual bindings of their common semantic features be augmented. However, in Experiments 1a and 1b the baseline condition of unrelated distraction de-confounded semantic and context features in a particularly dramatic way, as distractors related to their targets were presented in different trials of the complex-span task. In this way, in the related-distraction condition targets and distractors shared exactly the same context, while in the unrelated-distraction condition targets and distractors were presented in the contexts of different study lists. This raises the question of how exact the confounding needs to be for our effect of interest to emerge. Would the benefits of related distractors following their respective targets still emerge if they were compared with an unrelated-distraction condition in which targets and their distractors were presented within the same list context? Experiment 2 addressed this issue by modifying the unrelated-distraction condition so that distractors were presented within the same list context but not immediately after their respective target.

Experiment 2

In the present experiment, we aimed at establishing the extent to which temporal proximity of targets and related distractors determines the benefits of related distraction for both WM and LTM performance. Here, in the related-distraction condition distractors from the same category immediately followed their respective targets, while in the modified unrelated-distraction condition distractors from the same category were presented within the same trial of the complex span task, but after the next target. Thus, if EMERALD was the first word in the modified unrelated-distraction condition and PIKE was the second word, then distractors *topaz*, *amber*, *diamond*, and *opal* were presented after PIKE. In this way, in both related- and unrelated-distraction conditions, targets and their related distractors shared the same list context, but only in the related-distraction condition did they share exactly the same context due to their close temporal proximity. Because we assume that the benefits of related distraction are due to augmented bindings between semantic features common to targets and distractors and contextual features present when both targets and distractors are processed, we expected the greater contextual overlap in the related-distraction condition to result in benefits of related distraction also in the present design, both for WM and LTM performance.

Method

Participants

Thirty participants who reported Polish as their first language were recruited via Prolific. In the honesty-check question displayed after the completion of the study, five participants reported not committing to the experimental instructions and their results were excluded from the analyses and replaced with data from five new participants. Each participant was remunerated with £6 for their participation.

Materials, Design, and Procedure

The same materials as in Experiments 1a and 1b were used. As this study was not supervised by an experimenter, a prerecorded demonstration of the experimental task was added at the beginning of the procedure and a question asking whether the participant followed the experimental instructions by reading the targets silently and the distractors out loud was included at the end of the experiment. The experimental procedure was the same as in Experiment 1a, with serial recall on all trials of the complex-span task, except for the design of the unrelated-distraction trials (see Figure 1). In the modified unrelated-distraction trials, each target was followed by distractors related to the previous target, with the first target followed by the distractors related to the fourth target. To illustrate, if the targets in an unrelated-distraction trial were to be APPLE, CAR, UNCLE, and EMERALD, the first target would be followed by four distractors taken from the “gemstones” category, the second target would be followed by four fruits, the third would be followed by four vehicles, and the last target would be followed by four family members.

Results

Descriptive statistics for all serial-recall and cued-recall measures are presented in Table 1. Aggregated and participant-level data are presented in Figure 3.

Immediate Serial Recall

As in this experiment targets presented on positions 1–3 in the unrelated-distraction trials differed from targets presented on position 4, with only targets in positions 1–3 adhering to our design of having related distractors following the next target in the list, we excluded targets from position 4 from all analyses, regardless of the distraction condition. The analysis using correct-in-position scoring revealed that performance in the related-distraction condition was significantly higher than in the unrelated-distraction condition, $t(29) = 2.48$, $p = .019$, $d = .45$, and similar results were obtained when item scoring was employed, $t(29) = 2.11$, $p = .044$, $d = .38$.

Delayed Cued Recall

For the analyses of cued recall, we again excluded targets presented in position 4. We obtained a significant difference between related- and modified unrelated-distraction conditions, $t(29) = 3.54$, $p = .001$, $d = .65$, demonstrating that related distraction immediately following targets benefits LTM performance compared with a situation when such distraction is delayed to after the presentation of the next target.

Discussion

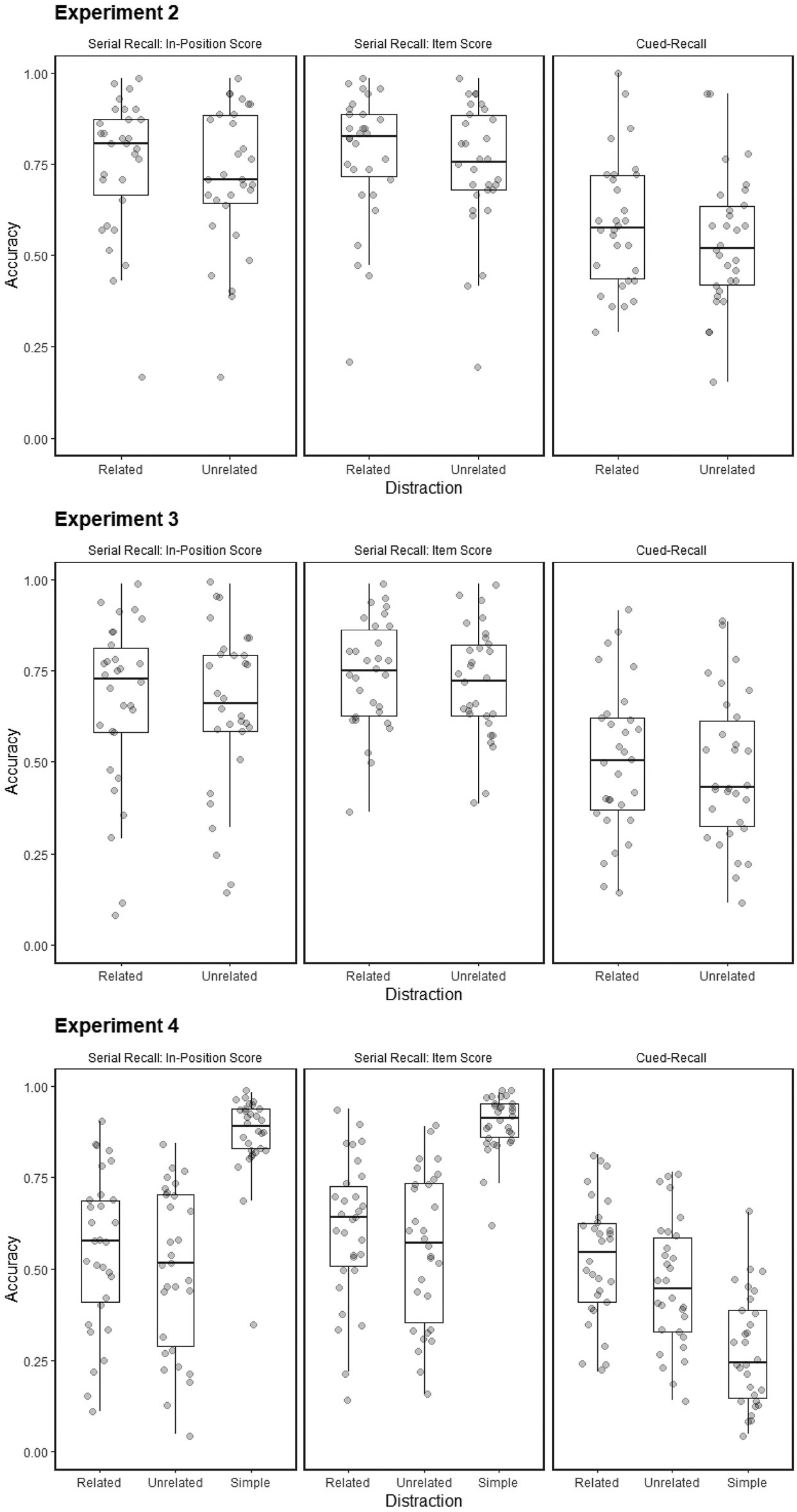
Experiment 2 extended the results of Experiments 1a and 1b by again showing that related distractors that immediately follow their respective targets augment memory performance for these targets both when assessed immediately in the WM task and after a delay in the LTM task. This time these benefits emerged relative to a situation in which related distractors shared list contexts with their targets but not close temporal proximity in the modified unrelated-distraction condition. Again, this remains consistent with the assumptions of the interference-by-superposition mechanism operating in WM, and by extension the elaboration-by-superposition mechanism we postulate for LTM. When a novel target is presented, it creates either a new position cue (Oberauer, Lewandowsky, et al., 2012), or—as we argue in the present study—a new context representation, to which distractors following it become bound. Due to this change in cues with the presentation of a new target, distractors no longer augment cue-feature bindings that determine performance for the previous target to which these distractors were semantically related. The parallel effects observed here for WM and LTM performance again suggest that the process initially described as updating position cues that determine WM performance can be reformulated as updating context cues that also determine LTM performance. Ultimately, it seems that close temporal proximity between targets and distractors is necessary for the benefits of related distraction to emerge as it ensures that these are processed within highly overlapping context cues.

However, is temporal proximity sufficient to produce the benefits of related distraction in both WM and LTM? Somewhat counterintuitively, the interference-by-superposition hypothesis predicts that a mere co-occurrence of targets and related distractors in close temporal proximity may not always be sufficient to affect WM performance. According to the SOB-CS model, the benefits of related distraction—in the form of reduced interference—are most apparent when related distractors *follow* their respective items. This is because distractors in this model are bound to the position cues of their preceding targets and these position cues are updated only with the presentation of the next study item. Thus, if distractors precede their related targets, they are bound to position cues of a different target than the one they are related to. There is some room for moderating interference also under these conditions because there is partial overlap in features of position cues across neighboring targets in a study list, but such moderation is markedly reduced compared with a situation in which distractors are bound to the same position cues as their respective targets.

Oberauer, Farrell, et al. (2012) confirmed this specific prediction of the interference-by-superposition hypothesis in a study examining WM, using nonwords as study materials and phonetically related distractors. In this study, related distractors did not affect serial-reconstruction performance when they preceded rather than followed their respective targets. Throughout the present study, we have proposed that position-to-target bindings determining WM performance are identical to context-to-target bindings determining performance in tests of episodic memory, exemplified by a category-cued recall test of LTM. If so, then LTM performance in the category-cued recall test should evidence exactly the same regularities as these previously assigned to changes to position-to-target bindings

Figure 3

Immediate Serial Recall and Delayed Category-Cued Recall Performance in Experiments 2 (Top), 3 (Middle), and 4 (Bottom)



Note. Boxplots represent group-level data and dots depict accuracy scores of individual participants. For all experiments in-position, as well as item scores of serial recall performance are presented.

assumed to determine WM performance. Thus, the effects of elaboration by superposition should likewise be reduced when related distractors precede rather than follow their respective targets. This prediction was tested in Experiment 3.

Experiment 3

The present experiment assessed whether the benefits of related distraction for LTM performance are merely due to occurrence of related distractors in temporal proximity to their respective targets. If the elaboration-by-superposition hypothesis is to encompass also the interference-by-superposition hypothesis formulated for WM, it necessitates a prediction that such temporal co-occurrence is not sufficient, and that related distractors elicit changes in episodic memory representations primarily when they follow their respective targets, and not when they precede them. This asymmetry is predicted explicitly in the SOB-CS model (Oberauer, Lewandowsky, et al., 2012), where new position cues are created when a target in a particular list position is presented for study but not when distractors are processed. Consequently, related distractors are bound to position cues of targets that precede them and WM performance is improved only by related distractors following, not preceding, their respective targets, despite equated temporal proximity across these two situations (see Oberauer, Farrell, et al., 2012). If our argument about identity of position and context cues is to be upheld, context cues also need to be updated by processing targets and not by processing distractors. This should lead to an asymmetry in the benefits of related distraction for LTM performance, with those benefits being observed when related distractors follow but not precede their respective targets.

Method

Participants

Thirty undergraduate students, recruited in the same way as in Experiments 1a and 1b, participated in exchange for partial course credit.

Materials, Design, and Procedure

Materials and design were the same as in Experiment 1a. The procedure was the same as in Experiment 1a, with the sole exception that the order of presentation of targets and distractors was flipped (see Figure 1). Thus, trials started with four to-be-read distractors, after which the first target was presented (e.g., *topaz*, *amber*, *diamond*, *opal*, and EMERALD). A serial-recall test immediately followed the presentation of the last target and was administered on all trials.

Results

Descriptive statistics for all serial-recall and cued-recall measures are presented in Table 1, and aggregated and participant-level data are presented in Figure 3.

Immediate Serial Recall

When correct-in-position scoring was applied to the data, there was no significant difference between the related- and unrelated-distraction conditions, $t(29) = 1.71$, $p = .097$, $d = .31$. By contrast, using item scoring revealed a significant difference between the two conditions, $t(29) = 2.55$, $p = .016$, $d = .47$, with higher performance in the related-distraction than in the unrelated-distraction condition.

Delayed Cued Recall

The analysis of category-cued recall performance failed to reveal a significant difference between the two experimental conditions, $t(29) = 1.58$, $p = .125$, $d = .29$.

Combined Analyses of Experiments 1a and 3

We compared the effects of relatedness found in the present experiment against the baseline established in Experiment 1a, which had the same method bar the ordering of targets and their distractors. An analysis of serial recall with in-position scoring with a 2 (distraction: related, unrelated) × 2 (Experiment: 1a, 3) mixed ANOVA yielded a significant main effect of distraction, $F(1, 29) = 20.45$, $MSE = .03$, $p < .001$, $\eta^2 = .005$, a significant main effect of Experiment, $F(1, 29) = 7.24$, $MSE = .67$, $p = .009$, $\eta^2 = .11$, and also a significant interaction between the two, $F(1, 29) = 5.01$, $MSE = .01$, $p = .029$, $\eta^2 = .001$. The same analysis for item scoring also yielded a significant main effect of distraction, $F(1, 29) = 26.18$, $MSE = .04$, $p < .001$, $\eta^2 = .01$, a significant main effect of Experiment, $F(1, 29) = 16.95$, $MSE = .98$, $p < .001$, $\eta^2 = .22$, and a nonsignificant interaction, $F(1, 29) = 2.80$, $MSE = .004$, $p = .10$, $\eta^2 < .001$. Finally, the same analysis for cued-recall performance yielded a significant main effect of distraction, $F(1, 29) = 22.55$, $MSE = .09$, $p < .001$, $\eta^2 = .02$, a significant main effect of Experiment, $F(1, 29) = 4.17$, $MSE = .26$, $p = .046$, $\eta^2 = .06$, and a significant interaction, $F(1, 29) = 6.75$, $MSE = .03$, $p = .012$, $\eta^2 = .01$. Significant interactions for immediate serial and delayed cued-recall tests reflected the fact that the effects of distraction relatedness for these measures were reduced in Experiment 3 compared with Experiment 1a.[3] A similar interaction for item scoring in immediate recall was not significant, which reflects the fact that this measure was the only one sensitive to distraction relatedness in Experiment 3.

Discussion

The present experiment tested the specific prediction of the superposition account by which the benefits of related distraction, observed in Experiments 1a, 1b, and 2, should be reduced when distractors precede rather than follow their respective study items. Indeed, this reduction was observed here for WM performance (albeit only with correct-in-position scoring) and, more importantly for the present purpose, for LTM performance. This pattern once again underscores the commonality of mechanisms that operate across WM and LTM. Whether performance is assumed to

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[3] The main effects of Experiment observed for serial-recall performance measures and which reflected reduced performance in Experiment 1a compared with Experiment 3 were most likely caused by differences in the lag to the serial-recall test in these experiments. In Experiment 1, each trial started with a target and the last target was followed by distractors. In Experiment 3, each trial started with distractors and the last target was followed immediately by a test. Thus, the lag to test was shorter in Experiment 3, accounting for improved performance. Note that this did not affect performance in cued recall.

depend on position cues delineating a place of an item within a study list, as theorized for serial recall tests used to assess WM performance (Oberauer, Lewandowsky, et al., 2012), or on broadly defined context defining entire study blocks and supporting LTM performance, the processes of binding these cues with features of targets and distractors appear to be the same. In both cases, it needs to be assumed that distractors are bound to the same cues to which the preceding targets were bound, resulting in stronger bindings for features shared across targets and their distractors. When the same distractors precede their related targets, they are not bound to exactly the same cues and no superposition for their featural bindings occurs. Ultimately, the similarity of empirical patterns once again suggests that position cues in WM and contextual cues in LTM are in fact one and the same.

The asymmetry in the effects of related distraction, depending on the timing of its presentation related to its corresponding target, stems—according to the SOB-CS model (Oberauer, Lewandowsky, et al., 2012)—from the assumption that targets update position cues, while distractors do not, and distractors are bound to position cues established by the preceding targets. Because our results for LTM performance parallel the results obtained for WM performance, our hypothesis of elaboration by superposition seems to require an analogous assumption that targets update context representations while distractors do not, or at least update them to a much lesser extent. Older models of context in LTM (Estes, 1955; Mensink & Raaijmakers, 1988) assumed that context evolved randomly with time, in a way independent of the presentation of targets. Clearly, such models would be inconsistent with the conclusions derived from the present experiment. However, a newer class of context models, referred to as retrieved-context models (Howard & Kahana, 2002; Polyn et al., 2009), assume that context and target processing are not independent and indeed context representations depend on thoughts elicited by processing targets within a memory task. In these models, experimental context to which items become bound at encoding evolves as it becomes updated by preexperimental contexts associated with the processed items. Adapting this perspective to our results would require an assumption that while target processing updates the experimental context with preexperimental contexts associated with those targets, such updating is markedly reduced when distractors are processed.

It is important to note that while context evolving randomly cannot accommodate our results, the assumption of differential context updating by targets and distractors is fully compatible with the retrieved-context models, even if not directly necessitated by them. Indeed, there are already suggestions in the literature that items processed intentionally (such as targets in our procedure) and items processed incidentally (such as distractors used here) lead to different manifestations of the context effects. Healey (2018; see also Mundorf et al., 2021) first showed that the contiguity effect in free recall—a hallmark context effect by which recalling an item reinstates its context, which in turn cues the next item that was bound at encoding to an overlapping context representation, resulting in serial-like pattern of free recall—is markedly reduced for incidentally processed items. This observation is consistent with the conclusions of the present experiment: distractors, or incidentally processed items more generally, do not update the experimental context in the same way as intentionally studied items. This differential updating of context by targets and distractors led in the case of our study to a temporal asymmetry in the benefits of related distraction.

One remaining feature of the present results that is worth discussing is that while they provide evidence for the *reduction* of the relatedness effects with flipping the order of items and distractors, they cannot be taken to argue that these effects are eliminated under these conditions. Although these effects were not significant for correct-in-position scoring in serial recall and in category-cued recall, such an effect was still obtained when item memory was scored in the serial-recall task and indeed the item-scoring method did not yield a statistically significant reduction in the magnitude of the relatedness effect compared to Experiment 1a. We also note that numerical trends in all measures pointed to somewhat better performance in the related-distraction conditions. However, the residual effects of relatedness do not pose serious problems for the superposition account advocated here. The SOB-CS model assumes some overlap in features of different position cues—a mechanism necessary for accounting for order errors in serial recall. Similarly, models evoking a mechanism of contextual drift to account for LTM performance (Howard & Kahana, 2002) postulate that although the presentation and retrieval of targets update features of context, such updating is incomplete and neighboring targets are associated with partially overlapping contexts. This overlap in position and context cues means that even distractors preceding their targets are bound to at least some position/context features associated with the following target, that is features carried over from previous targets. Consequently, the superposition account does not predict the elimination of the effects stemming from relatedness but rather their reduction when distractors precede rather than follow their respective targets.

Experiment 4

The results presented so far chime with the predictions of both the interference-by-superposition hypothesis for WM performance, as well as its LTM analog in the form of elaboration by superposition. Both hypotheses predict that being exposed to related distraction augments memory performance compared with unrelated distraction, and both use the same mechanism of superposition of bindings between item and position/context features to account for these patterns. However, there is one conceptual difference between these two hypotheses. The interference-by-superposition hypothesis accounts for forgetting in WM, showing how target-distraction relatedness minimizes interference accruing from processing distraction. However, even related distraction differs from targets and should be able to distort position-feature bindings for the preceding targets, resulting in some degree of interference. So far, we have not tested this prediction as our study lacked a baseline condition of no distraction.

Regarding LTM, the elaboration-by-superposition hypothesis accounts for processing information in LTM that creates episodic memory representations skewed toward features shared across targets and their related distractors. This leads to a different type of episodic memory representations, ones that are enriched with specific features that are only weakly encoded in the absence of related distraction following the study of targets. In other words, elaboration by superposition predicts that related distraction is more beneficial for LTM performance than both the condition that employs unrelated distraction (as in Experiments 1a, 1b, and 2) and a condition that eliminates distraction altogether, in which case no augmented episodic encoding occurs. Here we tested both the predictions of reduced interference in the case of WM and benefits for LTM of including related distractors by comparing performance across related- and unrelated-distraction conditions to a novel condition of no distraction.

It is worth noting the similarity of the present design to studies investigating the McCabe effect (Loaiza & McCabe, 2012; McCabe, 2008)—a phenomenon by which inclusion of distraction in the complex-span task reduces WM performance while augmenting LTM performance. Although the McCabe effect has not been tested specifically with the procedures used here, with distraction in the form of to-be-read words and a test of category-cued recall, we nevertheless predict that this pattern would generalize to the current conditions. In this case, target-distractor similarity should modulate the magnitude of the McCabe effect, reducing the overall costs of distraction for WM performance, while augmenting the overall benefit of distraction for LTM performance.

Method

Participants

Thirty undergraduate students participated in exchange for partial course credit.

Materials, Design, and Procedure

The same materials were used as in Experiments 1a–3. There were now three experimental conditions: the related-distraction and unrelated-distraction conditions were the same as in Experiments 1a and 1b (with distractors following their respective targets and unrelated distractors repaired across separate trials within a single block), and a novel simple-span condition was added in which there were no distractors (see Figure 1). Given that now we had three experimental conditions that had to be split across blocks consisting of four trials (in accord with previous experiments), we mixed the conditions so that only two were used within a single block. There were thus three types of blocks: mixing related- and unrelated-distraction conditions, related-distraction and simple-span conditions, and unrelated-distraction and simple-span conditions. There were four blocks of each type, with a total of 12 blocks. The procedure for distraction trials was the same as in Experiments 1a and 1b, and for the simple-span condition only target words in red were displayed at the rate of 1,400 ms with a 100 ms interstimulus interval. Before the experiment proper, participants performed two practice trials, one for the unrelated-distraction condition and another one for the simple-span condition.

Results

Descriptive statistics for all serial-recall and cued-recall measures are presented in Table 1. Aggregate and participant-level data are additionally depicted in Figure 3.

Immediate Serial Recall

A one-way within-participants ANOVA on performance calculated using correct-in-position scoring revealed significant differences across experimental conditions, $F(2, 58) = 69{,}52$, $MSE = 1.20$, $p < .001$, $\eta^2 = .71$. Post hoc comparisons showed that performance in the simple-span condition exceeded performance in the unrelated-distraction condition, $t(29) = 9.12$, $p < .001$, $d = 1.67$, as well as that in the related-distraction condition, $t(29) = 8.15$, $p < .001$, $d = 1.50$. Performance in the related-distraction condition also was higher than in the unrelated-distraction condition, $t(29) = 3.07$, $p = .005$, $d = .56$. The same analysis of performance with item scoring also revealed significant differences across conditions, $F(2, 58) = 75.31$, $MSE = 1.01$, $p < .001$, $\eta^2 = .72$. Performance in the simple-span condition was higher than in the unrelated-distraction condition, $t(29) = 9.50$, $p < .001$, $d = 1.73$, and in the related-distraction condition, $t(29) = 8.57$, $p < .001$, $d = 1.56$. Performance in the related-distraction condition also exceeded performance in the unrelated-distraction condition, $t(29) = 3.20$, $p = .003$, $d = .58$.

Delayed Cued Recall

The analysis of category-cued recall performance with a one-way within-participants ANOVA revealed significant differences across experimental conditions, $F(2, 58) = 69.45$, $MSE = .49$, $p < .001$, $\eta^2 = .70$. Post hoc comparisons revealed that performance in the simple-span condition was *worse* than both performance in the unrelated-distraction condition, $t(29) = 8.04$, $p < .001$, $d = 1.47$, and in the related-distraction condition, $t(29) = 11.49$, $p < .001$, $d = 2.10$. At the same time, performance in the related-distraction condition exceeded performance in the unrelated-distraction condition, $t(29) = 3.18$, $p = .003$, $d = .58$.

Discussion

The present experiment compared the effects of related distraction on WM and LTM performance relative to the baseline of not only unrelated distraction but also no distraction. Consistent with the interference-by-superposition hypothesis, processing distractors generally impaired WM performance but less so when they were related to the preceding item. Consistent with the elaboration-by-superposition hypothesis, processing related distractors after a study item led to benefits to LTM performance compared with processing unrelated distractors, as well compared with a case in which distraction was eliminated altogether. Related distractors mitigate the interference leading to forgetting from WM, while simultaneously producing LTM representations yielding better memory performance in a delayed cued-recall test.

The results reported here also revealed the McCabe effect (McCabe, 2008), showing that inclusion of distraction in a complex-span procedure simultaneously disrupts WM performance and benefits LTM performance. The current results extend the conditions under which this effect emerges from free-recall testing of LTM to category-cued recall. Even though the mechanisms of the McCabe effect are not the topic of the current work, it is worth outlining some potential consequences of the present results for this line of research. On the empirical side, it is interesting that the main facet of the McCabe effect, the improved LTM performance due to inclusion of distractors in the complex-span task, was—somewhat surprisingly, given that the McCabe effect is sometimes absent when results are not conditionalized on correct immediate recall (see Souza & Oberauer, 2017)—particularlypronounced with the methods used here, with a difference between the unrelated and no-distraction conditions of 19 percentage points ($d = 1.47$). This could result from either of the two methodological choices we made: using a cued-recall task instead of free recall usually used in the studies on the McCabe effect (but see Loaiza & McCabe, 2012), or the distraction that we used, which involved multiple word repetitions. Regarding the retrieval task, the cued-recall test of the type used here taps item information at the exclusion of relational information linking study items to each other. Future studies could assess whether distraction in the complex-span task promotes encoding of item-specific over relational information, possibly meaning that the magnitude of the McCabe effect should be modulated by the type of the final LTM test.

Regarding the distraction task employed here, it is worth noting that the time to pronounce four words in the current procedure was longer than the duration of distraction—usually in the form of an arithmetic task—commonly used in research on the McCabe effect (McCabe, 2008). Current theories of the McCabe effect seem to suggest that the duration of distraction may be important for the benefits that distraction implemented in the complex span task confers on LTM performance. The original account of the McCabe effect argues that the benefits emerge there because targets are strengthened by covert retrieval in-between presentation of distractors (McCabe, 2008). More distractors should lead to more covert retrieval, augmenting the effect, and distractors that take longer to process should increase spacing across covert retrieval attempts, also potentially augmenting the effect. Thus, although the duration of distraction per se should not determine the magnitude of the McCabe effect if covert retrieval takes place, it may still remain correlated with this magnitude via indirect influence of the number and spacing of covert retrieval events.

Two other accounts of the McCabe effect give an even more direct role to time it takes to process distraction. First, Loaiza and Lavilla (2021) have recently proposed that the McCabe effect at least partially stems from additional elaboration that the targets are subjected to when distraction follows target presentation in the complex-span task. The effectiveness of elaboration could be dependent on the time available before the presentation of the next target or the immediate recall test. While such elaboration is not directly observed and remains outside experimental control, it remains possible that a unified account of all LTM effects documented in the present experiment could be proposed, where the presence of distraction determines the overall strength of encoding of study items, and the particular type of distraction determines the likelihood of encoding specific features of these items into episodic memory. Second, Souza and Oberauer (2017) have proposed that distraction is not necessary for observing the McCabe effect and instead the effect simply reflects the longer time for which targets remain in WM in the complex-span task compared with the simple-span task. The argument here is that encoding into LTM is a function of time for which targets are maintained in WM, and from this perspective the particularly pronounced benefit found in our data could stem directly from our use of long distraction-filled intervals. Thus, overall, the particular choice of distraction for our study could have contributed in a number of ways to the highly robust McCabe effect observed here, and future studies should focus not only on the type of distraction—such as related or unrelated to targets—but also its duration.

General Discussion

In the present study, we assessed the role of target-distraction similarity within the complex-span procedure for both WM and LTM performance. Building on the interference-by-superposition hypothesis (Oberauer, 2009; Oberauer, Farrell, et al., 2012; Oberauer et al., 2016), by which the extent to which distractors interfere with maintenance of targets in WM depends on the overlap in features across those targets and the distractors that follow their presentation in a study list, we predicted that a similar mechanism determines encoding into LTM. We tested this elaboration-by-superposition hypothesis by using the complex-span task with distractors that were either semantically related or unrelated to study items, and testing LTM via a category-cued recall task that was attuned to the features shared across distractors and study items in the related-distraction condition. Experiment 1a demonstrated that relative to unrelated distraction, related distraction improved both immediate serial-recall and delayed cued-recall performance. Experiment 1b ruled out the possibility that those benefits for cued-recall performance were due to carry-over effects from immediate serial-recall tests. Experiment 2 revealed that the benefits of related distraction that directly follows its target are still observed relative to a condition in which the same distraction shares the list context with its target but not temporal proximity. Experiment 3, however, showed that temporal proximity may not be sufficient for the benefits of related distraction to emerge as these benefits were reduced when related distractors preceded rather than followed their respective targets. This observation constitutes strong evidence that both effects in immediate and delayed performance are due to operation of the superposition mechanism, which specifically predicts this pattern of results. Finally, Experiment 4 showed that while related distraction mitigates the costs of interference in WM, it also produces net benefits for LTM performance compared with a condition in which distraction is absent from the encoding task. Overall, the results support the elaboration-by-superposition hypothesis, by which the very same mechanism that operates within the working WM system also determines the type of information that is encoded into LTM.

The mechanism of elaboration by superposition is an extension of the interference-by-superposition mechanism embedded in the SOB-CS model (Oberauer, Lewandowsky, et al., 2012). This model was proposed to account for performance in the complex-span task. It did so by making several theoretical assumptions, of which of particular interest for the present work are those of distributed representations of items and position cues that determine serial-recall performance. In this model, interference occurs because distributed representations of both targets and distractors are bound to distributed representations of position cues and these bindings are superimposed on each other. This superposition leads to a distortion of bindings whenever features of targets and distractors following them differ from each other, but also to strengthening of these bindings when these features are shared. This strengthening is what mitigates the interference that superposition generally causes, which is reflected in the relative benefits of related distraction—compared with unrelated distraction—for WM performance.

The fact that similar benefits are observed in LTM indicates that the logic of superposition can be extended beyond bindings of item features and position cues. The present study indicates that the benefits of related distraction can be observed in category-cued recall, in which the role of position cues should be minimal given the random order in which category cues are presented at test. Instead, performance in this task is determined by category information provided in a cue and the context of the study list preceding the particular test that needs to be reinstated to limit the search set (Unsworth, 2008). For the superposition mechanism to determine performance in such a test, the bindings established during encoding need to be between target/distractor features and features of the context, not position cues. Therefore, we propose that the mechanism of superposition described in the SOB-CS model is a specific case in which position cues serve as context to which item features are bound, and that allows participants to retrieve targets in the order in which they were presented at study. The same bindings are then responsible for performance across tests of episodic memory, including tests in which context is necessary to retrieve studied items independently of the order of their presentation.

The assumption by which target features are bound to context features is central to a prominent family of models of LTM—the retrieved-context models, such as the temporal-context model (Howard & Kahana, 2002; see also Lohnas et al., 2015; Polyn et al., 2009). These models are concerned mostly with describing free-recall performance, with a specific focus on contiguity effects at retrieval, by which transitions in recall are often local with respect to the position of items in the study list. These transitions are characterized by an asymmetry favoring for retrieval items which followed the last retrieved item at encoding; thus, giving rise to commonly observed serially ordered free recall. This asymmetry in recall transitions reflects the fact that context is updated by features of the study items and each study item is encoded in the context of the features of the preceding item(s). On a subsequent free-recall test, successful retrieval of an item also updates the context with its features, which then match the context to which the subsequent study item was bound, resulting in an increased probability of retrieving this subsequent study item. The way retrieved-context models account for forward transitions in free recall can be considered in light of the results obtained in our Experiment 3, where it was shown that while related distractors following targets augment both WM and LTM performance, these effects are markedly reduced when these distractors precede their respective targets (see also Oberauer, Farrell, et al., 2012). If we assume that distractors are also bound to contextual cues but do not update them substantially, then the retrieved-context models provide a straightforward account of why they are bound more strongly to the context of the preceding rather than the following target. This is so because when distractors are presented, the experimental context has already been updated with the features of the preceding target, but it does not yet contain features that will later update it with the presentation of the subsequent target. The assumption that context features and item features are not independent of each other—absent from most models of WM but recently adopted in Logan's (2021) model of serial-order effects in memory, perception, and action—provides an overarching account of asymmetries observed both in recall from LTM and in interference effects in WM.

In describing the LTM consequences of the postulated superposition of item and context features, we used the term elaboration, which we understand as any qualitative change in memory representations due to processing at study. This definition follows also from our previous work on the encoding variability effect (Zawadzka et al., 2021), where we showed that varying orienting questions (e.g., "Would this fit into a shoebox?")—rather than keeping them constant—across study presentations of to-be-remembered items leads to better memory performance if a memory test is used that taps the specific features that item representations accrue due to variable processing. We argued that in that study, variable processing served to skew memory representations toward semantic features highlighted by varying orienting questions and this process of stronger encoding of particular semantic features was termed "elaboration." However, this understanding of elaboration differs to some extent from how this concept is commonly understood. In the LTM literature, the concept of elaboration has been criticized for its vagueness (Lehman & Karpicke, 2016), bordering on circularity, where any manipulation introduced at encoding that leads to better subsequent memory is assigned to elaboration, which is in turn measured by better performance in a memory test. In the WM literature, elaboration is sometimes used as an explanatory term, but is usually understood narrowly as semantic processing and defined as strategic behavior participants may engage in lieu of various ineffective encoding strategies (Bailey et al., 2008, 2009; Dunlosky & Kane, 2007). As such, recent studies have suggested a limited role of elaboration in WM performance (Bartsch et al., 2018, 2019; Bartsch & Oberauer, 2021).

Here we argue that elaboration is a useful term for an umbrella of processes that lead to qualitative changes in memory representations that do not need to be strategic but can also be imposed by the local context in which study items are presented—be it an orienting question (e.g., Zawadzka et al., 2021) or distractors accompanying the to-be-remembered items. We also argue that elaboration need not be semantic in nature. Although our study used a semantic manipulation of target-distractor similarity, our WM results closely followed the results obtained by Oberauer, Farrell, et al. (2012), who manipulated phonological similarity. Because we argue that the same mechanisms are in operation in both of these studies, it is plausible that elaboration can also concern nonsemantic features. Indeed, work on the transfer-appropriate processing framework (Morris et al., 1977) has long established that memory representations can be elaborated both in terms of semantic and nonsemantic features, leading to variable results depending on whether a particular memory test is sensitive to features that had been encoded (Blaxton, 1989). This understanding of elaboration means that the use of the concept allows for specific predictions of how encoding can be changed by strategic and nonstrategic factors and how any such changes would be detectable in appropriately tailored memory tests, avoiding the criticism of circularity (Lehman & Karpicke, 2016).

The point of departure for the present work was a consideration of the extent to which WM and LTM share common processes, determining whether the mechanisms underlying WM can be adopted to understand the dynamics of LTM. This situates our work within a recently renewed discussion about the extent to which two separate systems are necessary to describe memory functioning at short and long delays (Abadie & Camos, 2019; Humphreys et al., 2020; Loaiza & Camos, 2018; Oberauer & Greve, 2022). A twofold interpretation of our results in this context is possible. There are models that assume separate constructs to explain memory performance across short and long timescales, often referred to as primary and secondary memory (Unsworth & Engle, 2007). In this formulation, it has already been argued that the contribution of secondary memory to WM performance can be described in terms of context-dependent processes (Unsworth & Engle, 2006). If such an account is adopted, then the present results provide additional evidence for the contribution of LTM (or secondary memory) to performance in the WM task, despite the latter measuring memory performance in a short term. This can be gleaned not only from the fact that target-distractor similarity affected LTM and WM performance in the same way, but also from the results of Experiment 2, in which the presence of WM testing affected LTM performance. As argued by Rose et al. (2014), such testing effects are a signature effect of retrieval from LTM and, thus, they confirm that performance in the WM task depends on secondary memory.

A simpler interpretation of our results, however, is that the same mechanisms operate at the stage of memory processing across short and long terms, or even—deriving an ultimate conclusion from the assumption of shared mechanisms—that there is only one episodic memory system, governed by the dynamics of continuous storage of superimposed item-context bindings. Indeed, as already argued, the reinterpretation of positional cues in terms of context links the present work with the retrieved-context models, which explicitly assume that a large number of memory phenomena can be described by a unitary model of memory, with contextual representations serving the role usually played by a short-term memory (STM) store (see Howard & Kahana, 2002; Logan, 2021, for a discussion)—explaining how access to memory information is lost due to context drift between encoding and retrieval and how items neighboring one another in a study list appear to become associated by the virtue of shared associated contextual representations.

This assumption of a unitary memory system requires an auxiliary assumption, by which memory processes can operate across different sets of codes, or—in other words—in different representational domains. The discussion of the previous studies on target-distraction similarity can serve as an example here. Oberauer (2009) introduced the paradigm we used in the present study—with words as study materials—and manipulated both semantic and phonological target-distractor similarity. In Oberauer's study, only the effects of the semantic manipulation were revealed, and we built on these results here. Phonological target-distractor similarity failed to affect WM performance, but its effects were revealed in a subsequent study by Oberauer, Farrell, et al. (2012) who used nonwords as study materials. According to Oberauer, Farrell et al., this discrepancy can be explained by participants using semantic coding for words and phonological coding for nonwords. Arguably, strengthening contextual bindings for phonological features through the target-distractor similarity effects of the sort described here would not affect performance when participants rely on semantic cues to reconstruct the study list. However, the underlying mechanism of superposition should be the same independent of how items are coded in the WM task. If participants encode targets in terms of their semantic features, then bindings of such semantic features to context can be strengthened by using semantically similar distractors, but if participants encode targets in terms of phonological features, then only bindings of such phonological features can be strengthened. The assumption of a unitary memory system does not imply that dissociations across WM and LTM systems are impossible. Instead, dissociations can be understood in terms of various features that are encoded and subsequently accessed during retrieval, and then subjected to the operations of a unitary set of mechanisms. Our findings show that superposition is one such mechanism, shaping both WM and LTM performance, serving as a demonstration of the power of this unitary approach.

Conclusion

The present study demonstrated how a mechanism recognized as one reason for which information is lost from WM—interference by superposition of context-to-item bindings across targets and distractors that follow them—can also explain patterns of performance in a test of LTM. When similar distractors follow targets in the complex-span task, shared features of these distractors and targets become strongly bound to context, augmenting subsequent LTM performance in a test tapping these shared features. We termed this change in memory representations induced by processing distraction elaboration by superposition, arguing that elaboration can be understood as the process of change in the encoded features that need not be a result of a strategic approach to the encoding task. The fact that a common mechanism can be traced back as underlying both WM and LTM performance suggests that a unitary approach to memory processes can serve as the basis of new insights into how memory operates across various delays.

References

Abadie, M., & Camos, V. (2019). False memory at short and long term. *Journal of Experimental Psychology: General*, *148*(8), 1312–1334. https://doi.org/10.1037/xge0000526

Bailey, H., Dunlosky, J., & Hertzog, C. (2009). Does differential strategy use account for age-related deficits in working-memory performance? *Psychology and Aging*, *24*(1), 82–92. https://doi.org/10.1037/a0014078

Bailey, H., Dunlosky, J., & Kane, M. J. (2008). Why does working memory span predict complex cognition? Testing the strategy affordance hypothesis. *Memory & Cognition*, *36*(8), 1383–1390. https://doi.org/10.3758/MC.36.8.1383

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, *133*(1), 83–100. https://doi.org/10.1037/0096-3445.133.1.83

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(3), 570–585. https://doi.org/10.1037/0278-7393.33.3.570

Bartsch, L. M., Loaiza, V. M., Jäncke, L., Oberauer, K., & Lewis-Peacock, J. A. (2019). Dissociating refreshing and elaboration and their impacts on memory. *NeuroImage*, *199*, 585–597. https://doi.org/10.1016/j.neuroimage.2019.06.028

Bartsch, L. M., & Oberauer, K. (2021). The effects of elaboration on working memory and long-term memory across age. *Journal of Memory and Language*, *118*, 104215. https://doi.org/10.1016/j.jml.2020.104215

Bartsch, L. M., Singmann, H., & Oberauer, K. (2018). The effects of refreshing and elaboration on working memory performance, and their contributions to long-term memory formation. *Memory & Cognition*, *46*(5), 796–808. https://doi.org/10.3758/s13421-018-0805-9

Bayliss, D. M., Jarrold, C., Gunn, D. M., & Baddeley, A. D. (2003). The complexities of complex span: Explaining individual differences in working memory in children and adults. *Journal of Experimental Psychology: General*, *132*(1), 71–92. https://doi.org/10.1037/0096-3445.132.1.71

Blaxton, T. A. (1989). Investigating dissociations among memory measures: Support for a transfer-appropriate processing framework. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(4), 657–668. https://doi.org/10.1037/0278-7393.15.4.657

Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review*, *106*(3), 551–581. https://doi.org/10.1037/0033-295X.106.3.551

Conlin, J. A., Gathercole, S. E., & Adams, J. W. (2005). Stimulus similarity decrements in children's working memory span. *Quarterly Journal* *of Experimental Psychology*, *58*(8), 1434–1446. https://doi.org/10.1080/02724980443000683

Craik, F. I. M., & Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology: General*, *104*(3), 268–294. https://doi.org/10.1037/0096-3445.104.3.268

Craik, F. I., & Watkins, M. J. (1973). The role of rehearsal in short-term memory. *Journal of Verbal Learning and Verbal Behavior*, *12*(6), 599–607. https://doi.org/10.1016/S0022-5371(73)80039-8

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*(4), 450–466. https://doi.org/10.1016/S0022-5371(80)90312-6

Davis, O. C., Geller, A. S., Rizzuto, D. S., & Kahana, M. J. (2008). Temporal associative processes revealed by intrusions in paired-associate recall. *Psychonomic Bulletin & Review*, *15*(1), 64–69. https://doi.org/10.3758/PBR.15.1.64

Dunlosky, J., & Kane, M. J. (2007). The contributions of strategy use to working memory span: A comparison of strategy assessment methods. *Quarterly Journal of Experimental Psychology*, *60*(9), 1227–1245. https://doi.org/10.1080/17470210600926075

Estes, W. K. (1955). Statistical theory of spontaneous recovery and regression. *Psychological Review*, *62*(3), 145–154. https://doi.org/10.1037/h0048509

Greene, R. L. (1987). Effect of maintenance rehearsal on human memory. *Psychological Bulletin*, *102*(3), 403–413. https://doi.org/10.1037/0033-2909.102.3.403

Hanczakowski, M., Beaman, C. P., & Jones, D. M. (2017). When distraction benefits memory through semantic similarity. *Journal of Memory and Language*, *94*, 61–74. https://doi.org/10.1016/j.jml.2016.11.005

Healey, M. K. (2018). Temporal contiguity in incidentally encoded memories. *Journal of Memory and Language*, *102*, 28–40. https://doi.org/10.1016/j.jml.2018.04.003

Howard, M. W., & Kahana, M. J. (2002). A distributed representation of temportal context. *Journal of Mathematical Psychology*, *46*, 269–299. https://doi.org/10.1006/jmps.2001.1388

Humphreys, M. S., Tehan, G., Baumann, O., & Loft, S. (2020). Explaining short-term memory phenomena with an integrated episodic/semantic framework of long-term memory. *Cognitive Psychology*, *123*, 101346. https://doi.org/10.1016/j.cogpsych.2020.101346

Hunt, R. R., & Einstein, G. O. (1981). Relational and item-specific information in memory. *Journal of Verbal Learning and Verbal Behavior*, *20*(5), 497–514. https://doi.org/10.1016/S0022-5371(81)90138-9

Kowialiewski, B., Lemaire, B., Majerus, S., & Portrat, S. (2021). Can activated long-term memory maintain serial order information? *Psychonomic Bulletin & Review*, *28*(4), 1301–1312. https://doi.org/10.3758/s13423-021-01902-3

Lehman, M., & Karpicke, J. D. (2016). Elaborative retrieval: Do semantic mediators improve memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(10), 1573–1591. https://doi.org/10.1037/xlm0000267

Lewandowsky, S., Geiger, S. M., Morrell, D. B., & Oberauer, K. (2010). Turning simple span into complex span: Time for decay or interference from distractors? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(4), 958–978. https://doi.org/10.1037/a0019764

Lewandowsky, S., & Oberauer, K. (2008). The word-length effect provides no evidence for decay in short-term memory. *Psychonomic Bulletin & Review*, *15*(5), 875–888. https://doi.org/10.3758/PBR.15.5.875

Lewandowsky, S., & Oberauer, K. (2009). No evidence for temporal decay in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(6), 1545–1551. https://doi.org/10.1037/a0017010

Lilienthal, L., Hale, S., & Myerson, J. (2014). The effects of environmental support and secondary tasks on visuospatial working memory. *Memory & Cognition*, *42*(7), 1118–1129. https://doi.org/10.3758/s13421-014-0421-2

Loaiza, V. M., & Camos, V. (2018). The role of semantic representations in verbal working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *44*(6), 863–881. https://doi.org/10.1037/xlm0000475

Loaiza, V. M., & Lavilla, E. T. (2021). Elaborative strategies contribute to the long-term benefits of time in working memory. *Journal of Memory and Language*, *117*, 104205. https://doi.org/10.1016/j.jml.2020.104205

Loaiza, V. M., & McCabe, D. P. (2012). Temporal-contextual processing in working memory: Evidence from delayed cued recall and delayed free recall tests. *Memory & Cognition*, *40*(2), 191–203. https://doi.org/10.3758/s13421-011-0148-2

Logan, G. D. (2021). Serial order in perception, memory, and action. *Psychological Review*, *128*(1), 1–44. https://doi.org/10.1037/rev0000253

Logan, G. D., & Cox, G. E. (2021). Serial memory: Putting chains and position codes in context. *Psychological Review*, *128*(6), 1197–1205. https://doi.org/10.1037/rev0000327

Lohnas, L. J., Polyn, S. M., & Kahana, M. J. (2015). Expanding the scope of memory search: Modeling intralist and interlist effects in free recall. *Psychological Review*, *122*(2), 337–363. https://doi.org/10.1037/a0039036

McCabe, D. P. (2008). The role of covert retrieval in working memory span tasks: Evidence from delayed recall tests. *Journal of Memory and Language*, *58*(2), 480–494. https://doi.org/10.1016/j.jml.2007.04.004

Mensink, G.-J. M., & Raaijmakers, J. G. W. (1988). A model for interference and forgetting. *Psychological Review*, *95*(4), 434–455. https://doi.org/10.1037/0033-295X.95.4.434

Morris, C. D., Bransford, J. D., & Franks, J. J. (1977). Levels of processing versus transfer appropriate processing. *Journal of Verbal Learning and Verbal Behavior*, *16*(5), 519–533. https://doi.org/10.1016/S0022-5371(77)80016-9

Mundorf, A. M. D., Lazarus, L. T. T., Uitvlugt, M. G., & Healey, M. K. (2021). A test of retrieved context theory: Dynamics of recall after incidental encoding. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *47*(8), 1264–1287. https://doi.org/10.1037/xlm0001001

Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, *18*(3), 251–269. https://doi.org/10.3758/BF03213879

Naveh-Benjamin, M., & Brubaker, M. S. (2019). Are the effects of divided attention on memory encoding processes due to the disruption of deep-level elaborative processes? Evidence from cued- and free-recall tasks. *Journal of Memory and Language*, *106*, 108–117. https://doi.org/10.1016/j.jml.2019.02.007

Oberauer, K. (2009). Interference between storage and processing in working memory: Feature overwriting, not similarity-based competition. *Memory & Cognition*, *37*(3), 346–357. https://doi.org/10.3758/MC.37.3.346

Oberauer, K., Farrell, S., Jarrold, C., & Lewandowsky, S. (2016). What limits working memory capacity? *Psychological Bulletin*, *142*(7), 758–799. https://doi.org/10.1037/bul0000046

Oberauer, K., Farrell, S., Jarrold, C., Pasiecznik, K., & Greaves, M. (2012). Interference between maintenance and processing in working memory: The effect of item-distractor similarity in complex span. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(3), 665–685. https://doi.org/10.1037/a0026337

Oberauer, K., & Greve, W. (2022). Intentional remembering and intentional forgetting in working and long-term memory. *Journal of Experimental Psychology: General*, *151*(3), 513–541. https://doi.org/10.1037/xge0001106

Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory and Language*, *55*(4), 601–626. https://doi.org/10.1016/j.jml.2006.08.009

Oberauer, K., Lange, E., & Engle, R. W. (2004). Working memory capacity and resistance to interference. *Journal of Memory and Language*, *51*(1), 80–96. https://doi.org/10.1016/j.jml.2004.03.003

Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review*, *19*(5), 779–819. https://doi.org/10.3758/s13423-012-0272-4

Page, M., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review*, *105*(4), 761–781. https://doi.org/10.1037/0033-295X.105.4.761-781

Polyn, S. M., Norman, K. A., & Kahana, M. J. (2009). A context maintenance and retrieval model of organizational processes in free recall. *Psychological Review*, *116*(1), 129–156. https://doi.org/10.1037/a0014420

Portrat, S., Barrouillet, P., & Camos, V. (2008). Time-related decay or interference-based forgetting in working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(6), 1561–1564. https://doi.org/10.1037/a0013356

Ricker, T. J., Sandry, J., Vergauwe, E., & Cowan, N. (2020). Do familiar memory items decay? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(1), 60–76. https://doi.org/10.1037/xlm0000719

Rose, N. S., Buchsbaum, B. R., & Craik, F. I. M. (2014). Short-term retention of a single word relies on retrieval from long-term memory when both rehearsal and refreshing are disrupted. *Memory & Cognition*, *42*(5), 689–700. https://doi.org/10.3758/s13421-014-0398-x

Saito, S., & Miyake, A. (2004). On the nature of forgetting and the processing–storage relationship in reading span performance. *Journal of Memory and Language*, *50*(4), 425–443. https://doi.org/10.1016/j.jml.2003.12.003

Schwartz, G., Howard, M. W., Jing, B., & Kahana, M. J. (2005). Shadows of the past: Temporal retrieval effects in recognition memory. *Psychological Science*, *16*(11), 898–904. https://doi.org/10.1111/j.1467-9280.2005.01634.x

Soemer, A. (2019). Task-unrelated thoughts and forgetting in working memory. *Journal of Memory and Language*, *106*, 118–134. https://doi.org/10.1016/j.jml.2019.03.004

Souza, A. S., & Oberauer, K. (2017). Time to process information in working memory improves episodic memory. *Journal of Memory and Language*, *96*, 155–167. https://doi.org/10.1016/j.jml.2017.07.002

Towse, J. N., Hitch, G. J., & Hutton, U. (2000). On the interpretation of working memory span in adults. *Memory & Cognition*, *28*(3), 341–348. https://doi.org/10.3758/BF03198549

Tulving, E., & Pearlstone, Z. (1966). Availability versus accessibility of information in memory for words. *Journal of Verbal Learning and Verbal Behavior*, *5*(4), 381–391. https://doi.org/10.1016/S0022-5371(66)80048-8

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*(2), 127–154. https://doi.org/10.1016/0749-596X(89)90040-5

Unsworth, N. (2008). Exploring the retrieval dynamics of delayed and final free recall: Further evidence for temporal-contextual search. *Journal of Memory and Language*, *59*(2), 223–236. https://doi.org/10.1016/j.jml.2008.04.002

Unsworth, N., & Engle, R. W. (2006). A temporal-contextual retrieval account of complex span: An analysis of errors. *Journal of Memory and Language*, *54*(3), 346–362. https://doi.org/10.1016/j.jml.2005.11.004

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*(1), 104–132. https://doi.org/10.1037/0033-295X.114.1.104

Vergauwe, E., Barrouillet, P., & Camos, V. (2009). Visual and spatial working memory are not that dissociated after all: A time-based resource-sharing account. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(4), 1012–1028. https://doi.org/10.1037/a0015859

Wagenmakers, E.-J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Selker, R., Gronau, Q. F., Dropmann, D., Boutin, B., Meerhoff, F., Knight, P., Raj, A., van Kesteren, E.-J., van Doorn, J., Šmíra, M., Epskamp, S., Etz, A., Matzke, D., . . . Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review*, *25*(1), 58–76. https://doi.org/10.3758/s13423-017-1323-7

Watkins, O. C., & Watkins, M. J. (1975). Buildup of proactive inhibition as a cue-overload effect. *Journal of Experimental Psychology: Human Learning and Memory*, *1*(4), 442–452. https://doi.org/10.1037/0278-7393.1.4.442

Zawadzka, K., Baloro, S., Wells, J., Wilding, E. L., & Hanczakowski, M. (2021). On the memory benefits of repeated study with variable tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *47*(7), 1067–1082. https://doi.org/10.1037/xlm0001013

(*Appendix follows*)

Appendix

Conditional Analyses of Cued-Recall Results

To confirm that the relatedness effects in cued-recall were not due to carry-over effects from serial recall, following Loaiza and Lavilla (2021) we ran additional analyses on cued-recall data conditionalized on recall success in the immediate serial-recall test. Here we present analyses of cued-recall results narrowed down to items that were correctly recalled before the cued-recall test (as indicated by the item-scoring method). Descriptive statistics for the resulting data are presented in Table A1.

Paired samples *t* tests for items that were successfully recalled in the serial-recall test revealed that performance was higher when distraction was related than unrelated in Experiment 1a, $t(29) = 4.04$, $p < .001$, $d = .74$, and Experiment 1b, $t(30) = 2.96$, $p = .006$, $d = .53$, but no significant differences were detected in Experiment 2, $t(29) = 1.82$, $p = .079$, $d = .33$, and Experiment 3, $t(29) = 1.91$, $p = .07$, $d = .35$. Also, a one-way within-participants ANOVA revealed significant differences between conditions in Experiment 4, $F(2, 58) = 139.69$, $MSE = 1.532$, $p < .001$, $\eta^2 = .82$, with post hoc comparisons showing significant advantage of related distraction over unrelated distraction, $t(29) = 3.28$, $p = .003$, $d = .60$, and over no distraction, $t(29) = 17.25$, $p < .001$, $d = 3.15$, as well as an advantage of unrelated distraction over no distraction, $t(29) = 12.47$, $p < .001$, $d = 2.77$.

Table A1

Mean Proportions of Correctly Recalled Items in the LTM Category-Cued Recall Task in Experiments 1a-4 Conditionalized on Whether Items Were Initially Correctly Recalled in the WM Serial Recall Task

	Previously recalled			Previously not recalled		
Experiment	Related distraction	Unrelated distraction	No distraction	Related distraction	Unrelated distraction	No distraction
Experiment 1a	.62 (.17)	.52 (.16)	—	.22 (.14)	.16 (.12)	—
Experiment 1b	.71 (.16)	.59 (.18)	—	.40 (.16)	.33 (.19)	—
Experiment 2	.69 (.15)	.66 (.15)	—	.26 (.20)	.20 (.16)	—
Experiment 3	.59 (.20)	.55 (.19)	—	.23 (.19)	.22 (.18)	—
Experiment 4	.72 (.14)	.63 (.17)	.29 (.16)	.21 (.12)	.24 (.14)	.19 (.29)

Note. Standard deviations are given in parentheses. LTM = long-term memory; WM = working memory.

Received November 8, 2021
Revision received June 24, 2022
Accepted August 20, 2022 ■

Warszawa, dnia 27.02.2024

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy

Piątkowski, K., von Bastian, C. C., Zawadzka, K., & Hanczakowski, M. (2023). Elaboration by superposition: From interference in working memory to encoding in long-term memory. Journal of Experimental Psychology: Learning, Memory, and Cognition, 49(3), 371–388.

mój udział polegał na konceptualizacji przedmiotu badań i opracowaniu ich metodologii, zaprogramowaniu i przeprowadzeniu eksperymentów, rozpowszechnianiu wyników badań i napisaniu pierwszej wersji manuskryptu. Mój udział w powstaniu pracy wynosi 60%.

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Podpis

Co-authorship statement

Piątkowski, K., von Bastian, C. C., Zawadzka, K., & Hanczakowski, M. (2023). Elaboration by superposition: From interference in working memory to encoding in long-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 49,* 371-388.

We declare that the authors' contribution to the manuscript, according to the CRediT scheme, comprised the following:

Krzysztof Piątkowski: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft

Claudia C. von Bastian: Conceptualization, Methodology, Writing – review & editing

Katarzyna Zawadzka: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing

Maciej Hanczakowski: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing

We also declare that Mr. Krzysztof Piątkowski's percentage contribution to the study was 60%.

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JOURNAL OF COGNITIVE PSYCHOLOGY
https://doi.org/10.1080/20445911.2024.2313570

Forgetting during interruptions: the role of goal similarity

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ABSTRACT

Resuming an interrupted task requires remembering the goals that governed behaviour immediately before the interruption. Here we examined whether forgetting of goals can be mitigated when goals of both the interrupting and the interrupted task are related. Participants performed a sequence task with operations denoted by letters. This task was occasionally interrupted by a secondary task, also involving letter processing. The hypotheses were that resumption of the primary task would be facilitated if, within the interrupting task, either the letters processed (Experiment 1) or the operations denoted by these letters (Experiment 2) matched the goals immediately preceding the interruption. There were fewer errors at resumption when the letters processed or the operations performed used letters processed immediately before the interruption compared to a random letter from the sequence task. These results indicate that forgetting of goals is moderated by the similarity of the goals pursued across interrupting and interrupted tasks.

ARTICLE HISTORY
Received 10 April 2023
Accepted 6 December 2023

KEYWORDS
Interruptions; memory for goals; rehearsal; interference

Interruptions are a ubiquitous feature of today's lives. Any complex behaviour we engage in, ranging from trivial chores of everyday life to performing demanding tasks in safety-critical environments—for example in health care, transport or control-centre settings—is likely to be at least occasionally interrupted by various types of electronic alerts, phone calls, or other manifestations of increased social interconnectedness and associated demand for our attention from other people. As a result, our performance in the primary, interrupted task often suffers from the requirement to engage in a secondary task such as fending off some call for our attention. Research has amply documented that interruptions lead to costs in the form of not only slowing down when the main task needs to be resumed (Hodgetts & Jones, 2006a; 2006b; Labonté et al., 2019; Monk et al., 2004; Radović & Manzey, 2019; see Trafton & Monk, 2007), but also increased chances of committing errors in the primary task (Altmann et al., 2014; 2017; Altmann & Hambrick, 2017; Li et al., 2008). But are all interruptions created equal? Does it matter for the performance in the primary task what kind of a secondary task is performed during the interruption interval? Here we aimed to assess the hypothesis that contents of the interrupting task do matter. Specifically, we investigated the possibility that some secondary tasks—those having similar goals to the ones that govern the primary task—reduce the negative impact an interruption might otherwise have.

The most common way of investigating the impact of interruptions is to give participants a procedural task that requires them to perform a set of subtasks in a particular order and then occasionally interrupt this primary task by a requirement to complete a certain secondary task. Of interest then is how the requirement to complete the secondary task affects performance in the primary task for a subtask immediately following the resumption of the primary task, compared to standard subtasks

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not preceded by an interruption. The most common observation from employing this kind of paradigm is that it takes longer to perform a subtask immediately after an interruption—a so-called resumption lag (e.g. Hodgetts & Jones, 2006a, 2006b; Trafton et al., 2003). While this extended time necessary to perform the primary task obviously constitutes a cost to performance, such a cost is not unique to the case of interruptions. A literature on task switching (see Koch et al., 2010, for a review)—a case in which two consecutive subtasks are either changed or switched in the course of performing a procedural task—documents the cases of extended reaction times after task switches, and it could be argued that interruptions are a special case of task switching (see Hirsch et al., 2023, for a more detailed discussion). Here resuming the primary task after an interruption would mean switching from a task set of the secondary to the primary task, generating a task switch cost that is absent when the primary task continues uninterrupted. However, recent advances in research on the impact of task interruptions tend to focus on a unique signature of interruptions—not only do they slow down performance at resumption of the primary task, but also lead to a number of errors, and more specifically sequence errors that manifest in participants performing an incorrect subtask when the primary task is resumed.

The focus on sequence errors due to interruptions to procedural task has gained prominence with the development of a novel paradigm by Altmann et al. (2014). In the UNRAVEL task, participants are asked to perform a sequence task with seven different subtasks. Participants see displays consisting of a central frame and two characters, one letter and one digit. For each display, participants need to perform a single operation such as deciding whether a letter in a particular display is underlined or in italics, or deciding whether a digit is even or odd. Importantly, the seven to-be-performed subtasks are described by unique letters that together give rise to the acronym UNRAVEL. So, for example, the underlined-or-in-italics operation is denoted by the letter U, while the even-or-odd operation is denoted by the letter E. There are seven unique operations and participants are instructed to perform them in the sequence defined by the UNRAVEL acronym, starting with the U operation and going back to the U operation after performing the L operation. To perform this task, participants need to mentally keep track of their position in the sequence of subtasks.

Crucially, in the UNRAVEL paradigm participants are sometimes interrupted while performing the primary sequence task, immediately after performing a random subtask. During interruptions, participants are asked to perform a secondary task such as copying letters or digits displayed on the computer screen. Altmann et al. (2014) showed that such interruptions—even if only very brief, lasting less time than one operation in the primary task, and simple, requiring participants merely to copy two characters—lead to a significant decrement in performance in the primary task as evidenced by an increase in the rate of sequence errors (performing an incorrect subtask) at resumption.

Given the robust effects of interruptions on sequence errors observed in the UNRAVEL task, the question to be asked is what factors determine the rates of those errors. What are the conditions under which one is particularly likely to err on the subtask one is supposed to perform immediately after an interruption? Not surprisingly, research on this topic has so far been inspired by previous studies focused on interruption costs in the form of resumption lags. Altmann et al. (2014; see also Altmann et al., 2017) assessed the effect of the duration of interruptions and found that longer interruptions lead to more sequence errors when the task is resumed, paralleling findings from studies examining resumption lags (e.g. Monk et al., 2008). Radović and Manzey (2022), with a German adaptation of the UNRAVEL task, examined the complexity of the cognitive operations performed during interruptions and found that more complex operations increase the rate of sequence errors at resumption, again paralleling the patterns observed for resumption lags (e.g. Cades et al., 2007; Hodgetts & Jones, 2006a; Monk et al., 2008). However, Radović and Manzey also examined another factor, which previous studies (Ratwani et al., 2008) suggested was a determinant of interruption-dependent impairment—similarity between the primary and the interruption task. The focus here was on similarity in terms of the types of material processed. The adapted UNRAVEL task engaged verbal codes, and the interruption tasks were manipulated to require processing of either verbal or spatial information. In two experiments, Radović and Manzey found no evidence that similar codes across the primary and the interruption tasks increase the rate of sequence errors at resumption.

The main question driving the present study is also concerned with the role of similarity between the primary and interrupting tasks in determining the disruptiveness of interruptions. However, rather than focus on particular material or codes engaged in different tasks, we were interested in a more direct similarity between the goals behind a particular subtask in the primary sequence task on the one hand and those behind the secondary task performed during the interruption on the other.

To understand this kind of similarity relationships, it is necessary first to describe the theoretical apparatus specifically proposed by Altmann and Trafton (2015; see also Altmann et al., 2017) to describe the mechanisms of interruption-related impairment in a sequence task such as the one used in the UNRAVEL paradigm. The assumption of this framework is that performance in a sequence task engages two memory systems, semantic and episodic memory. First, the sequence is stored in semantic memory and performing any subtask from this sequence (e.g. U) automatically primes all other subtasks, with a diminishing gradient as activation spreads from the next subtask (N), then the one after that (R), and so on. When the interruption occurs (after U), this activation of all primed subtasks fades, most markedly for the correct to-be-performed subtask (N) that was activated to the greatest extent. This fading means that, following the interruption, the priming of the correct subtask is lower than it would be without the interruption and this may sometimes lead to participants erroneously choosing the next most activated subtask (R), resulting in the error of skipping one subtask. Indeed, the analysis of sequence errors in Altmann et al. (2017) showed that such errors of skipping, referred to here as errors of the lag +1, were markedly more frequent than errors of different lags. However, one exception was the rate of errors of the lag −1, repetitions of the already performed subtask, which were actually the most frequent of all sequence errors.

To account for lag −1 errors, the framework postulates a crucial involvement of an episodic memory system. Altmann and Trafton (2015) proposed that participants maintain the last operation they needed to perform in their episodic memory. Once the interruption ends, they use this episodic memory representation—in conjunction with their memory representation of the entire sequence—to derive the next to-be-performed subtask. However, even a short delay (such as that caused by an interruption) allows for some forgetting of episodic representations, which could result in erroneous retrieval not of the last performed subtask but the one which immediately preceded it. This erroneous retrieval misleads participants into repeating the last subtask once the primary sequence task is resumed after the interruption—making an error of lag −1. Crucially, in this model, forgetting of episodic representations is due to a process of decay—episodic representation is forgotten as a function of the duration of the interruption. This accounts for a common observation that longer interruptions are more disruptive than shorter ones (Monk et al., 2008), also in terms of resulting sequence errors (Altmann et al., 2017).

The ubiquity of sequence errors with lag −1 in the UNRAVEL task points to the crucial importance of an episodic memory system in dealing with interruption costs. In the formulation of an influential memory-for-goals framework (Altmann & Trafton, 2002), dealing with an interruption requires holding in episodic memory a goal that was achieved just before the interruption, while pursuing the goal of the secondary task. However, it is worth noting that even long interruptions, simultaneously maximising the fading of priming in semantic memory and the decay of goals in episodic memory, do not lead to particularly high levels of sequence errors at resumption. From this, it is clear that a compensatory mechanism must be upholding the activation of goals during interruptions. Many current theories of working memory (an episodic system for storing information for a short period of time) assume that forgetting is at least to some extent counteracted by restorative processes, such as rehearsal of verbal information (i.e., subvocal repetition of to-be-remembered information, Lucidi et al., 2016) or attentional refreshing (i.e., a brief re-orientation of attention to to-be-remembered information that serves to strengthen its memory representation, Camos et al., 2009). In relation to interruptions, Altmann et al. (2017) argued that decay of episodic representations of the last performed operation is minimised—and thus errors of repetition at resumption at least some extent avoided—because during interruptions the last performed operation is actively rehearsed. A questionnaire administered to participants who performed the UNRAVEL task revealed that 83% of them reported the use of rehearsal strategy in this task.

The outline of the theory of sequence errors in the interruption task developed by Altmann and Trafton (2015) allows the formulation of predictions as to how similarity across the primary sequence task and the interruption task may affect the costs of interruptions. This theory explains why similarity in terms of engaged codes—verbal vs. semantic—seems not to matter, as shown by Radović and Manzey (2022). Within currently prominent models of working memory that assume forgetting via decay, such as the time-based resource-sharing model of Barrouillet et al. (2004), forgetting is solely a function of the proportion of time for which an attentional bottleneck is engaged by a distracting task. During this time, attention cannot be devoted to operations of rehearsal and/or refreshing that would support decaying representations. From this, it follows that more complex secondary tasks should exacerbate interruption costs, because they demand more processing time and thus maximise forgetting of goals from episodic memory, but no effect of similarity in terms of codes is to be expected (consistent with the results obtained by Radović & Manzey, 2022). The restorative processes engaged in supporting decaying goal representations do leave open a gate for the role of similarity, however: more specifically, the similarity of goals across the primary and secondary tasks. If an active strategy of maintaining the last realised goal contributes to performance in the primary task, then it seems likely that the secondary task performed during the interruption could facilitate this process if it employs representations that are the same as to-be-rehearsed representations from the primary task. In other words, assume that participants strive to remember either the letter that denotes the subtask they had just performed before the interruption occurred, or a specific cognitive operation required by this subtask. In this case, a secondary task that requires processing of that very same letter, or performing the very same kind of task, could facilitate setting up of the rehearsal process and thus more effectively counter decay in episodic memory, reducing the rate of repetition errors once the sequence task is resumed. For example, if participants who have just completed the subtask indicated by the letter "E" in the UNRAVEL task are required to process the same letter during the interruption, it is less likely that "E" will decay and be forgotten during that period. Thus, when the interruption is ended, "E" will be available to return to.

In the current study, we assessed the role of similarity between representations processed during interruptions and those of the subtasks of the primary sequence task. We adapted the UNRAVEL task into Polish by developing a different acronym encompassing a set of seven operations—MILONGA. In Experiment 1 the secondary task introduced multiple trials of a visual search task during the interruption period. In this task, participants were asked to find a letter that defined one of the four experimental conditions. In the *other* condition, the sought-for letter was not used in the MILONGA task. In the *random* condition, the sought-for letter was one of the letters denoting a subtask of the MILONGA task, but it was never either of the letters referring to the subtasks that preceded or followed the interruption. In the *pre-interruption* condition, the sought-for letter was the letter that denoted the subtask participants performed before the interruption. In the *post-interruption* condition, the sought-for letter was the letter that denoted the subtask participants should perform after the interruption. Experiment 2 used a similar procedure but instead of performing a visual search task for letters, participants were instructed to perform the operations required in the subtasks denoted by these letters in the sequence task.

The main focus of the study was the comparison of the pre-interruption condition to the remaining conditions. We hypothesised that if, when interrupted, participants try to maintain their position within the MILONGA sequence by rehearsing the letter denoting the last performed subtask, then the processing of the same letter within the secondary task should facilitate this rehearsal process in the pre-interruption condition of Experiment 1, reducing the rate of sequence errors once the primary task is resumed. Similarly, performing the very subtask denoted by the same letter in Experiment 2 should facilitate the rehearsal process, reducing the rate of sequence errors once the primary task is resumed. Given that the contribution of episodic memory to dealing with interruptions is evidenced by the number of lag −1 sequence errors at resumption, we would expect that facilitated rehearsal would specifically reduce the rate of such errors.

Experiment 1

Method

Participants. Sixty participants were recruited via the Prolific platform and performed the task online in exchange for monetary compensation. Two participants were excluded for not following task instructions. Thus, the final sample consisted of fifty-eight participants (age: $M = 26$, $SD = 7.1$; gender: 36 males, 22 females). The study was approved by the ethics committee at the SWPS University (37/2018).

Materials. A Polish adaptation of the UNRAVEL task, employing the MILONGA acronym, was used in the present experiment. The task consisted of a series of displays, presenting a rectangular black frame on a white background, together with one letter and one digit. The letter and the digit were presented in two out of six possible locations on the screen: inside the frame, below it, or above it, and either on the left or the right, with the constraint that always one and only one character was displayed inside the frame and always one character was presented on the left and the other on the right side of the display (see Figure 1, for an example). The set of letters used consisted of A, B, Y, and Z, while the set of digits consisted of 2, 3, 7, and 8. Letters were presented either with an accent mark above it or in italics. One of the characters was always presented either in indigo or pink font, while the other was presented in black font. The subtasks participants were asked to perform were defined by the MILONGA acronym, which in translation required participants to decide whether: (1) M: the digit was smaller or greater than five, (2) I: one of the characters was presented in indigo or pink font, (3) L: a letter or a digit was presented on the left side of the frame, (4) O: a letter was close to or far from the beginning of the alphabet, (5) N: a digit was odd or even, (6) G: a character displayed outside the frame was above or below it, (7) A: a letter was presented with an accent mark or in italics. Participants provided their responses by pressing one of two response keys, of which one was always a letter from the MILONGA acronym that defined the particular subtask—for example, for the M operation the key M stood for *mniejsze*, meaning *lower* (here: than five) in Polish—while the other was a different unique letter (e.g. W for *większe*, or *higher*). Performing one subtask of the MILONGA task is described as a single experimental trial. The main sequence task was presented in six blocks, each consisting of 16 iterations of the acronym, which meant a total of 112 trials of the primary task in one block (672 trials total).

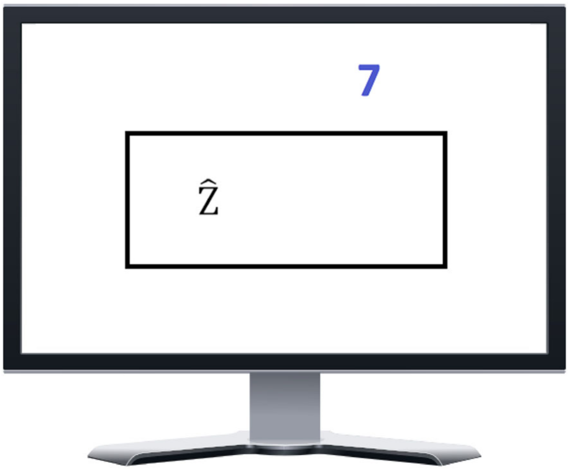

Figure 1. An example display from the MILONGA task showing an *odd* digit *greater than 5*, presented in *indigo* and *above* the frame, and a letter *close to the end* of the alphabet, presented on the *left* side of the display, and with an *accent*.

The main sequence task was occasionally interrupted by a secondary task. In the secondary task, participants were first presented with a single letter, displayed for two seconds, which they were then instructed to identify from among a set of four letters displayed simultaneously on the screen and numbered from one to four. The other letters in each display were taken from among letters not included in the MILONGA task or any of potential responses in sequence operations. The duration of the secondary task was set to 8 s, with as many self-paced search trials as fitted into this interval. The occurrence of interruptions was determined randomly, with each operation in the main sequence task having a 1 in 8 (12.5%) chance of being followed by an interruption. This meant that interruptions on average occurred a little less often than once per the MILONGA sequence, although there were no imposed limits of how many times one sequence could be interrupted. The type of the interruption —as described in the next section—was also determined randomly, which means that all experimental conditions were intermixed.

Design. A single independent variable was manipulated—the relationship between the to-be-identified letter in the secondary task to the just-performed operation in the MILONGA task. This variable had four levels, with the to-be-identified letter coming from outside responses possible in the MILONGA task (the *other* condition), being one of the seven letters comprising the MILONGA acronym but not matching the operation that was either performed just before or to be performed just after the interruption (the *random* condition),

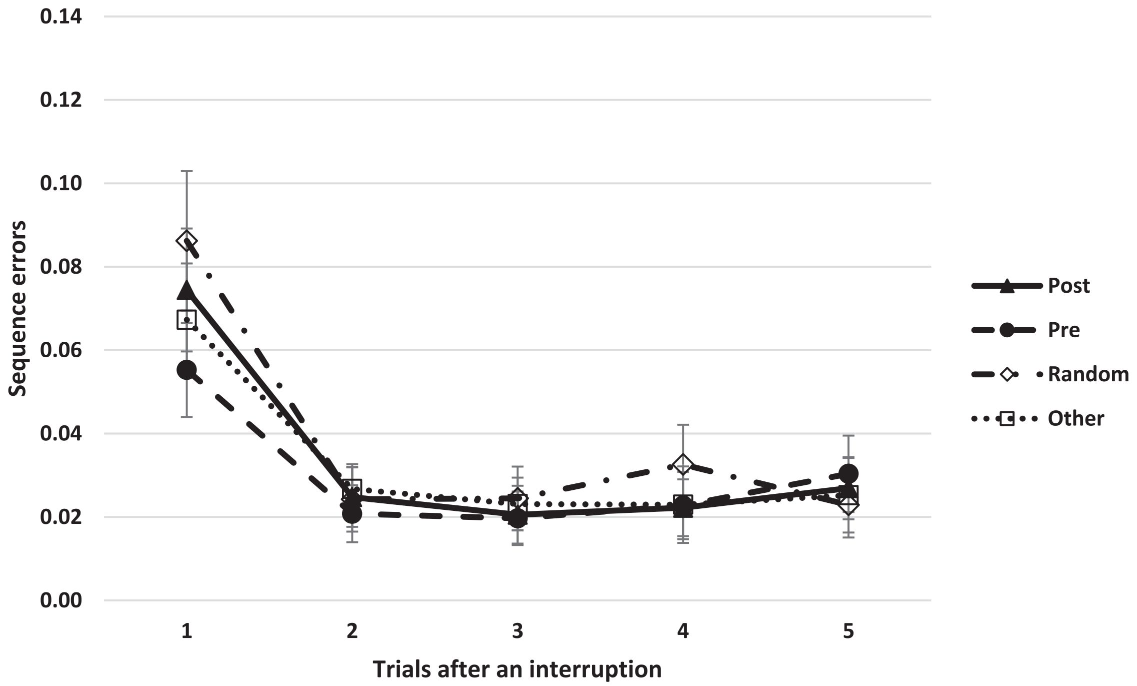

Figure 2. Proportions of sequence errors after resumption of the primary task (out of all responses made after resumption) as a function of experimental condition in Experiment 1. Error bars denote standard errors.

being the letter that denoted the operation performed just before the interruption (the *pre-interruption* condition), or being the letter that denoted the operation to be performed right after the interruption (the *post-interruption* condition). The main dependent variable was the rate of sequence errors in the trials of the main sequence task that immediately followed the interruptions.

Procedure. Before participants were asked to perform the main sequence task, a training session was administered, where they first learned the individual subtasks of the sequence task and then performed four cycles of seven trials of the task. During this training session, participants were also interrupted four times and asked to perform the secondary task. Participants were explicitly instructed that the purpose of the study was to assess their ability to resume the correct position of the sequence task after the interruption, for which they should depend on their memory only. After training, participants completed six blocks of the sequence task. Self-paced pauses in-between blocks were provided, during which the reminder of the subtasks and the corresponding answers were displayed.

Results and discussion

The rates of sequence errors following immediately after interruptions and in four subsequent subtasks are presented in Figure 2. It can be seen that sequence errors were committed mostly in trials immediately following an interruption, after which performance quickly levelled off. Given that the focus was on sequence errors caused by interruptions, the proportions of those errors on the first trial after interruption were analysed as a function of experimental condition (other, random, pre-interruption, post-interruption) with a one-way ANOVA, $F(3, 171) = 2.71$, $p = .047$, $\eta^2 = .045$, which showed that these conditions differed from each other. Post-hoc tests with Bonferroni corrections revealed that only one set of conditions reliably differed from one another—there were fewer sequence errors in the pre-interruption condition than in the random condition, $t(57) = 2.78$, $SE = .01$, $p = .036$, $d = 0.365$. All other comparisons were not significant (lowest $p = .536$).

Figure 3 presents a distribution of sequence errors made immediately after an interruption as a function of lag from the correct response, with lag −1 meaning a repetition of the operation that preceded the interruption and lag +1 meaning skipping one operation when the task was resumed after the interruption. Two things are of interest in the plot. First, it is apparent that for the pre-interruption and the random conditions the distribution of sequence errors peaks at lag −1, with the other conditions showing a less pronounced peak. While this

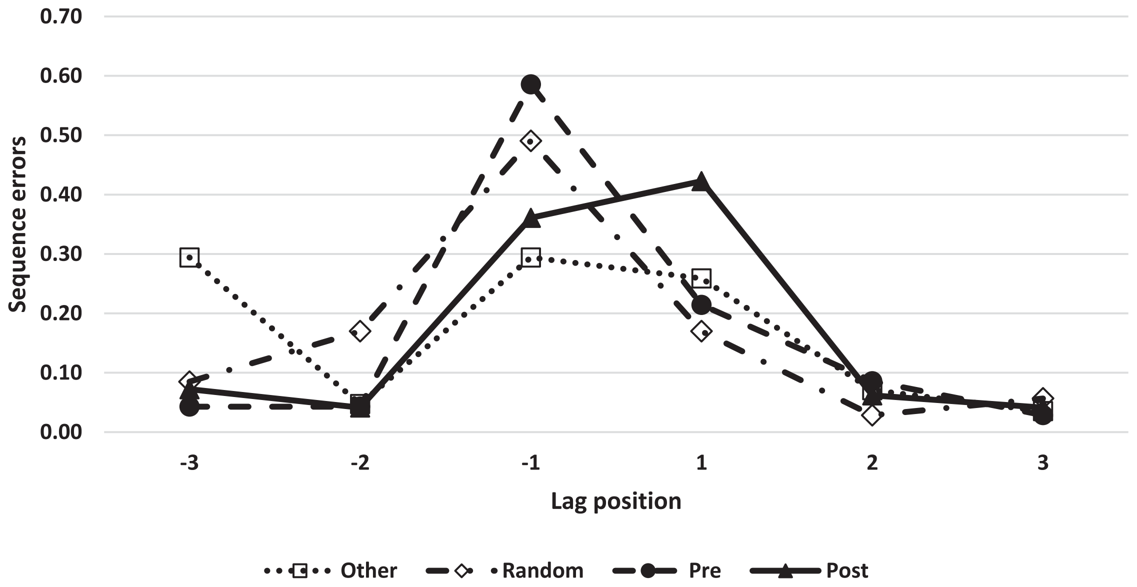

Figure 3. Proportions of sequence errors after resumption of the primary task (out of all sequence errors) as a function of experimental condition and the lag from the correct response in Experiment 1.

pattern resembles the usual pattern of errors documented with the sequence task (Altmann et al., 2017), it is worth noting that errors in the pre-interruption condition are clearly inconsistent with our initial hypothesis—we expected lag −1 errors to be reduced in this condition due to more efficient retrieval of goals from episodic memory. Second, the post-interruption condition also has a relatively high proportion of errors at lag −1 but also a more pronounced peak at lag +1, which clearly differs from all other conditions.[1]

Although the focus of the study was on sequence errors, for completeness we also analysed two other dependent variables. First, Figure 4 presents non-sequence errors, again for up to five trials following an interruption. As can be seen, non-sequence error rates were generally low and not affected by the presence of interruptions. A one-way ANOVA found no difference in non-sequence errors on trials immediately following interruptions, $F(3, 171) = 1.46$, $p = .226$, $\eta^2 = .025$. Second, we also looked at reaction times for the first subtask after an interruption (see Table 1), with the exclusion of sequence errors, and found them not to differ significantly across conditions, $F < 1$. This shows that the pattern of sequence errors after interruptions was not mirrored in the patterns of resumption times. Finally, we also analysed the average number of visual search trials participants were able to perform within 8 s of the interruption period across experimental conditions. A one-way ANOVA showed significant differences across conditions, $F(3, 171) = 13.86$, $p < .001$, $\eta^2 = .196$. Bonferroni-corrected post-hoc comparisons showed this stemmed predominantly from a lower number of trials completed in the other condition ($M = 5.93$) than in all other conditions ($M = 6.18$, $p < .001$, for the pre-interruption condition; $M = 6.30$, $p < .001$, for the post-interruption condition; $M = 6.14$, $p = .002$, for the random condition). Additionally, the average number of trials was slightly higher in the post-interruption than the random condition, $p = .043$. These results seem to suggest that participants were delayed in setting a task set for the visual search task that required them to process a letter that was from the outside of the set of letters used in the primary sequence task.

Here we tested a hypothesis that when the main task is interrupted, performing a secondary task that requires maintaining a goal congruent with the last goal of the interrupted task would facilitate performance—minimise the rate of sequence errors—when the main task is resumed. The results were only partly consistent with the hypothesis. When there was a match in terms of the letter that denoted the last performed subtask and the one

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[1] The data could not be subjected to a statistical analysis due to a large number of missing cells at participant level. The same issue applies to sequence error distributions in Experiment 2.

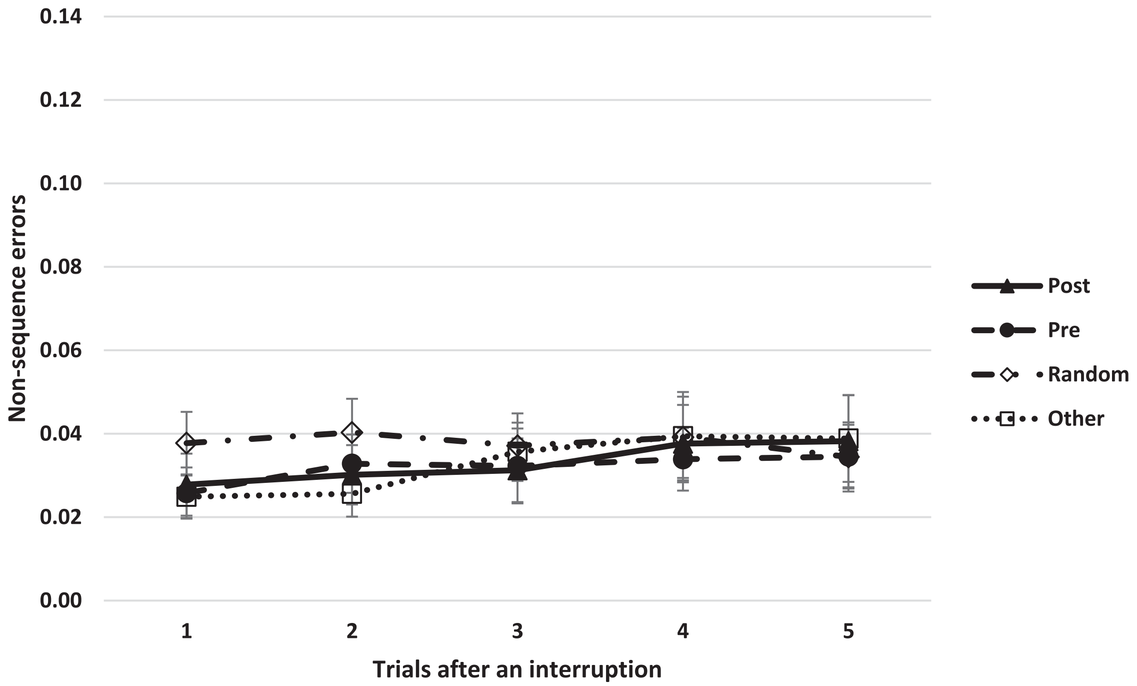

Figure 4. Proportions of non-sequence errors after resumption of the primary task (out of all responses made after resumption) as a function of experimental condition in Experiment 1. Error bars denote standard errors.

that needed to be identified in the secondary task, the rate of sequence errors at resumption was reduced but only in comparison to the random condition. From this, it is not entirely clear whether the consistency of goals across the main and the secondary task facilitates performance, or there is something particularly disruptive about the random condition. Moreover, the distribution of sequence errors as a function of lag did not support our hypothesis that consistency of goals would reduce errors of lag −1, which would indicate less forgetting of these goals, maintained in episodic memory, in the course of an interruption. If anything, for the pre-interruption condition the peak of errors at lag −1 was the most apparent out of all conditions.

One further interesting feature of the results which emerged post-hoc was an apparent change in the lag of sequence errors in the post-interruption condition. In this condition, participants committed errors at a rate similar to the rates in all other experimental conditions, but these errors were qualitatively different inasmuch as they were most often the errors of skipping one operation of the main task, rather than repeating an operation that preceded the interruption. This observation is generally consistent with the premise of the model developed by Altmann et al. (2017), where performing an operation primes the next step in a sequence. Interestingly, though, here this priming seemed to occur not due to performing operations per se but due to processing of letters that denote subtasks in the sequence task. This is consistent with the idea that the acronym used in the main task remains stored in semantic memory and priming operates at the level of this acronym denoting operations. There is, however, insufficient data from this study—in terms of the number of errors of different types per condition—to be confident in drawing conclusions from this one experiment.

Experiment 2

In Experiment 2 we made another attempt at elucidating the role of similarity across the goals

Table 1. Mean resumption times—times to perform a subtask immediately after an interruption—as a function of the type of interruption in Experiments 1 and 2.

	Other	Pre-interruption	Post-interruption	Random
Experiment 1	3305 (195)	3151 (150)	3143 (146)	3188 (153)
Experiment 2	-	2789 (100)	2307 (171)	2632 (124)

Note: Standard errors of the means are given in parentheses.

organising the primary sequence task and those implemented in the secondary, interrupting task for performance when the primary task is resumed. In Experiment 1, this similarity was manipulated at the level of letters denoting subtasks in the primary task and targets of a visual search in the secondary task. However, what is maintained in memory when the primary task is interrupted might not be letters but rather the actual goals of subtasks denoted by these letters and realised before the interruption commenced. If participants maintain goals (e.g. lower or higher than five) rather than the letters that denote them (M), then any effect of similarity to to-be-identified letters in the secondary task would be limited. A stronger manipulation of similarity would be to require participants to actually perform particular operations in the secondary task that either match or mismatch the subtasks maintained in episodic memory during interruptions.

Accordingly, in the present experiment we implemented a manipulation of similarity in terms of the operations rather than the letters denoting subtasks. Here, during interruptions participants were asked to perform operations indicated by a letter that either matched the letter denoting the subtask completed prior to the interruption (the *pre-interruption* condition), matched the letter denoting the subtask to be performed following the interruption (the *post-interruption* condition), or matched another letter from the sequence task (the *random* condition). If the last performed operation is maintained in episodic memory during interruption, we would expect this maintenance to be facilitated when the same goal needs to be realised in the secondary task, facilitating performance at resumption in the pre-interruption condition compared to other conditions.

Method

Participants. Sixty-one participants (age: $M = 27$, $SD = 7.84$; gender: 41 males, 20 females) completed the experiment in exchange for monetary compensation. One participant with error rates exceeding 50% of resumption trials was excluded, leaving 60 participants for the analyses. All participants were recruited via the Prolific platform and performed the task online.

Materials, design, and procedure. The same main sequence task was used here as in Experiment 1. The only change pertained to the secondary task. It started with the presentation of a letter, which denoted one of the subtasks from the primary sequence task. Four displays from the sequence task were then presented and for each of them, participants were asked to perform the same operation denoted by the letter presented at the beginning of the secondary task. The primary task was resumed after the fourth trial of the secondary task. The design of the experiment included a single independent variable defined by the relationship between the letter used in the secondary task to the operation performed before the interruption commenced. There were three experimental conditions: pre-interruption, post-interruption, and random. The *other* condition was not included in the present experiment because letters from outside the acronym did not define any subtasks that could be executed during interruptions and thus the random condition served as the only baseline condition in the present design. The use of three rather than four experimental conditions meant also that participants were now randomly interrupted on average on 9.4% of the sequence task trials. Apart from the details of the secondary task, all other elements of the procedure were the same as in Experiment 1.

Results and discussion

The rates of sequence errors following immediately after interruptions and in four subsequent subtasks are presented in Figure 5. The proportions of those errors on the first trial after interruption were analysed as a function of experimental condition (random, pre-interruption, post-interruption) with a one-way ANOVA, $F(2, 118) = 3.76$, $p = .026$, $\eta^2 = .06$, which showed that these conditions differed from one another. Planned comparisons revealed that sequence error rates in the random condition were higher than either those in the pre-interruption, $t(59) = 2.52$, $p = .015$, $d = 0.325$, or post-interruption, $t(59) = 2.27$, $p = .027$, $d = 0.293$, conditions.

Figure 6 presents a distribution of sequence errors as a function of lag from the correct response. From these, it is clear that distributions for the pre-interruption and random condition peak at lag −1, while the distribution for the post-interruption condition peaks at lag +1. Overall, these distributions are similar to those observed in Experiment 1. First, they suggest that a reduction of sequence errors in the pre-interruption condition may not be a result of facilitated maintenance in episodic memory, in which case a reduction of lag −1 errors would be expected. Second, they confirm that performing a subtask

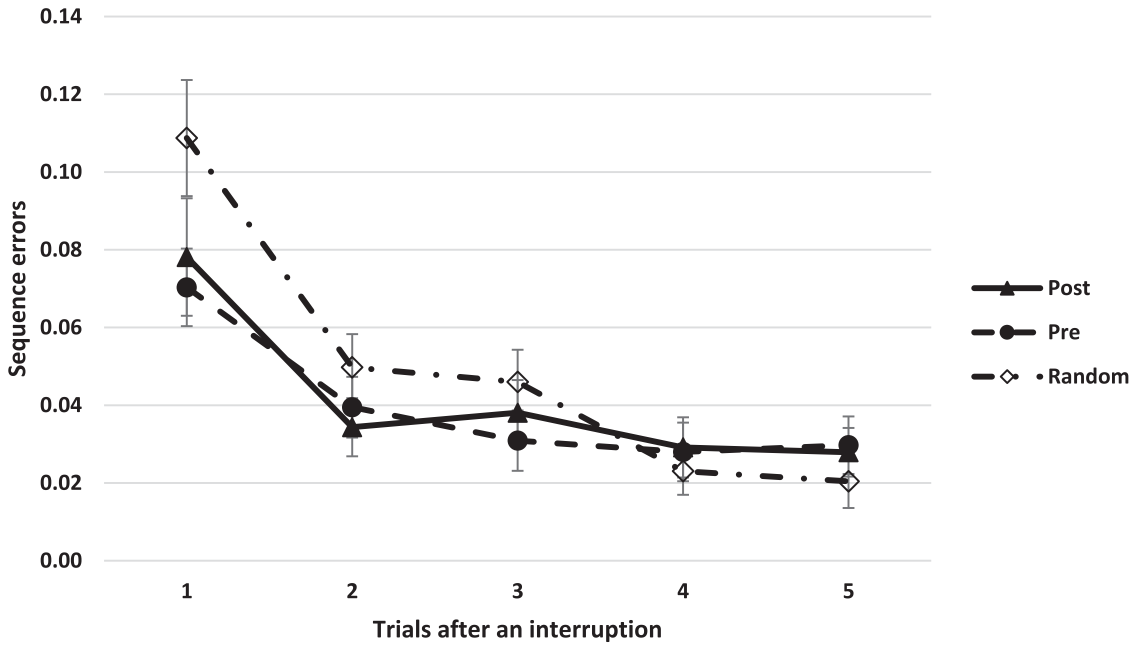

Figure 5. Proportions of sequence errors after resumption of the primary task (out of all responses made after resumption) as a function of experimental condition in Experiment 1. Error bars denote standard errors.

denoted by a particular letter primes the semantic memory representation of the next subtask in a sequence, which leads to an increased probability of making a lag +1 error in the post-interruption condition, where the goal realised during interruption actually primes the wrong subtask at resumption.

Apart from sequence errors, several other dependent variables were also analysed. First, Figure 7 presents non-sequence errors for up to five trials following an interruption. A one-way ANOVA on rates immediately following interruptions showed no differences across experimental conditions, *F*(2, 118) = 1.75, *p* = .179, $\eta^2 = .029$.

Second, we again looked at reaction times for the first subtask after an interruption, with the exclusion of sequence errors (see Table 1), and found that this

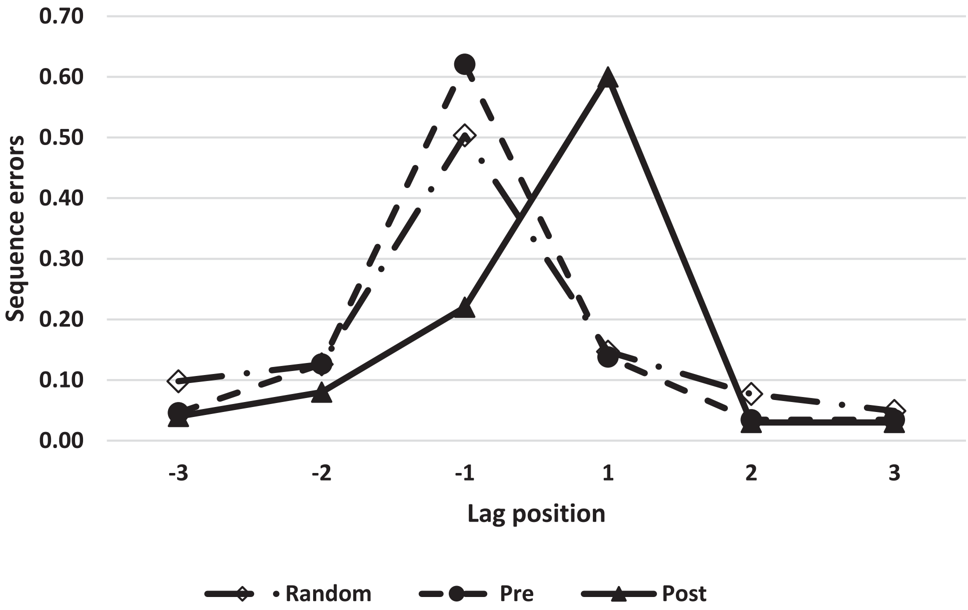

Figure 6. Proportions of sequence errors after resumption of the primary task (out of all sequence errors) as a function of experimental condition and the lag from the correct response in Experiment 2.

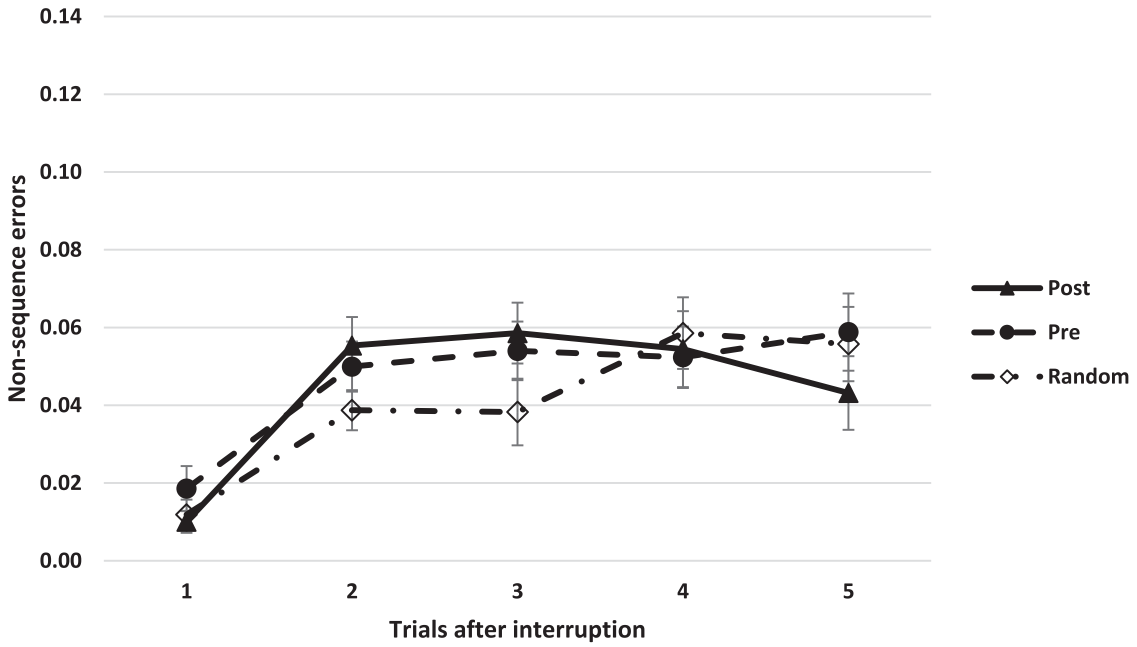

Figure 7. Proportions of non-sequence errors after resumption of the primary task (out of all responses made after resumption) as a function of experimental condition in Experiment 2. Error bars denote standard errors.

time, unlike in Experiment 1, they differed across conditions, $F(2, 118) = 6.29$, $p = .003$, $\eta^2 = .096$. Bonferroni-corrected post-hoc tests showed only that reaction times were faster in the post-interruption condition than in either the pre-interruption, $p = .002$, or the random condition, $p = .062$ (with the latter result being non-significant after a Bonferroni correction). One thing to note is that this result differs from the pattern of sequence errors because the reduced rates of sequence errors in the pre-interruption condition—relative to the random condition—were in no way mirrored in the reaction times. Thus, it is not simply that a condition in which lower rates of sequence errors are observed is generally easier, facilitating also faster resumption of the primary task as reflected in lower reaction times. Instead, the facilitation found for the post-interruption condition, i.e., the reduction of errors, may reflect a different mechanism. Based on the model developed by Altmann and Trafton (2015) it is possible to argue that while sequence errors reflect predominantly failures of episodic memory, reaction times reflect the operations of the semantic system, where performing the next subtask of the primary task during the interruption primes the corresponding goal and thus facilitates resumption.

Finally, it is worth noting a difference in methodology between Experiments 1 and 2. While in Experiment 1 the duration of interruptions was set, here the duration of interruptions was determined by the time it took to perform four operations of a particular subtask. Thus, while in Experiment 1 we analysed the number of trials performed in a particular time period, here we analysed the time to complete four trials of the interruption tasks across experimental conditions. Figure 8 presents those results, which were analysed with a 3 (condition) x 4 (trial) ANOVA. This yielded a significant main effect of condition, $F(2, 118) = 23.46$, $p <$ 001, $\eta^2 = 0.012$, a significant main effect of trial, $F(3,177) = 234.11$, $p < .001$, $\eta^2 = 0.683$, and a significant interaction, $F(6, 354) = 29.06$, $p < .001$, $\eta^2 = 0.034$. Figure 8 clearly shows that differences across conditions were limited to the first of the four interruption trials, where participants were slower in the random condition than in both the pre-interruption, $p < .001$, and the post-interruption, $p < .001$, conditions. The difference in this trial across the latter conditions was not reliable, $p = .068$. This slowing in the random condition likely reflects the need to retrieve from memory the task set that differs both from the task set that has been already completed and the next to-be-performed subset, which remains primed. It needs to be noted that this pattern mirrors the pattern observed for sequence errors, which could be taken to suggest that sequence errors following

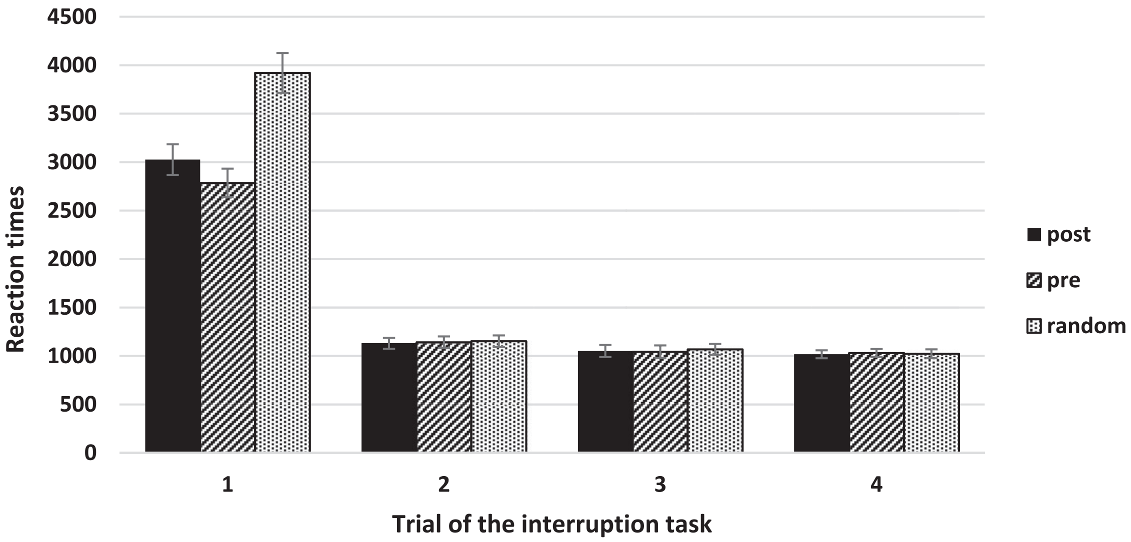

Figure 8. Reaction times in the four trials of the interruption task as a function of the experimental condition—post-interruption, pre-interruption, and random—in Experiment 2. Error bars denote standard errors.

interruptions are more common in the random condition simply due to an additional decay of goals that is a function of slowing down on the first trial of an interruption. While possible, we think this explanation unlikely because the additional time cost observed in the random condition is relatively minor. An approximately 1 s of slowing down on the first trial means that the duration of the entire interruption in the random condition is only about 15% longer than the corresponding durations in the pre- and post-interruption conditions.

To summarise, here we again hypothesised that similarity across goals maintained for the purpose of performing the secondary task and the last realised goal in the interrupted task would benefit performance when the primary task is resumed by virtue of facilitating episodic maintenance of goals during interruptions. However, the results proved to be largely inconsistent with this prediction. Sequence errors were committed less often when such a match was present in the pre-interruption condition compared to the random condition, where goals used for the interruption task matched a random subtask from the primary sequence task. This pattern would be predicted if processing a certain goal during the secondary task helped maintain it in memory also for the purpose of resuming the main task. However, the same pattern of reduced sequence errors also emerged when goals used for the interruption task matched the operation that needed to be performed at resumption of the primary task in the post-interruption condition, which was not predicted. Moreover, the distribution of errors again showed no reduction in lag −1 errors for the pre-interruption condition, which would be expected if retrieval of suspended goals was facilitated in this condition.

The comparable facilitation of task resumption in the pre- and post-interruption conditions—compared to the random condition—implies one of at least three scenarios. First, participants, when performing the secondary task, could maintain via rehearsal both the pre- and post-interruption operations in episodic memory, in which case similarity of the secondary task goal to either of these operations would have some power of facilitating maintenance. This solution seems overcomplicated, as it is unclear what additional benefit would stem from maintaining two goals compared to a much simpler task of always remembering just the last realised goal. Second, participants could differ in their strategies, with some trying to maintain the just realised operation and some trying to maintain the operation that should be performed at resumption (see Altmann & Trafton, 2015). This solution does not, however, address the issue of the distribution of errors—why there is no specific reduction of lag −1 errors in the pre-interruption condition, which at least for some participants should facilitate goal maintenance. Third, it could also be that it is not that pre- and post-interruption conditions are made easier because the process of episodic maintenance is facilitated for both of them, but that the random condition is particularly difficult because the process of forgetting is exaggerated there. We discuss this possibility in greater length in the General Discussion. Finally, other, more complex scenarios could of course be devised, such as participants rehearsing—if possible—how the task performed at interruption relates to the next subtask to be performed in the primary task (e.g., "next"), and only rehearsing the to-be-performed operation if this is not possible. Ultimately, this issue awaits future research that would additionally probe participants' strategies.

General discussion

It has long been known that interrupting a primary task with a requirement to perform a secondary task impairs performance when the primary task is resumed (Hodgetts & Jones, 2006a). Recent years have seen that such impairment can take a form of increased rate of errors in executing a correct operation in a procedural sequence task (Altmann et al., 2014). Here we assessed whether an overlap in goals pursued across interrupted and interrupting tasks modulates such an impairment. We specifically hypothesised that the congruency of goals pursued in the interrupting task on the one hand and maintained in episodic memory in the service of accurate resumption on the other would prove beneficial, preventing forgetting of goals from the interrupted, primary task and thus allowing for a reduced rate of sequence errors when this task is resumed. In two experiments, we used an adaptation of a sequence task used to investigate interruptions (Altmann et al., 2014), where operations are defined by specific letters that together create an acronym specifying a sequence of operations. In this task, we varied the relationship across goals pursued in the secondary, interrupting task and goals defined for the primary sequence task. We found that the rate of errors at resumption was indeed related to the specific goals realised during the interrupting task.

In Experiment 1, we investigated the role of overlap in terms of letters denoting subtasks in the primary sequence task and those used in the secondary task. We found that the rate of errors at resumption was lower when the goal in the secondary task overlapped with the last goal realised in the primary sequence task rather than with a random goal from the sequence. In Experiment 2, we investigated the role of an overlap not only in terms of letters denoting operations but in terms of the operations themselves. Here we found that the rate of errors was again lower when the secondary task goal overlapped with the last goal realised in the primary sequence task rather than with a random goal from the sequence, but we also found the same reduction when this goal of the interrupting task overlapped with the goal that should be realised only after resumption. These results confirm that the contents of the interrupting task—or, more specifically, the relationship of the goals pursued in the interrupting task to the goals of the interrupted task—do matter when the primary task needs to be resumed. However, the pattern of these results does not confirm our initial hypothesis of benefits accruing from a specific overlap between the goal realised just before the interruption and the goal pursued during interruption.

We built our initial hypothesis based on the assumption that the last realised goal before the interruption is rehearsed during interruption and this rehearsal counters forgetting of this goal, preventing errors at resumption. We speculated that this rehearsal process should be facilitated when the same goal—either in the form of a letter denoting an operation in the sequence task (Experiment 1), or in the form of an actual to-be-performed operation (Experiment 2)—would organise performance in the interrupting task. While both experiments did find a reduction of errors in this pre-interruption condition, when compared against the baseline of random goals pursued in the interrupting task, such reduction was not specific: Experiment 2 showed a similar reduction in the post-interruption condition, when goals pursued in the interrupting task overlapped with the next goal, to-be-performed after resumption of the interrupted task. It seems, then, that the reason why some types of goals pursued during interruptions modulate the rate of errors at resumption is not related to a rehearsal process supporting the last realised goal.

Additional evidence against the rehearsal account of our results comes from a pattern of sequence errors participants committed across experimental conditions in both experiments. We expected facilitated rehearsal to reduce the rate of lag −1 errors specifically, which are errors assumed to stem from lapses of maintenance of goals in an episodic memory system (Altmann & Trafton, 2015). This result failed to materialise in either of our experiments, with the pre-interruption condition showing a pronounced peak in terms of sequence errors at resumption precisely at lag −1. It is worth noting that this is not because this measure is insensitive to experimental manipulation. Both experiments showed a pattern of altered sequence errors in the post-interruption condition, where the peak was shifted to lag +1 errors. This we interpret as consistent with the contribution of the semantic system to performance in the sequence task, where realising the goal of the next subtask during interruptions primes the following subtask, which—when executed—constitutes a lag +1 error.

What is then the reason for changes in task performance at resumption if not the modulation of the rehearsal process? Clearly, the types of goals pursued during interruptions do matter for episodic forgetting of goals of the primary task—the mechanism by which errors arise at resumption (Altmann & Trafton, 2007). It is worth noting, however, that rehearsal is not ubiquitously agreed to be relevant to forgetting. Although there are models of working memory in which rehearsal is deployed to counter forgetting that accrues from decay of representations maintained in working memory (see Camos, 2015, for a discussion), it has also been argued that rehearsal is epiphenomenal and may play no role in modulating forgetting by countering decay (Lewandowsky & Oberauer, 2015). In interference models of forgetting in working memory, forgetting occurs because of interference from concurrent or immediately consecutive stimuli with to-be-maintained memoranda, and in many such models the degree of forgetting is determined by the similarity of memoranda and distractors (Nairne, 1990; Oberauer et al., 2012). Rehearsal plays no role in such models of forgetting because they assume no decay that rehearsal would need to counteract. It is then perhaps worth looking at the interruption task through the lens of interference theory. From this perspective, the issue becomes not why certain goals pursued in the interruption task may support the process of countering decay, but why some such goals cause greater interference than other goals. One possibility is that it is not that in the pre- and post-interruption conditions the maintenance of goals during interruptions is supported, but rather that in the random condition this maintenance is particularly vulnerable to interference.

It is one of the premises of the interference theories that the similarity of memoranda and distractors that cause dislocation of attention from memoranda matters a lot for the process of forgetting (although note that such similarity relationships are not straightforward and have been critiqued elsewhere, Beaman & Jones, 2016). On the one hand, when distractors come from the same domain as memoranda, interference processes are presumed to be exacerbated (Turner & Engle, 1989). Thus, for example, processing letters when letters need to be maintained is more disruptive than processing digits. From this perspective, processing letters from the sequence task during interruptions should be particularly disruptive for memory of goals. While Experiment 1 did have a comparison between the random condition, using such sequence letters in the interruption task, and the other condition, where letters were taken from outside the sequence task, this did not yield a reliable difference in terms of errors at resumption, albeit the means were in the expected direction. Possibly, the manipulation in Experiment 1, with only letters—not operations—overlapping across the interrupted and interrupting task was too weak to reliably demonstrate increased interference for the random condition. Importantly, however, increased similarity across memoranda and distractors does not always exacerbate forgetting. When these are taken from the same domain and presented in close temporal proximity—with distractors immediately following a similar to-be-remembered element—interference may be reduced (Oberauer, 2009; Piątkowski et al., 2022). This is because similar distractors have numerous features overlapping with their respective memoranda and these features become strengthened when a distractor is processed.

The process of strengthening of features overlapping across goals realised in the interrupted task and those pursued in the interrupting task could —on the basis of the interference theory—account for the pattern of reduced errors in the pre-interruption conditions of Experiments 1 and 2. But what about the comparable reduction for the post-interruption condition of Experiment 2? If the already realised goal from the primary task needs to be maintained in memory during interruption, then why would a dissimilar goal matching the next to-be-realised goal interfere less with it despite having no common features? The important point may be here that, according to some versions of interference theory, what is stored in memory are not so much individual features of memoranda but rather bindings (Oberauer, 2019); for example between memoranda and context in which they were presented. Arguably, contexts associated with consecutive letters in a sequence should be highly similar to each other due to repeated processing of the exact same sequence in the course of the experimental task. If interference is understood in its contextual form, then the expected pattern would be that distractors—in this case goals pursued in the interrupting task—should be disruptive for memory of the to-be-maintained goal to the extent to which these goals are similar in terms of their features, defining their domain, but dissimilar in terms of associated contextual features, determined by their position within a sequence. This would account for reduced interference when both goals in the interruption task come from positions nearby from the position of the last realised goal, as compared to other positions from the same sequence.

At this point, the interference account of forgetting of goals due to interruptions remains only a tentative proposal to account for the surprising patterns resulting from the current Experiment 2. The decay-plus-rehearsal model, on which current theorising about interruptions in the sequence task is based (Altmann et al., 2017), remains a viable framework and specific experiments would need to be devised to explicitly contrast these two approaches. One idea could be to directly test one of the main tenets of interference theory—that varied distractors cause more interference than constant distractors due to stronger contextual bindings of new stimuli (Oberauer & Lewandowsky, 2008). Adapted to the interruption task, the interference theory would thus predict that varying goals pursued during interruptions should lead to more forgetting of the last realised goal in the interrupted task—and thus more errors at resumption—than a repeated pursuit of the same goal. This and other contrasting predictions of decay and interference models of forgetting remain to be tested in future experiments. The conclusion of the present study remains that —although the underlying mechanism is yet to be determined—the disruptiveness of interruption is at least to some extent the function of what goals organise performance of the interrupting task.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Science Centre (Poland) grant 2017/27/B/HS6/02001 awarded to Maciej Hanczakowski.

Data availability statement

The data that support the findings of this study are openly available on osf at http://doi.org/10.17605/OSF.IO/7Y2ZS.

References

Altmann, E. M., & Hambrick, D. Z. (2017). Practice increases procedural errors after task interruption. *Journal of Experimental Psychology: General*, *146*(5), 615–620. https://doi.org/10.1037/xge0000274

Altmann, E. M., & Trafton, J. G. (2002). Memory for goals: An activation-based model. *Cognitive Science*, *26*(1), 39–83.

Altmann, E. M., & Trafton, J. G. (2007). Timecourse of recovery from task interruption: Data and a model. *Psychonomic Bulletin & Review*, *14*(6), 1079–1084. https://doi.org/10.3758/BF03193094

Altmann, E. M., & Trafton, J. G. (2015). Brief lags in interrupted sequential performance: Evaluating a model and model evaluation method. *International Journal of Human-Computer Studies*, *79*, 51–65. https://doi.org/10.1016/j.ijhcs.2014.12.007

Altmann, E. M., Trafton, J. G., & Hambrick, D. Z. (2014). Momentary interruptions can derail the train of thought. *Journal of Experimental Psychology: General*, *143*(1), 215–226. https://doi.org/10.1037/a0030986

Altmann, E. M., Trafton, J. G., & Hambrick, D. Z. (2017). Effects of interruption length on procedural errors. *Journal of Experimental Psychology: Applied*, *23*(2), 216–229. https://doi.org/10.1037/xap0000117

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, *133*(1), 83–100. https://doi.org/10.1037/0096-3445.133.1.83

Beaman, C. P., & Jones, D. M. (2016). The item versus the object in memory: On the implausibility of overwriting As a mechanism for forgetting in short-term memory. *Frontiers in Psychology*, *7*, 1664–1708. https://doi.org/10.3389/fpsyg.2016.00341

Cades, D. M., Davis, D. A. B., Trafton, J. G., & Monk, C. A. (2007). Does the difficulty of an interruption affect our ability to resume? *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *51*(4), 234–238. https://doi.org/10.1177/154193120705100419

Camos, V. (2015). Storing verbal information in working memory. *Current Directions in Psychological Science*, *24*(6), 440–445. https://doi.org/10.1177/0963721415606630

Camos, V., Lagner, P., & Barrouillet, P. (2009). Two maintenance mechanisms of verbal information in working memory. *Journal of Memory and Language*, *61*(3), 457–469. https://doi.org/10.1016/j.jml.2009.06.002

Hirsch, P., Moretti, L., Askin, S., & Koch, I. (2023). Examining the cognitive processes underlying resumption costs in task-interruption contexts: Decay or inhibition of suspended task goals? *Memory & Cognition*, Advance online publication.

Hodgetts, H. M., & Jones, D. M. (2006a). Interruption of the Tower of London task: Support for a goal-activation approach. *Journal of Experimental Psychology: General*, *135*(1), 103–115. https://doi.org/10.1037/0096-3445.135.1.103

Hodgetts, H. M., & Jones, D. M. (2006b). Contextual cues aid recovery from interruption: The role of associative activation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(5), 1120–1132. https://doi.org/10.1037/0278-7393.32.5.1120

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A review. *Psychonomic Bulletin & Review*, *17*(1), 1–14. https://doi.org/10.3758/PBR.17.1.1

Labonté, K., Tremblay, S., & Vachon, F. (2019). Forewarning interruptions in dynamic settings: Can prevention bolster recovery? *Journal of Experimental Psychology: Applied*, *25*(4), 674–694. https://doi.org/10.1037/xap0000219

Lewandowsky, S., & Oberauer, K. (2015). Rehearsal in serial recall: An unworkable solution to the nonexistent problem of decay. *Psychological Review*, *122*(4), 674–699. https://doi.org/10.1037/a0039684

Li, S. Y. W., Blandford, A., Cairns, P., & Young, R. M. (2008). The effect of interruptions on postcompletion and other procedural errors: An account based on the activation-based goal memory model. *Journal of Experimental Psychology: Applied*, *14*(4), 314–328. https://doi.org/10.1037/a0014397

Lucidi, A., Langerock, N., Hoareau, V., Lamaire, B., Camos, V., & Barrouillet, P. (2016). Working memory still needs verbal rehearsal. *Memory & Cognition*, *44*(2), 197–206. https://doi.org/10.3758/s13421-015-0561-z

Monk, C. A., Boehm-Davis, D. A., & Trafton, J. G. (2004). Recovering from interruptions: Implications for driver distraction research. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *46*(4), 650–663. https://doi.org/10.1518/hfes.46.4.650.56816

Monk, C. A., Trafton, J. G., & Boehm-Davis, D. A. (2008). The effect of interruption duration and demand on resuming suspended goals. *Journal of Experimental Psychology: Applied*, *14*(4), 299–313. https://doi.org/10.1037/a0014402

Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, *18*(3), 251–269. https://doi.org/10.3758/BF03213879

Oberauer, K. (2009). Interference between storage and processing in working memory: Feature overwriting, not similarity-based competition. *Memory & Cognition*, *37*(3), 346–357. https://doi.org/10.3758/MC.37.3.346

Oberauer, K. (2019). Working memory capacity limits memory for bindings. *Journal of Cognition*, *2*(1), 40. https://doi.org/10.5334/joc.86

Oberauer, K., & Lewandowsky, S. (2008). Forgetting in immediate serial recall: Decay, temporal distinctiveness, or interference? *Psychological Review*, *115*(3), 544–576. https://doi.org/10.1037/0033-295X.115.3.544

Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review*, *19*(5), 779–819. https://doi.org/10.3758/s13423-012-0272-4

Piątkowski, K., von Bastian, C. C., Zawadzka, K., Hanczakowski, M. (2022). Elaboration by superposition: From interference in working memory to encoding in long-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *49*(3), 371–388.

Radović, T., & Manzey, D. (2019). The impact of a mnemonic acronym on learning and performing a procedural task and its resilience toward interruptions. *Frontiers in Psychology*, *10*, 2522. https://doi.org/10.3389/fpsyg.2019.02522

Radović, T., & Manzey, D. (2022). Effects of complexity and similarity of an interruption task on resilience toward interruptions in a procedural task with sequential constraints. *Journal of Experimental Psychology: Human Perception and Performance*, *48*(2), 159–173. https://doi.org/10.1037/xhp0000981

Ratwani, R. M., Andrews, A. E., Sousk, J. D., & Trafton, J. G. (2008). The effect of interruption modality on primary task resumption. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *52*(4), 393–397. https://doi.org/10.1177/154193120805200441

Trafton, J. G., Altmann, E. M., Brock, D. P., & Mintz, F. E. (2003). Preparing to resume an interrupted task: Effects of prospective goal encoding and retrospective rehearsal. *International Journal of Human-Computer Studies*, *58*(5), 583–603. https://doi.org/10.1016/S1071-5819(03)00023-5

Trafton, J. G., & Monk, C. A. (2007). Task interruptions. *Reviews of human factors and ergonomics*, *3*(1), 111–126.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*(2), 127–154. https://doi.org/10.1016/0749-596X(89)90040-5

Warszawa, dnia 27.02.2024

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy

Piątkowski, K., Beaman, C. P., Jones, D. M., Zawadzka, K., & Hanczakowski, M. (2024). Forgetting during interruptions: The role of goal similarity. Journal of Cognitive Psychology, 1–16.

mój udział polegał na konceptualizacji przedmiotu badań i opracowaniu ich metodologii, zaprogramowaniu i przeprowadzeniu eksperymentów, rozpowszechnianiu wyników badań i napisaniu pierwszej wersji manuskryptu. Mój udział w powstaniu pracy wynosi 60%.

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Podpis

Co-authorship statement

Piątkowski, K., Beaman, C. P., Jones, D. M., Zawadzka, K., & Hanczakowski, M. (2024). Forgetting during interruptions: The role of goal similarity. *Journal of Cognitive Psychology*. Advance online publication.

We declare that the authors' contribution to the manuscript, according to the CRediT scheme, comprised the following:

Krzysztof Piątkowski: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft

C. Philip Beaman: Conceptualization, Methodology, Writing – review & editing

Dylan M. Jones: Conceptualization, Methodology

Katarzyna Zawadzka: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing

Maciej Hanczakowski: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing

We also declare that Mr. Krzysztof Piątkowski's percentage contribution to the study was 60%.

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Co-authorship statement

Piątkowski, K., Beaman, C. P., Jones, D. M., Zawadzka, K., & Hanczakowski, M. (2024). Forgetting during interruptions: The role of goal similarity. *Journal of Cognitive Psychology*. Advance online publication.

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