MAINTENANCE OF RELATIONAL BINDINGS: WORKING MEMORY OR LONG-TERM MEMORY?

Dissertation presented to

the Faculty of the Graduate School

at the University of Missouri-Columbia

In Partial Fulfillment of the

Requirements for the Degree

Doctor of Philosophy

---

by

REED DECKER

Dr. Moshe Naveh-Benjamin, Dissertation Supervisor

MAY 2022

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

MAINTENANCE OF RELATIONAL BINDINGS: WORKING MEMORY OR LONG-TERM MEMORY?

presented by Reed Decker,

a candidate for the degree of doctor of philosophy,

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

Professor Moshe Naveh-Benjamin

Professor Nelson Cowan

Professor Jeffrey Johnson

Professor Bruce Bartholow

Professor Roxana Botezatu

ACKNOWLEDGMENTS

I would like to express my sincerest gratitude to my advisor, Dr. Moshe Naveh-Benjamin for lending his expertise, feedback, and resources towards making this dissertation possible. Additionally, I'd like to thank my committee members. Drs. Nelson Cowan, Jeff Johnson, Bruce Bartholow, and Roxana Botezatu for their patience and support in developing the project. Special thanks to Dr. Cowan, for his extensive advice.

Additionally, I'd like to thank Conor and Riley Smith, Morgan Slight, and the Lovely Skeleton Pals for a few brief windows of normalcy during this time, as well as Johnny Chiodini and the Oxboxtra team for producing materials to help keep me grounded during the twin tribulations of COVID and dissertation research.

Finally, I'd like to thank my parents as well as my brothers, Bandon and Lee, for their support across my graduate career, their patience in listening to my frustrations, and for never criticizing, but always heckling.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

While there has been a wealth of research examining the effects of feature binding in working memory (WM), it remains unclear how relational bindings (pairings of items, or of an item to its presented serial position) are stored in WM. We proposed a hypothesis in which relational bindings are not maintained in WM, but rather pass directly to long-term memory (LTM), even over short spans. In order to test this hypothesis, we performed a series of experiments examining the effects of short-term memory conditions, as well as both temporally distinct and non-distinct LTM conditions, on serial position curves for words and for relational bindings. We predicted that, unlike in item memory, for relational bindings there would be no effect of either LTM condition on recency relative to the STM condition. In Experiment 1, we presented participants with sets of unrelated word pairs and measured performance on an associative recognition test after a short-term interval, a long-term interval, and a long-term interval in which interstimulus interval was also increased to maintain temporal distinctiveness of the items. In Experiment 2 we used a similar procedure but attempted to increase serial position effects by testing binding between word and serial position, rather than between items. In Experiment 3, the study procedure was again similar, but participants were tested on item recognition and on item-position binding using an order reconstruction test. While the experiments demonstrated either no effect of condition on recency, or evidence against such an effect, post-hoc analysis was able to demonstrate that many participants responded in a unique way to the STM test, with the unique pattern predicting success for this test. As such, we conclude that relational bindings are likely stored in WM, rather than being passed directly to LTM.

Keywords: relational memory, long-term memory, working memory, short-term memory, binding, temporal distinctiveness

Introduction

Episodic memory, our ability to recall and replay specific life events, is deeply unreliable and prone to distortion (see Schacter et al., 2011 for a review). One keystone to forming episodic memories that are both accurate and lasting may well be not simply information storage, but the ability to form associations between different pieces of information. For example, if one recalls a significant life event, such as the meeting of a significant other, or long-term friend, that memory involves not only the memory of the individual, but also the memory of the location, the time of day, events that lead to that interaction, and personal context (Tulving, 1972; Underwood, 1969). The ability to associate all of these elements together, known as relational binding when in working memory (WM) or associative memory when in long-term memory (LTM), is what allows for the encoding and storage of a cohesive episode. Indeed, one of the potential causes of the loss of episodic memory seen in older adults is a loss of associative memory, as detailed by the associative deficit hypothesis (Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008). Given the importance of associations in episodic LTM, there's been extensive research on this topic (e.g Aue et al., 2012; Hockley et al., 2016; Kelley & Wixted, 2001; Shing et al., 2008). As there is evidence that WM maintenance of information supports later LTM recall (Forsberg et al., 2021, 2022; Hartshorne & Makovski, 2019; Lewis-Peacock & Postle, 2008), there is reason to believe that a firm understanding of how binding information is stored in WM and transferred to LTM is important to understanding episodic memory. Such an understanding would not only have theoretical benefits in helping to clear up the nature of WM and LTM differences but would additionally allow us to make better predictions as to what interventions would be most effective in educational contexts, or for the preservation of episodic memory in older adults. However, the mechanics of relational binding across WM and LTM are still unclear. For example, while divided attention at encoding does not appear to cause associative memory deficits, relative to item memory in LTM, it does cause these deficits in WM. This leads to a confusing situation in which bindings presumably not present in a short-term test re-appear in a long-term test (Peterson et al., 2017; Peterson et al, 2019b, 2019a). Additionally, effects that have been previously thought to be unique to WM have appeared in LTM as well, as in the long-term recency effect demonstrated by Bjork and Whitten (1974), in which the authors demonstrate that maintaining relative distinctiveness between items allows the recency effect to persist beyond the apparent limits of WM, leading to doubts as to if WM and LTM are even truly separate systems.

In the present series of experiments, we examine short and long-term recency effects on both item and binding information by modifying the methods of Bjork and Whitten (1974), in order to test the hypothesis that relational information is not maintained in WM at all, but rather stored primarily as part of LTM. To pursue this hypothesis, we find it necessary to specify a distinction in terms. Namely, we use WM to refer to the specific system of memory theorized to store and manipulate information over short intervals. Because we hypothesize use of LTM storage over short time intervals, we find it useful to use the phrase 'short-term memory' as a way to refer to tests of memory that take place over a brief time scale without specifying if information is stored in the WM or LTM system. In order to understand this hypothesis fully, we review previous literature on associative memory in LTM, including early verbal learning theory for paired associates, context binding, mathematical models, and neural evidence. We then review similar evidence for WM, including relational binding models, or lack thereof, as well as noting the connections between WM and LTM on a behavioral, theoretical, mathematical, and neurological levels as evidence for the potential of short-term binding storage in LTM. Finally, we clarify our case for the current hypothesis based on the reviewed data and explain the structure and specific hypotheses of the experiments presented.

Associative Memory in LTM

In order to understand the hypothesis of bindings in short-term tasks being the same as associations in LTM, we must first understand how associations work in LTM. Much of the early work in binding in LTM was done by verbal learning theorists, and these ideas continue to be prominent in the field. As explained in a review by Tulving and Madigan (1970), the framework of verbal learning theory is much like that of behaviorism. Certain stimuli grow to become associated with a memory response over time, allowing for the presentation of those stimuli to cause the appropriate response to be remembered. Likewise, forgetting is explained via the mechanism of behavioral extinction: if the association between stimulus and response is eliminated, then the information has been forgotten. Indeed, this focus on the same sort of stimulus-response associations seen in behavioral research is the reason why the term ‘association’ is used to describe bindings in LTM to this day.

Much of the verbal learning research was guided by the two-stage theory of association (Underwood et al., 1959), which states that for the formation of associations, first the response must be encoded well enough so it can readily recallable. Only after the response is encoded can it then be behaviorally associated with a given stimulus, though they do note that it is possible for a partially encoded response to form these associations (e.g. if only the first syllable of a response on a paired-associate learning task is encoded fully, it may still be associated with the cue word). As noted by Tulving and Madigan (1970), however, the distinction between stimulus and response on such a task is something of a behavioral holdover, as, while the stimulus is able to evoke the response, the 'response' is also able to evoke the stimulus. As they indicate, if we assume that encoding of the response is a pre-requisite for the response being evoked by the stimulus, then the encoding of the stimulus should also be a pre-requisite for the stimulus being evoked by the response, as the relationship flows both ways. This idea of association as a separate and secondary stage after item learning appears to still hold true. For example, while Hockley and Cristi (1996) don't directly cite the earlier two-stage model, they were able to demonstrate that when learning of item information is emphasized during the study phase of an experiment, participants perform well on an item test, but not an associative test. However, when associative learning is emphasized at the study phase, participants perform better on the associative test, but show no decline, relative to the item encoding condition, on an item memory test (see also Guitard et al., 2021; 2022).

Additionally, the basic act of retrieving information from LTM seems heavily linked to the formation of associations. As noted previously, the formation of an episodic memory relies on the successful binding of multiple elements together (Tulving, 1972; Underwood, 1969), any one of which may then later serve as a retrieval cue for the full episode. Even outside of the typical paired-associate learning task used to study associations in LTM, we can see how recall is shaped by associations. For example, the encoding specificity principle (Tulving & Thompson, 1973), shows that information is better recalled when the context at retrieval matches the context at encoding. In other words, associations between information and context are also stored in memory, allowing context to act as a cue to retrieve the information, even when other retrieval cues cannot be found. Even in the absence of external cues, associations also appear to be formed between information and a person's physiological state (e.g Goodwin et al., 1969) or even current mood (e.g. Maratos et al., 2001). Overall, present research shows association as being inextricable from LTM, as it forms a foundational element of how information is retrieved from memory in order to be used (see Kahana et al., 2008 for a full review).

Mathematical Models of Binding in LTM

In addition to the behavioral evidence for the formation of associations being a fundamental element of LTM, current mathematical models similarly emphasize association. For example, the Search of Associative Memory (SAM) model (Raaijmakers & Shiffrin, 1981) assumes that an information cue and the context surrounding it both prompt a global retrieval of all information associated with it. Essentially, in this model, there are multiple competing associations between a given cue and various potential responses. For example, if the word pair 'nature-grenade' was given as part of a paired associate learning test, the word 'nature' would, at test, evoke multiple different associations, such as related concepts (e.g. trees, flowers, fresh-air) as well as prior learned associations, such as the target word, 'grenade', and others (e.g. if the person attempting recall has been subjected to particularly aggressive all-natural food marketing campaigns, they may have inadvertently formed a relationship between 'natural' and 'potato-chips,' much to the advertising agency's delight). The additional context of the current task also has associations with all the words on the study list. On a successful trial the combined strength of the cue-target association and the context-target association allow the participant to select the correct response out of the multiple options retrieved.

This idea of a cue activating all relevant traces, called 'global matching' is also shared by the MINERVA 2 model (Hintzman, 1984). The main difference between these models is that, while the SAM model proposes that individual items are stored, and the associative strength between each item is compared, MINERVA 2 instead proposes that what is stored are the associations themselves, as a mathematical vector containing information from both items. For recall, the cue vector is compared against the associative vectors in memory, much like how individual items are tested for in SAM. A potential example would be during an associative recognition test, in which a participant has to determine if a word pair is intact or recombined from its original study presentation. The features of both words in a trial would be combined and stored together and compared against the contents of memory. On a successful intact trial, the participant should then find a vector in memory that matches the features of the current trial more strongly than any other vector. If multiple word pairs were shown that involved the same words (e.g. 'science – teapot' and 'rainbow – science' may have both appeared at study), and the participant is later presented with one of those intact pairs at test, they would then have two matching vectors in memory. One of these vectors would contain the features of both items, and thus be a strong match, whereas the other would contain features of only one item and be a weaker match by comparison, allowing the participant to still have one unambiguously stronger vector response and thus know that the pair is intact. By contrast, on a successful recombined trial, the participant would presumably find two or more vectors, depending on if words were repeated as part of different pairs during study.

These vectors would be the same as the weaker vector in the previous example, each containing information related to one, but not to both of the recombined pair items. Because there would be no vector that contained information related to both items in the recombined pair, all of these partial vector matches would have roughly the same strength, meaning there would be no one unambiguously superior match. Because the participant would expect an unambiguous match if the pair was intact, as detailed above, they can then conclude that the pair must be recombined.

Regardless of the particulars, these global matching models have become almost universal for models of LTM (Huber et al., 2015). In this way, mathematical modeling quite nicely complements the behavioral findings that indicate association as a central element to how information in LTM is stored and retrieved.

Neurological Binding in LTM

There are multiple neural mechanisms by which binding occurs in LTM. Naturally, binding of memories cannot be directly observed in LTM, but we are able to make observations about how neurons become associated with each other that presumably reflects binding processes. The simplest of these processes is co-activation binding. In this form of binding, neurons that are part of a larger cell array and are activated at the same time will become linked to each other, such that the triggering of one neuron will then trigger the other (Hebb, 1949). For example, say you read a passage from a particularly old book. The neurons responding to the smell of old paper will be activated at the same time as those that respond to the passage. Repeat the action enough times, and the smell of old paper by itself may be enough to trigger the neurons involved in the passage of text, without the text itself being present, causing you to remember it.

Or, even more simply, as it is often put, that which fires together wires together. These Hebbian learning principles are generally not applied to memory but focus more on the connections formed between individual neurons. With that said, when studying behavioral conditioning on organisms with relatively simple neural structures, such as sea slugs, it's possible for Hebbian learning to be directly observed (e.g. Antoniv et al., 2003).

Outside of this Hebbian learning, which often focuses on individual neurons, models of LTM typically examine the role of the hippocampus in binding. The hippocampus has been a major area of interest to LTM since the findings of Scoville and Milner (1957), who reported a case study of a patient, H.M, who had undergone bilateral removal of the hippocampus as part of treatment for a seizure disorder and subsequently developed a form of amnesia known as anterograde amnesia in which he lost the ability to form new LTM representations, though his ability to retrieve old representations was largely intact up until a certain point before his operation. Likewise, H.M. showed little to no cognitive impairment in most other areas, including WM. Other case studies on patients with hippocampal damage have shown similar results with varying levels of LTM impairment depending on the extent of hippocampal damage (e.g. Zola-Morgan et al., 1986; Wilson et al., 2008). Similar patterns of anterograde amnesia as a result of hippocampal damage can be seen in patients suffering from Korsakoff's syndrome, a disease related to alcoholism, which likewise causes damage to the hippocampus when compared against patients with non-Korsakoff's alcoholism (Visser et al., 1999), though, again, hippocampal damage related to Korsakoff's syndrome appears to affect LTM but not WM (Cave & Squire, 1992). Several models, known as connectionist models, assume that the hippocampal role in LTM is via the learning of associations, alongside the neocortex. Specifically, they assume that the hippocampus learns associations required for episodic memory quite quickly, but that these associations are also learned more slowly by the neocortex. In a sense, the neocortex holds the item information, with weak connections between the relevant items. The hippocampus allows for reactivation of the relevant items. Via the Hebbian learning technique described above, the connections between these items grow stronger with retrieval until hippocampal involvement is no longer needed for the association to be retrieved, at which point the association can be said to be well consolidated. Alternative models follow a similar process but argue that the hippocampus is always involved in retrieval, and that consolidation occurs via the strengthening of the hippocampal association (see Murre et al., 2006 for a review of connectionist models). As before, however, neural models of LTM tend to agree with both mathematical and behavioral models in that the formation and retrieval of LTM is done primarily through the binding of representations together, and later use of some sort of activation of a single element of the association, such as a retrieval cue, in order to recall the rest of the relevant information.

Binding in WM

For relational binding in WM, there are two options: either WM performs its own separate binding operations, or relational bindings in WM are one and the same with associative memory in LTM. Unfortunately, determining which is the case is complicated by a relative lack of emphasis on relational binding in the WM literature in favor of feature binding. The concept of feature binding is a result of Treisman and Gelade's (1980) feature-integration theory, which states that individual elements of a single object, such as its shape and color, are not automatically represented together in memory. Instead, these individual features must be bound together in order for correct recall to occur later. This finding has led to a bevy of research examining bindings in WM, generally either as part of a single, bound representation in WM (Luck & Vogel, 1997), or as separate entities that must be held together with attention (Wheeler & Treisman, 2002). Thus, we have multiple feature binding models that could be compared to the associative memory literature, but little in the way of relational models.

We could assume that relational bindings and feature bindings share a common mechanism, which would both allow us to compare the WM and LTM evidence more easily, as well as provide a more parsimonious account of binding in WM. However, it appears that there are fundamental differences between the two that make this impossible. For example, relational binding appears to have a much higher attentional requirement than feature binding does. Ecker et al (2013) presented participants with shape and color combinations. Participants were only asked to encode either the shapes or the colors, but were never instructed to try and encode both, or given any indication that any sort of binding was required. However, when these stimuli were presented in a format suitable for feature binding (e.g. shapes filled in with colors) participants performed better when the color-shape combinations were maintained between study and test. When participants were presented with the stimuli in a format suited for relational binding (i.e. blank shapes on top of color squares), it made no difference if the color-shape combinations were maintained between study and test. The authors concluded that participants formed incidental feature bindings that served as additional memory cues during the test phase but did not form implicit relational bindings. Additionally, on an updating task Artuso and Palladino (2014) found that response time was dramatically increased when participants were asked to update a relational binding in memory, compared to when they had to update a feature binding. It's important to note that these differences occur even when there is no increase in stimuli complexity between relational and feature binding. For example, Ecker et al (2013) were able to manipulate the same stimuli to appear either as either relational or feature based pairs by manipulating their context. When stimuli were presented in a relational context, there was no incidental binding, but when they were presented in a feature binding context, incidental binding still occurred. As such, the increased attentional demand for relational binding seems to arise entirely from the relational nature of the task, and not any inherent difference between the stimuli. Given these differences, it seems unlikely that the same mechanisms can explain both feature and relational binding in WM. Additionally, as feature binding models examine how the features of a single item are bound together in memory, they don't help to answer questions about how storage of relational associations affects overall WM capacity.

Fortunately, while it may be difficult to directly relate relational binding and associative memory, there is increasing support for the idea of increased integration in general between WM and LTM. For example, the act of 'chunking' in which WM capacity can be apparently increased by grouping individual memoranda together can be explained by use of LTM representations which stand in for multiple individual memoranda (Miller, 1956; Cowan, 2001). For example, a string of letters such as "F – B – I – E – P – A – F – C – C" would normally exceed WM capacity. However, a participant could replace these nine memoranda with the names of U.S. government agencies, likely already stored in LTM: the FBI, the EPA, and the FCC. This would allow the participant to comfortably store three items in WM, rather than nine, with no loss of information, thanks to the use of LTM information. Long-term semantic information also appears to facilitate WM even when chunking is not directly involved, with words being remembered over non-words (Hulme et al., 1991) as well as highly imageable words showing better performance than words with low imageability (Bourassa & Besner, 1994). Additionally, Loaiza and Camos (2018) performed a free-recall WM task in which participants were allowed to gain memory retrieval cues from the program if they had forgotten a given word. These cues were either phonological in nature (i.e. the middle and last phonemes matched the target word) or rated for high semantic similarity. They found that semantic cues were more likely to lead to correct recall. When different participant groups were asked to either sub-vocally rehearse the information, or refresh the information as a maintenance strategy, they additionally found that semantic cues only provided a benefit in the refreshing condition. This would initially appear to indicate that attentional refreshing draws on semantic representations in LTM to reactivate WM representations, thus strengthening the benefit of semantic cues.

General models of WM have, likewise, shifted to allow for this co-operation between WM and LTM. The well-known Baddeley and Hitch (1974) multi-component model, for example, was updated to include an episodic buffer (Baddeley, 2000), a system designed specifically to allow for information to pass back and forth between WM and LTM. Some models go even further and directly implement WM as a part of LTM. Cowan's (1988) embedded processes model, for example, proposes that WM is actually an interaction between activation in LTM, and attention, with multiple LTM representations active at a given time, and that activation being maintained via the focus of attention, which can be thought of roughly as the current contents of consciousness. The controlled attention model (Kane & Engle, 2002) makes similar assumptions, but focuses more heavily on how the number of items captured by attention, as well as how effectively attention can be focused. In either case, however, WM exists as more of an interaction between LTM and attention, which is greater than the sum of its parts, rather than as a fully separate system. Regardless of if we view WM as a separate system that interacts with LTM or as a subsystem of LTM, however, it opens the possibility of WM offloading relational binding to LTM. Given how the fundamental structure of LTM seems to be built around binding, it wouldn't be unreasonable to suggest that WM might make use of that structure in order to retain a higher item capacity when presented with the need to store both items and bindings together.

Serial Position Effects

Going beyond models indicating an overlap or an interaction between WM and LTM, findings in the serial position literature have called into question if there is sufficient evidence to continue to separate the systems at all. In general, examinations of serial position data have shown that stimuli at the start and end of a list are better remembered than those in the middle, known as the primacy and recency effect respectively (Murdock, 1962). The recency effect has traditionally been attributed to information presented later in the list still being in WM at the time of test, allowing for easier recall (Brodie & Murdock, 1977; Capitani et al., 1992; Glanzer & Cunitz, 1966; McElree, 2006). By contrast, primacy effects are held to be the result of extensive rehearsal for early items in the list, creating stronger LTM traces (Brodie & Murdock, 1977). On top of this, increase in RI has been shown to reduce recency effects (Atkinson

& Shiffrin, 1971). This recency reduction as a function of RI has previously been held to be in-line with the interpretation of recency effects as a function of WM. The initial interpretation of these findings were based in decay theory (Brown, 1958), in which information is lost from WM as a factor of how long it's been held for. Thus, increasing the RI allows for the WM traces to decay, removing any recency effects (Glanzer & Cunitz, 1966; Postman & Phillips, 1965). However, Bjork and Whitten (1974) were able to demonstrate that there is no loss of recency when RI is increased as long as the inter-stimulus-interval (ISI) is increased alongside it. One potential explanation for this is the idea of temporal distinctiveness: that the loss of recency from increased ISI is not caused by memoranda decaying out of WM, but by the more recent memoranda seeming less distinct from older ones after the passage of time (Brown et al., 2007). A popular analogy for temporal distinctiveness theory is that of telephone poles receding into the distance, with the telephone poles acting as memoranda, and physical distance between the poles acting as temporal distance between the memoranda (Crowder, 1976). Just as poles closer to an observer appear further apart than those far away, more recent items are more distinct to the participant and thus easier to recall. Just as moving the observer away from the nearest pole causes all poles to appear closer together, increasing the RI reduces distinctiveness between the items, thus reducing the distinctiveness advantage for recent items. Increasing the ISI is then equivalent to increasing the physical distance between the poles in proportion to the increased distance of the observer, so that they all appear as distinct as they originally had. Variations of temporal ratios between items, such as distinctiveness, form the basis for many single-store models of memory, such as the Scale Invariant memory and Perceptual Learning (SIMPLE) model proposed by Neath and

Brown (2006). However, dual-store models (e.g Davelaar et al., 2005), supported by neuropsychological evidence of double dissociations between immediate and delayed serial position effects (Talmi et al., 2005; though see Nee et al., 2008), have also been proposed to account these recency effects while maintaining a distinction between WM and LTM. As such, the mechanisms by which the recency effect functions remain quite controversial.

Mathematical Models of WM

In addition to the behavioral data, mathematical models have also shifted to indicate a role of interaction between WM and LTM, or no distinction at all. Several early researchers attempted to create mathematical models of paired-associate memory across short retention intervals (RIs) that integrated both primary memory (i.e. STM as it was known at the time or WM in the vocabulary of the current paper) and secondary memory (i.e. LTM) systems (e.g. Atkinson & Crothers, 1964; Calfee & Atkinson, 1965; Greeno, 1967; Waugh & Norman, 1965). The common assumption of these models is that subjects either do not remember the proper response to a cue, or that the response is stored in primary memory, secondary memory, or both. As such, in spite of the RI always being short-term, participants may be recalling information from either primary and/or secondary memory. A common assumption of these models is all-or-nothing encoding. That is that if an association is held in memory, it will always be correctly recalled. The distinction between primary and secondary memory in these models is that information is first stored in primary memory. Once the information is in primary memory it may be additionally stored into secondary memory, but will eventually fall out of primary memory, whether or not it has been copied to secondary memory. Information stored in secondary memory, however, is permanent. Unfortunately, the particulars of these models make them difficult to apply to our present hypothesis, as the models assume both perfect recall from both memory stores as well as perfect retention in secondary memory. As such, when there is a failure in memory, the models can only attribute that failure to a failure to successfully store the memory in either primary or secondary memory, or a failure for the memory to be copied from primary to secondary memory before forgetting in primary memory takes place. As such, the models are difficult to apply to any framework that allows for failure of retrieval from secondary memory, as they do not include a mechanism for this. This may not affect the predictive ability of these models, but it does put some limitations on their application, as they will inherently attribute retrieval failure to other mechanisms. These all-or-nothing models also faced some criticism at the time. For example, Peterson et al (1962), in an early study, found that factors known to influence long-term retention, such as repetition and testing effects, also had an effect on short-term retention of paired-associate stimuli, which they found incompatible with all-or-nothing models such as the ones discussed above, as well as suggesting that it may be more parsimonious to assume that primary and secondary memory operated similarly. Murdock and Hockley (1989) also suggest that though the mathematics of such models are powerful, they may not be able to conceptually support higher level cognition.

As noted previously, some models based on temporal distinctiveness do not use separate WM and LTM systems at all. The Oscillator-Based Associative Recall (OSCAR) model (Brown et al., 2000) links objects together via association to temporal context. The oscillators in this model are essentially signals that vary over different time scales. As such, individual items can be associated with the state of the signal at the time of encoding. Replay of this signal then allows for recall. As the items are linked to a signal that changes in a continuous manner over time, temporal distinctiveness allows for easier recall, as the more spacing there is in time between items, the more each item will be associated with a distinct oscillator signal. The Bottom-Up Multi-scale oscillator Population (BUMP) model by Hartley et al. (2016), uses similar temporal oscillators. However, BUMP refines on OSCAR by allowing the properties of the oscillators to be determined by the incoming stimuli, allowing for specific oscillators to be chosen to match the input frequency of the items presented. The SIMPLE model by Neath and Brown (2006) mentioned earlier also operates similarly but, rather than examining the relationship of items to a signal that oscillates over time it instead examines the local distinctiveness between items. In essence, unlike with the OSCAR model, in which increased spacing predicts better recall, due to more distinct cues, or the BUMP model in which an oscillator of appropriate distinctiveness is selected based on input, the SIMPLE model only cares about the consistency of the spacing. If all items are presented two seconds apart, or if all items are presented four seconds apart, the amount of distinctiveness is the same, as the presentation rate was uniform. However, if the spacing between items is uneven or, as described previously, there is an RI that is significantly longer than the presentation rate, the items become more or less distinct relative to each other.

In spite of the popularity of these temporal based models, some models continue to distinguish between WM and LTM operations, such as the convolution-correlation model (Murdock & Hockley, 1989). This model assumes all information is stored in a common memory store, with WM serving to perform the convolution operation, in which both pieces of item information are merged into a single gestalt representation. By way of explanation, the authors compare this convolution process to that of baking, in which individual ingredients, such as eggs, milk, and flour, are combined into a cake batter, with the ingredients taking the role of items, and their unified batter state being the final associative representation. This idea has transferred into the later Theory of Distributed Associative Memory 2 (TODAM2) model (Murdock, 1999), which re-iterates this idea of a single-store system for both item and associative WM. Kelley and Wixted (2001) additionally found that the characteristics of receiver operating characteristic (ROC) curves were best explained by a model in which item and binding information both contribute to the likelihood of a correct response. They dubbed this a some-or-nothing model, so named because binding information alone is necessary, but not sufficient for correct recall. As such, either no binding information is present, or some of the required information is stored as binding information, but participants must sum both item and binding information to reach a conclusion on a recognition test. However, the authors note this model is at least potentially compatible with TODAM2.

Interestingly, TODAM2 would seem to offer a potential solution to how associative information is stored in WM, with regards to capacity, given that multiple vectors can be convoluted into a single vector for storage. This would seem to imply that both items in a paired-associate test start as separate vectors, which would each take up one slot in WM, but once convoluted into a single vector would only take up a single slot in WM. However, TODAM2 does not actually predict that associative information is held in WM. Rather, as mentioned above, it predicts that the convolution process, as well as the inverse correlation operation needed for retrieval, take place in a WM system with five arrays available to hold these item vectors, but that actual storage takes place in a separate ‘query’ system (Murdock, 1995). TODAM2 does not, however, directly correlate their query system with other models of memory or propose a verbal model to match the mathematical model. Mathematical models such as TODAM2 are often powerfully predictive, and useful in disambiguating verbal models, which can sometimes have vague or contradictory predictions, based on personal interpretation of the model. However, we believe a verbal level interpretation of these models is still important if our findings are to have practical effects outside the field or allow for understanding of the systems involved. Nevertheless, we believe the hypothesis tested in the current study, that relational bindings pass through the focus of attention but are not maintained there, and thus not stored in WM even across short time spans, matches nicely with TODAM2’s conception of bindings being held in a query system outside of WM.

Neurological Similarities Between WM and LTM

Neurological research additionally provides evidence that relational bindings may be held in a way more similar to LTM than WM. Studies of patients with anterograde amnesia, a form of amnesia in which the encoding of new LTM information is impaired, have typically found that patients show a severe detriment in relational binding in WM, while maintaining normal WM feature binding abilities (Jonin et al., 2019; Olson et al., 2006a,b; Parra et al., 2015; Shrager et al., 2008). It’s unclear if this deficit is due to the hippocampal damage commonly held to be a cause of anterograde amnesia, or damage to the outlying areas near the hippocampus. In a case study of a patient with highly localized hippocampal damage Baddeley et al (2010) found no impairment in relational binding abilities and argues that the relational deficit is due to damage to outlying areas, and not the hippocampus itself, which they maintain is not involved in WM processes. Interestingly, Shrager et al (2008) found that patients with anterograde amnesia were only impaired in WM relational binding when a concurrent task prevented rehearsal. They interpreted this finding as being due to intact WM processes allowing for relational information to be stored via WM rehearsal, but LTM deficits preventing relational information from being stored when rehearsal was prevented. One implication of this interpretation may then be that, when relational bindings are not able to be maintained through active rehearsal, they rely on use of participant's LTM, even across a short time-scale. Given prior studies had found this relational deficit without specific manipulations on rehearsal, it would appear that while rehearsal may act as reasonable compensatory mechanism for relational maintenance in the absence of LTM, it is not the default means by which relational information is maintained.

Outside of case studies on patients with amnesia, evidence for relational WM being similar to LTM have been shown in subsequent memory research as well. In this subsequent memory paradigm, participants perform the encoding stage of a memory experiment while inside an fMRI scanner, and then perform the test phase outside of the scanner. Correct responses on this subsequent test are then correlated with activity at study in order to determine what areas support successful encoding. These studies have generally shown that very similar hippocampal areas predict success in both WM and LTM binding tasks. Subsequent correct answers on WM binding tasks have been associated with the left parahippocampal gyrus (Bergmann et al., 2012), and left anterior hippocampus (Hannula & Ranganath, 2008). In a review Davachi (2006) notes a general finding of left anterior hippocampal activity correlating with subsequent LTM memory for relational stimuli and states the research is consistent with the idea that the perirhinal cortex supports item memory in LTM, while the hippocampus supports relational LTM memory. She also notes mixed findings on the posterior parahippocampal cortex, which has been shown to support item memory in some studies, and relational memory in others. Overall, the findings that relational binding in WM is handled by the same structures as in LTM are in line with the idea that relational information is stored in LTM regardless of the timescale used.

Current Studies

In the present studies, we hypothesize that relational memory is stored primarily in LTM even over short time spans. We believe this hypothesis is best explained using the embedded processes model (Cowan, 1988, 2019). Specifically, we propose that while individual items are retained in the focus of attention across short intervals, leading to the classic WM effects, relational information between items passes through the focus of attention and is held in activated LTM instead, but is not maintained via the focus of attention. As noted previously, the current understanding of LTM is based in the formation and retrieval of associations, and most if not all current verbal models of WM allow for transfer of information both to and from LTM. While the fact that it's possible for WM to potentially borrow binding resources from LTM does not guarantee that this is what is taking place, we believed it to be highly likely, given the limited capacity and resources that characterize WM, that the system would take advantage of its links to a specialized binding system in order to operate more efficiently. This would also match the neural evidence, which shows areas typically associated with LTM processes are also used specifically for WM binding, as well as case-studies showing that patients with impaired LTM do not show impairment for WM except in the specific case of relational binding tasks.

Additionally, this hypothesis would help to answer the question of how storage of relational information affects WM capacity. Current theories typically focus on the number of items and chunks which can be held in WM, but rarely if ever are associations between items factored into capacity outside of the context of chunking. While chunking provides good explanations of binding when participants already have an LTM representation to fall back on, (such as a pre-existing relationship, or through having been trained in the association by the experimenters) it's less useful for novel unrelated pairs in which the participants have no pre-existing LTM association to allow them to chunk the information but must still remember a connection between the pairs. As a real-world example, when being introduced to new people, there will not usually be a pre-existing LTM relationship between their face and their name to aid with chunking, and yet these face-name bindings must still be stored to avoid social embarrassment. Storage of relational bindings as LTM associations, in addition to seeming likely for the reasons mentioned above, would resolve this issue without conflicting with current theories as to WM item capacity. Additionally, this hypothesis would act as a verbal counterpoint to the TODAM2 model, making it easier to conceptualize the more abstract components of the model, as well as lending additional evidence to help determine which of the myriad of models most match reality. Finally, use of LTM for storage of relational bindings may act as an alternative explanation for why serial position tasks do not appear to show evidence of a distinction between WM and LTM.

Conditions and Predictions

As we are primarily interested in how relational bindings are stored in WM, and their relationship to associative LTM, we examined serial position effects on relational bindings, as this task has been hypothesized to show both LTM and WM effects. It should be noted that for our choice of conditions we generally use a dual-store interpretation of previous findings. While this is still controversial in the literature, any argument for a single-store interpretation of the predicted effect of our conditions would, by extension, automatically require our hypothesis of relational binding in WM and associative LTM being the same to be correct, given WM and LTM being the same across all measures is the defining aspect of a single-store model. We began our design with a fairly standard serial position paradigm in which participants are presented with a list of memoranda, presented one at a time, with no inter-stimulus interval (ISI), and then tested after a very brief RI, with the distinction that our memoranda are paired associates, rather than items. Because of the minimal RI, bindings in the later serial positions only need to be retained for a short term. As such, we refer to this as the STM condition. While a common assumption would be that these short-term bindings are held in WM, we hypothesize that they are held in LTM, regardless of the duration, hence the label of STM rather than WM for this condition. If recency effects in serial position are caused by WM storage, we could then expect that, if our hypothesis is correct, we should not replicate recency effects for relational bindings, as even the most recent bindings would be stored in LTM. This would be consistent with previous findings showing that a recency effect is not shown in recognition memory for bindings (Murdock & Hockley, 1989), while such an effect is found for recognition memory for items (e.g. Crites et al., 1998; Monsell, 1978; Neath, 1993).

However, observation of a recency effect alone may not be enough to disconfirm the hypothesis. For example, dual-store models of long-term recency (e.g. Davelaar et al., 2005) attribute recency effects in LTM to different mechanisms than effects in WM, such as contextual retrieval. It's possible, however unlikely, that an effect outside of WM storage could lead to recency effects. However, if this is the case, then manipulations designed to remove information from WM should have no effect on LTM performance. As such, we also included an LTM condition, in which the RI was increased so as to remove information from working memory. If a recency effect is found, and relational bindings are held in WM, then this should remove or reduce recency effects, as it does for item memory. However, if the recency effect is due to factors outside WM, there should be no effect of increased RI. We have labeled this as the LTM temporally non-distinct condition.

Given we also wish to clarify temporal distinctiveness effects, we additionally include a temporally distinct LTM condition, in which the ISI is increased alongside the RI to maintain distinctiveness. As has been noted above, dual-store models typically attribute the long-term recency effect to different factors than the short-term recency effect, such as differential context. Because of this, if relational bindings are held in WM over the short-term, or in LTM over the short-term, it should make no difference with regards to long-term recency. Either hypothesis would predict a long-term recency effect under dual-store models. However, temporal distinctiveness models would predict a similar recency effect between our STM condition and a temporally distinct LTM condition, given distinctiveness is roughly the same in both. By contrast, we predict no recency effect in STM, but a recency effect in temporally distinct LTM, in direct contrast to temporal distinctiveness models.

Finally, we also chose to include an unfilled control condition for LTM. The purpose of this condition was not to directly test a hypothesis, but simply to rule out any undue effects of the secondary task used to prevent rehearsal in the other LTM conditions. For this condition, we use the same increased ISI and RI as in the temporally distinct condition, but we neglect to fill this interval with a secondary task. As a result, participants are free to rehearse during the unfilled intervals. As a result, if our hypothesis is correct, we would expect performance in this condition to be higher overall than the other conditions, given the increased time to form stable LTM representations for the bindings. If our hypothesis is incorrect, this condition should look fairly similar to the STM condition, but with increased performance, as the unfilled RI would allow participants to continue to refresh the recent bindings in WM until the start of the test, in addition to the increased time to form stable representations of the older pairs in LTM. For an overview of these hypothesis and conditions, see Table 1 and Figure 1 respectively.

Table 1

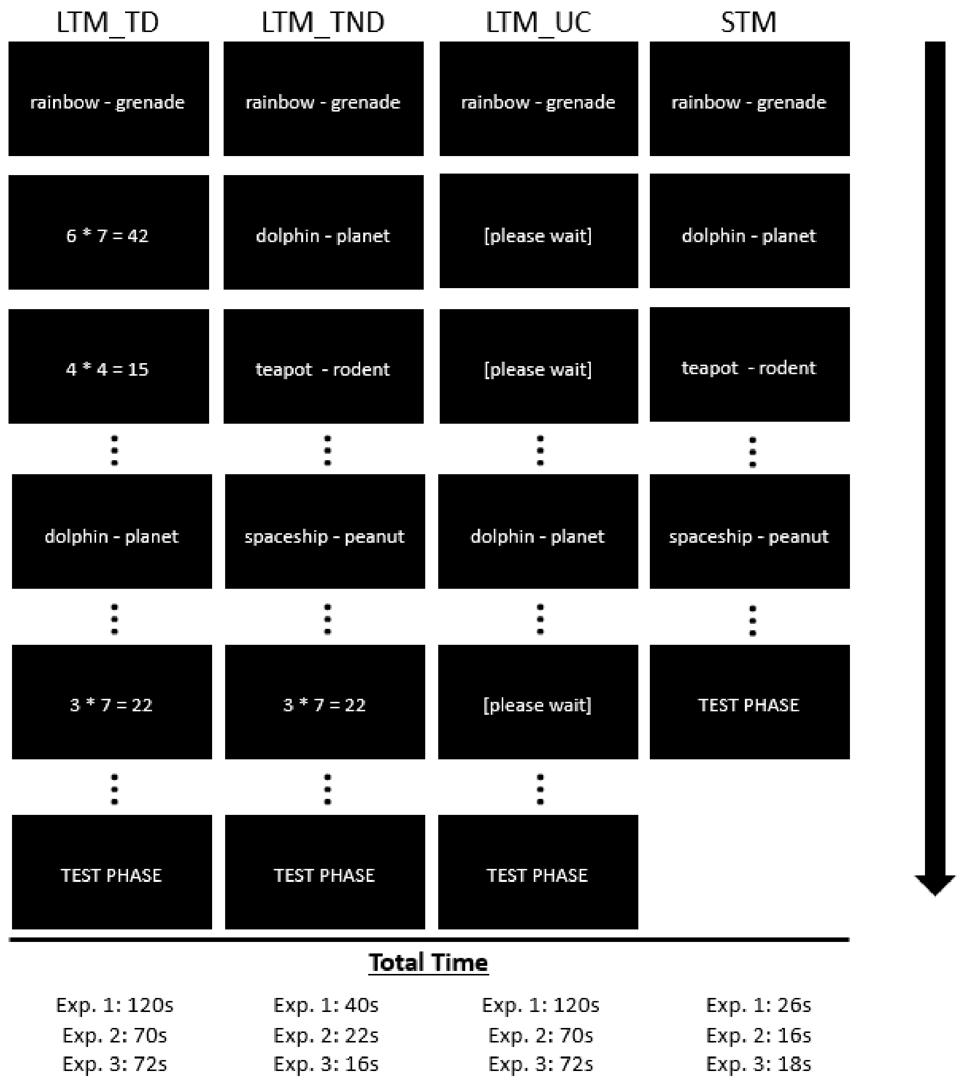
Hypothesis by Model for Each Condition

	Short-Term Binding in WM	Short-Term Binding in LTM
LTM Temporally Non-Distinct (LTM_TND)	Recency effect not observed	Recency effect matches STM
LTM Temporally Distinct (LTM_TD)	Recency effect observed	Recency effect observed
LTM Unfilled Control (LTM_UC)	Recency effect observed	Recency effect not observed
STM	Recency effect observed	Recency effect matches LTM Non-Distinct

Note. Short-Term Binding in WM and Short-Term Binding in LTM models are both dual-store models. Single-store models make the same predictions as Short-Term Binding in WM.

Figure 1

Overview of Study Phase by Condition



Note. LTM_TD = temporally distinct long-term, LTM_TND = temporally non-distinct long-term memory, LTM_UC = unfilled control long-term memory, STM = short term memory. Ellipses do not represent equivalent amounts of time across all conditions. Study slide examples correspond to the paired associates in Experiment 1 but can be replaced with singletons for Experiments 2 and 3.

Experiment 1

For Experiment 1 we wanted to directly examine how delay and distinctiveness affected relational binding. In order for conditions to be similar to Bjork and Whitten's (1974) study, we tried to replicate their conditions as closely as possible. This included the use of unrelated word pairs as study stimuli, with the primary difference being that, unlike Bjork and Whitten, we instructed participants to remember words as pairs, and tested them on their ability to recall the association. Unfortunately, due to the COVID-19 pandemic, we were not able to collect participant data in-person. Our online data collection software was not able to record participant dialog, and based on previous experience, we did not believe that asking participants to type their responses inside the time constraints of the study would allow for them to respond effectively. As such, rather than using a cued-recall test, which would have likely been the closest relational analog to Bjork and Whitten's original test, we instead opted to use an associative recognition test in which participants would have to determine if pairs at test were intact or recombined. Additionally, due to the large number of conditions in the study, and concerns about participant fatigue or waning attention in an online format, the overall length of the word lists was shortened in comparison to the original study.

Similar to the Bjork and Whitten study, we tested an STM condition against a condition in which the RI was increased, so as to remove information from WM and forcing participants to rely on LTM. Additionally, we tested a condition in which ISI was increased alongside RI in order to maintain the same temporal distinctiveness between word pairs that exists in the STM. In order to prevent rehearsal in the longer RI and ISI in these conditions, we used the same equation verification task as in the original study.

However, in order to make sure that there were no unintended effects of this task on memory performance, we additionally included a condition that maintained temporal distinctiveness, but which had unfilled intervals.

We predicted that, unlike in prior item memory experiments, there would be no recency effect observed in the STM condition, but that long-term recency effects would continue to be observed. Alternatively, if a recency effect was found in STM, it would not be reduced in the temporally non-distinct LTM condition, in contrast to item literature.

As our predictions rely on null effects, we additionally opted to test using Bayesian model comparison, so that we would be able to show evidence in favor of the null hypothesis where applicable.

Methods

Participants.

56 participants were recruited in total with 32 participants recruited via Prolific (www.prolific.co) in exchange for a minor cash reward with an additional 24 via the University of Missouri SONA system in exchange for course credit. 12 participants were dropped from the analysis due to an a-priori decision criterion to drop participants performing below chance level in the equation verification interpolated activity. Of the remaining 44 participants, 29 were from Prolific, and 15 from the University of Missouri (age range: 18-29 [*M* = 21.20, *SD* = 3.12]. Gender distribution: 33 male, 9 female, 2 non-binary).

Stimuli and Materials.

Stimuli were 192 disyllabic high-frequency concrete nouns organized into 96 unrelated word pairs presented in 20-point Arial font. Each word pair was sampled from the set of unrelated word pairs used by Naveh-Benjamin & Kilb (2014). For online data collection, the software PsyToolkit was used (Stoet, 2010, 2017).

Design.

Experiment 1 used a within-subjects 4 (condition: STM, temporally distinct LTM, temporally non-distinct LTM, control LTM) by 6 (position: 1 through 6) design.

Procedure.

During the study phase, participants saw lists of six unrelated word pairs, with each pair presented for four seconds. In the STM condition, there was no ISI and an RI of only two seconds. In the temporally non-distinct LTM condition, there was also no ISI, but an RI of 16 seconds, during which participants performed an equation verification task, described below. In the temporally distinct LTM condition, there was an ISI and RI of 16 seconds each, during which participants completed the same equation verification task. Finally, the LTM control condition had the same 16 second ISI and RI as the temporally distinct condition, but with no equation verification task. Instead, participants were given a screen cuing them to wait for the next event during this time. The equation verification task consisted of simple multiplication equations. Each equation consisted of the multiplication of two single digits, with each digit always being greater than one. Half of the equations were correct, while half were incorrect. The incorrect equation results were always wrong by a factor of plus or minus one, in equal proportion. Equations were presented at a rate of two seconds per problem. Participants were asked to respond to an incorrect problem by pressing the “0” key on their keyboard, and a correct problem by pressing “1.” For the test phase, participants were given a recognition test in which they were presented with six word pairs one at a time. In half of these test trials, which were randomized, participants were shown intact word pairs from the study phase (targets) and in the other half consisted of recombined word pairs from the study phase (lures). Participants were given four seconds to press either “1” if they had seen the two words presented together previously, or “0” if the two words had originally been part of different pairs. Because there is a speed and accuracy advantage for associations in the forward direction (Yang et al., 2013), when pairs were recombined, we considered their serial position to be the original position of the first word in the pair, as participants were more likely to recognize the incorrect association based on that word first. Participants were presented with four total study/test pair blocks for each of the four conditions.

Results

Due to our choice of logistic regression for data analysis, we opted to calculate odds ratios for condition and position for the dataset as a whole as a descriptive statistic (see Table 2). As logistic regression estimates odds ratios on a logarithmic scale for regression coefficients, rather than mean correct as an ANOVA would, we believed these metrics best describe the data as our model views it. Note that for mixed logit models, such as the ones conducted in this experiment, each trial is considered an observation, rather than each participant being an observation. As such, each observation is discrete and binary, rather than continuous, meaning standard dispersion metrics are not applicable to the raw data. Instead, we report the log odds and standard deviation of a random intercept value fitted by the model to handle inter-participant differences, described in more detail below. Averages of each participant’s proportion correct data and related standard errors were also calculated (see Table A1, Figure B1) but we stress that these individual averages were not used as input data, nor does the model consider variability in the same way as ANOVA, so inferences based on standard error reported there may not apply to the current models. However, the proportion correct data themselves can be applied to the models when taken as proportion correct for the entire data set, rather than averages of each participant's proportion correct (i.e. ignoring standard error).

Table 2

Experiment 1 – Odds Ratios

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6
LTM_TD	2.32	1.75	2.14	1.93	2.52	3.09
LTM_TND	1.75	1.44	2.09	2.14	2.32	1.89
LTM_UC	2.83	1.98	2.45	3.09	3.19	3.19
STM_ND	2.03	2.45	2.59	2.09	2.14	2.59

Note. LTM_TD = temporally distinct long-term memory (ISI = 16s, RI = 16s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 16s), LTM_UC = unfilled control long-term memory (ISI = 16s, RI = 16s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Data were analyzed using a series of mixed logit models. Separate models were fit for the effect of each condition individually, together, and finally together with an interaction effect. These are considered to be estimates of fixed effects by the models. However, each model also included a random effect of participant. The model intercept for each participant is considered to be drawn from a random distribution. This random intercept distribution is estimated by the model for best fit. Bayes factors for each model were calculated via comparison of all models against a null model, which contained the random intercept only, with posterior odds being divided among each model based on likelihood. Model comparison showed strongest evidence for the condition only model, but also evidence for the position + condition model, as well as the full model, compared to the null (see Table 3).

Table 3

Experiment 1 – Bayes Factor Comparison

	BF
Condition	30.90
Position	0.40
Condition + Position	12.88
Condition + Position + (Condition * Position)	11.40

Note. Comparison is against null hypothesis of random intercept only.

Bayes factors for inclusion were also conducted by iteratively adding in each model element and comparing against the previous model without that element, similar to Type I Sums of Squares in an ANOVA. Inclusion factors showed strong evidence in favor of the condition only model, but no evidence for additional inclusion of the position effect or interaction term (see Table 4). Based on the combination of these results, we concluded that while there was some evidence for the condition + position model, as well as the full model, when compared against the null, there was not sufficient evidence for their inclusion when compared against each other and that the condition only model was preferable.

Table 4

Experiment 1 - Bayes Factors for Model Inclusion

	Prior	Posterior	Inclusion BF
Condition	.60	.98	26.65
Condition + Position	.60	.43	.50
Condition + Position + (Condition * Position)	.20	.20	.99

Examining the random intercept and deviation of the selected model allows us to get an idea of variability between participants. Using the condition only model, the log odds ratio for the model random intercept was 1.15 (*SD* = .89). The estimated probability of correct response for the STM condition was .72 (*HDI* .66 - .78). For the non-distinct LTM condition, estimated probability correct was .68 (*HDI* .61 - .74), whereas for temporally distinct LTM it was .68 (*HDI* .66 - .78). Finally, for the LTM control condition, it was .76 (*HDI* .70 - .82)[1].

Pairwise comparisons among the four conditions were conducted on fixed effect values using the Region of Practical Equivalence (ROPE) test. For the ROPE test, a region is defined around the hypothesized null value that is considered 'practically equivalent' to the null value. For the current test we used the recommended default range of -.18 to .18 for logistic models (Kruschke & Liddell, 2018). If more than a given amount of the estimate's Highest Density Interval (HDI) falls inside this region, then the estimate is considered to be identical to the hypothesized null value. However, if a given percentage of the HDI falls outside this region, then we consider it as evidence against

[1] Due to the selected model using only one factor of four levels, it was decided that a figure of the posterior fixed effects was not necessary for this experiment.

the null. Based on Makowski et al (2019), the null hypothesis of no difference between means was considered to be rejected if less than 2.5% of the HDI fell within the ROPE and accepted if more than 97.5% of the HDI fell within the ROPE. All other values were considered inconclusive. The only significant difference between conditions was that performance in the LTM control condition was higher than that in the non-distinct LTM condition (1.47% inside ROPE).

Discussion

Our results show evidence for an effect of condition, but no conclusive evidence for or against effects of position or a position by condition interaction. The former is particularly surprising, as, while we did not find evidence against a position effect, we believe there should be strong evidence for an effect of position in a sample of this size. While a lack of a recency effect for STM would be in line with our hypothesis of bindings being stored in LTM, we would still expect to see primacy effects for early items in the list as well as a long-term recency effect in the temporally distinct LTM condition. As such, while the results are partially in line with the hypothesis, we cannot ignore the possibility that the alterations to the Bjork and Whitten (1974) procedure affected the ability of the study to detect serial position effects.

As support for this possibility, we note that Hockley (1989) previously found recency effects for associative recall, but not recognition using an item-item binding paradigm. They attribute this recency effect for recall to be due to mechanisms of the confabulation process predicted by TODAM2. However, this was not the intended hypothesis of their study and does not appear to have been replicated in other research. There is a possibility that recognition tests on item-item binding fail to provide the usual serial position effects in general. Due to the lack of research focusing on this area, it's difficult to hypothesize as to why item-item bindings might show recency effects for recall, but not recognition tests, but we cannot rule out the possibility, given the lack of expected effects, that the lack of recency in STM is due to a peculiarity in the experiment, rather than lack of WM storage.

Experiment 2

For Experiment 2 we wished to correct for the possibility that item-item binding effects on serial position existed but were not being reflected in our test paradigm. As noted above, due to the COVID-19 pandemic we were unable to simply move to a cued-recall paradigm. Instead, we decided to try to amplify potential serial position effects by testing participants on item-position bindings, rather than item-item bindings. This would force participants to attend more to the position information of each item, and the position of each item relative to the other, hence potentially amplifying any serial position effects and making them more evident on the test phase. In order to create a recognition test of item-location binding that participants would be able to easily perform during the study, we opted to show participants singletons instead of word pairs at study. In addition, rather than having intact and recombined pairs at test, participants were instead shown intact or recombined orders, where they would be shown two words that were either, from left to right, in the same order, or the reversed order compared to the study phase, with participants responding if the order was intact or recombined. These pairs were always contiguous words in the study phase. However, in order to prevent participants from simply forming item-item bindings, participants were not aware of which two words in a given study phase would form the first and second words of a test pair.

As before, we hypothesized that no recency effects would be observed for the STM or temporally non-distinct LTM condition but would be observed in the temporally distinct LTM condition.

Methods

Participants.

37 participants from the University of Missouri participated for course-related credit. 3 were dropped from analysis due to failure to perform over chance level at the interpolated activity, for a remaining total of 34 (age range: 17-36 [M = 19.19, SD = 3.10]. Gender distribution: 29 male, 6 female, 2 non-binary).

Stimuli and Materials.

Stimuli were the same words as in Experiment 1 but presented as singletons, rather than paired associates. For online data collection, the software PsyToolkit was used (Stoet, 2010, 2017).

Design.

The experimental design was the same as Experiment 1.

Procedure.

The study phase was the same as in Experiment 1, except that instead of presenting 12 words per block as six paired associates, we presented seven words per block as singletons. In order to maintain the overall study time per word, the presentation time was likewise reduced to two seconds. The extended RI, the three LTM conditions, as well as the extended ISI for the temporally distinct and control LTM conditions was also reduced from 16 to eight seconds. In order to make up for the reduction in overall words presented, the number of blocks per condition was doubled from four to eight. Finally, instead of being instructed to remember which words were presented together, participants were instructed to remember the order in which words were presented.

During each test phase trial participants were presented with two words from adjacent serial positions during the study phase. In half of the trials, the words were presented in their original order. In the other half, the word order was reversed. Participants were instructed to press “1” if the words were in an intact order, or “0” if words were in a reversed order. In order to prevent participants from forming inter-item bindings instead of item-position bindings, different combinations of serial position were used. Half of the blocks tested on pairs in positions 1-2, 3-4, and 5-6, and the other half tested on pairs 2-3, 4-5, and 6-7. The order in which participants received the different pair tests was randomized between blocks, but each set of pair tests was used in exactly half of the trials of each condition.

Results

We calculated odds ratios for the full data set (see Table 5. For average participant proportion correct data see Table A2, Figure B2).

Table 5

Experiment 2 – Odds Ratios

	Position 1-2	Position 2-3	Position 3-4	Position 4-5	Position 5-6	Position 6-7
LTM_TD	0.74	1.35	1.00	1.24	0.95	1.55
LTM_TND	1.21	1.28	1.64	1.14	1.51	1.43
LTM_UC	1.74	0.80	1.28	1.31	1.28	1.60
STM	0.95	0.97	1.03	1.31	2.79	1.28

Note. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Participant data were analyzed using the same set of mixed-logit models as in Experiment 1. Comparison of models against the null hypothesis of variable intercept only showed strong evidence in favor of the interaction model (see Table 6).

Table 6

Experiment 2 – Bayes Factor Comparison

	BF
Condition	0.14
Position	0.99
Condition + Position	0.15
Condition + Position + (Condition * Position)	1.51e+06

Note. Comparison is against null hypothesis of random intercept only.

Bayes factor tests on inclusion of each individual model parameter showed strong evidence in favor of including both condition + position factors, as well as the interaction (see Table 7).

Table 7

Experiment 2 - Bayes Factors for Model Inclusion

	Prior	Posterior	Inclusion BF
Condition	.60	1.00	4.90e+05
Condition + Position	.60	1.00	8.71e+05
Condition + Position + (Condition * Position)	.20	1.00	2.58e+06

Using the full model, the log odds ratio for the model random intercept was .57 (SD = .43). Log odds ratios of the fixed effects and their HDI have been transformed into probabilities for ease of understanding (see Table 8, Figure 2).

Table 8

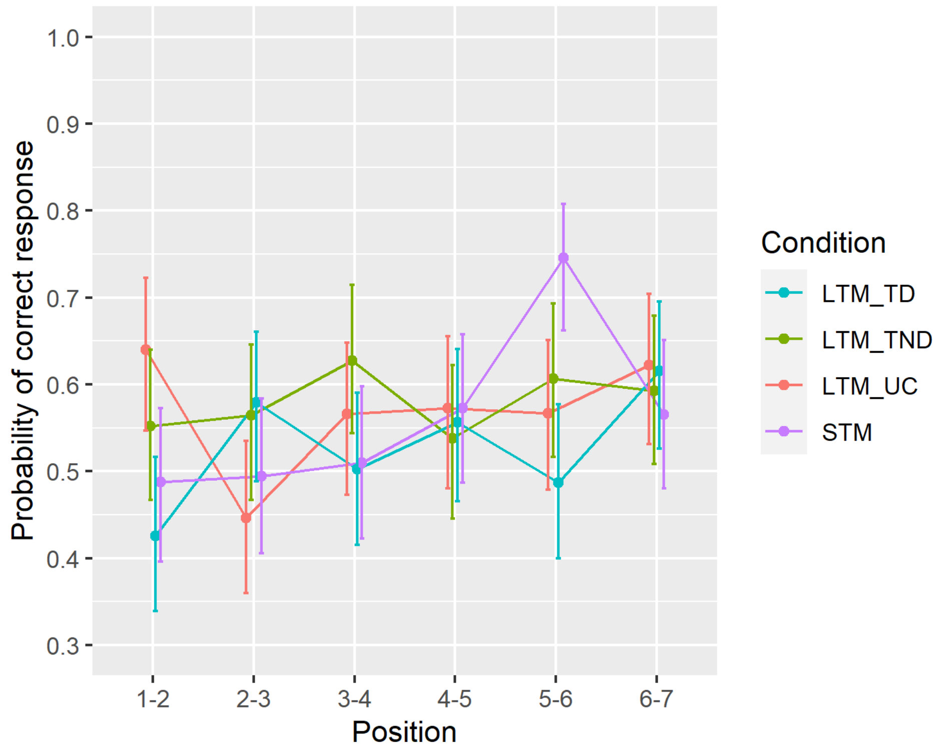
Experiment 2 – Posterior Fixed Effects

	Position 1-2	Position 2-3	Position 3-4	Position 4-5	Position 5-6	Position 6-7
LTM_TD	.43 (.34 - .52)	.58 (.49 - .66)	.50 (.42 - .59)	.56 (.47 - .64)	.49 (.40 - .57)	.62 (.53 - .70)
LTM_TND	.55 (.47 - .64)	.56 (.47 - .65)	.63 (.54 - .71)	.54 (.45 - .62)	.61 (.52 - .69)	.59 (.51 - .68)
LTM_UC	.64 (.55 - .73)	.45 (.36 - .53)	.57 (.47 - .65)	.57 (.49 - .66)	.57 (.48 - .65)	.62 (.53 - .70)
STM	.49 (.40 - .57)	.49 (.41 - .58)	.51 (.42 - .60)	.57 (.49 - .66)	.75 (.67 - .82)	.57 (.48 - .65)

Note. Posterior fixed effects represented as probabilities. Parentheses represent 95% High Density Interval (HDI). LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Figure 2

Experiment 2 - Posterior Fixed Effects



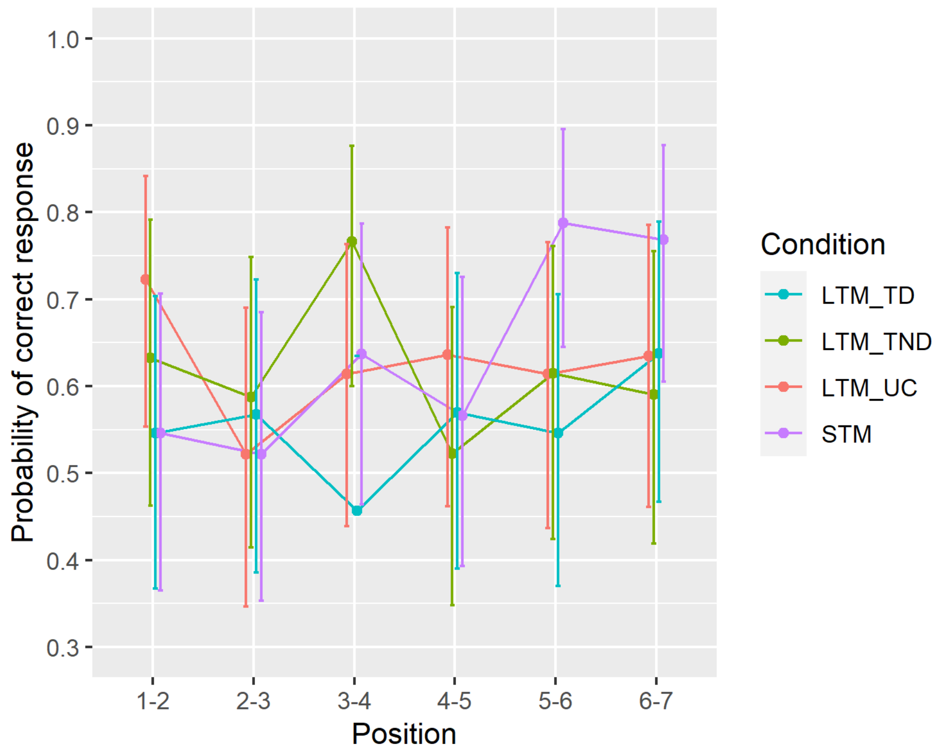
Note. Posterior fixed effects represented as probabilities. Error bars represent 95% HDI. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Examination of the model fit shows participants generally failing to perform above chance (50%) level of performance, making interpretation of the data difficult due to floor level effects. Of note, however, is the dramatic increase in performance for STM in the 5-6 position. Pairwise comparison, conducted using the same method as in Experiment 1, show that the probability of a correct response for position 5-6 was higher for the short-term condition than all other conditions with ROPE values < .001 in all cases.

In order to examine this effect, we looked at the participants' self-reported strategies gathered as part of the post-test questionnaire (PTQ). We grouped the strategies into five groups: binding words into pairs, sentence creation, story creation, repetition, and no clearly reported strategy. Examination of proportion correct data for each group showed above chance level performance for participants using deeper strategies (pair binding, sentence creation, and story creation) compared to those using repetition only or no strategy. As such we fit the full model again using only the 12 participants who reported using one of the three effective strategies (Figure 3, Table A3), as well as with the remainder of participants who used either repetition or no clear strategy (Figure 4, Table A4).

Figure 3

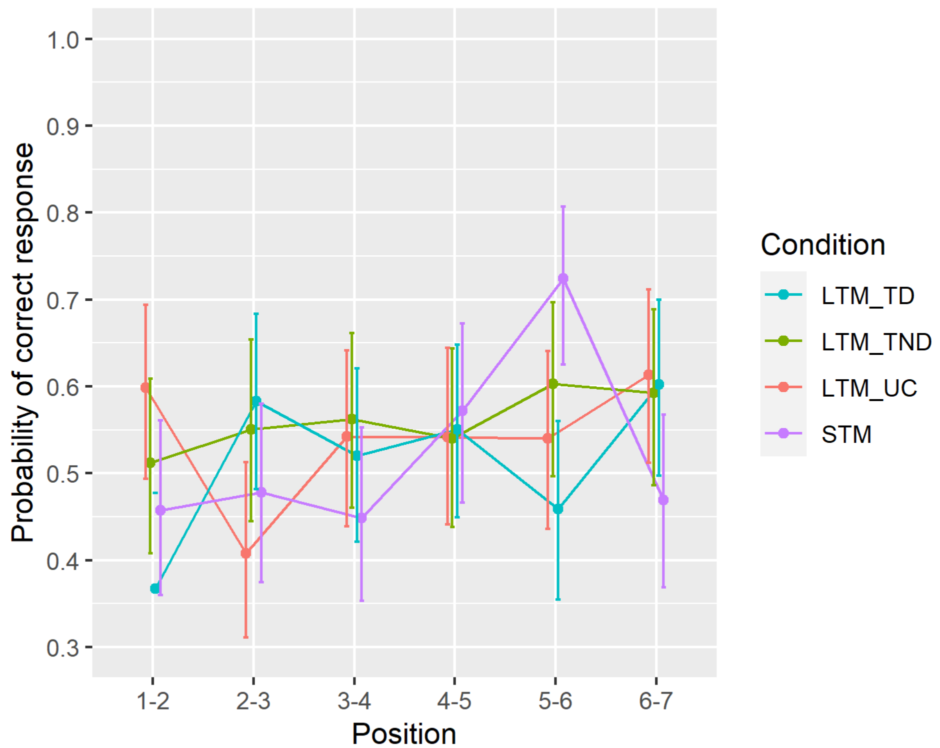
Experiment 2 – Posterior Fixed Effects for Deep Strategy Use



Note. Posterior fixed effects represented as probabilities. Error bars represent 95% HDI. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Figure 4

Experiment 2 – Posterior Fixed Effects for Shallow Strategy Use



Note. Posterior fixed effects represented as probabilities. Error bars represent 95% HDI. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Examination of these two figures makes it apparent that, for those using higher level strategies, there is a clear recency effect for the STM condition that does not appear in any other condition. The repetition or unclear strategy group, however, continues to show a spike in performance for position 5-6, which then falls sharply in position 6-7.

Discussion

Due to the overall low performance in Experiment 2, there is little clear evidence for or against our hypothesis. However, post-hoc examination of the use of strategy in the experiment reveals an interesting effect: participants who used strategies with more depth of processing showed a clear recency effect but only in the STM condition. This is particularly notable, as there is no recency effect in any LTM condition, even when temporal distinctiveness is maintained. In addition, use of repetition as a strategy was ineffective for position 6-7, whereas strategies with greater depth of processing, known to facilitate LTM (Moscovitch & Craik, 1976) showed recency effects in both positions 5-6 and 6-7. One potential explanation for this is that while associations were not maintained in the focus of attention, they may still have been in activated LTM during the test phase of the STM condition. As such, strategies that increase long-term retrieval increased performance for the more recent words still in activated LTM disproportionately. However, this does not account for the STM spike in position 5-6 seen regardless of strategy use. While position 5-6 could still be in activated long-term memory, it's unclear why the benefit only transfers to position 6-7 when deeper processing strategies are used. One possibility is that position 6-7 is too recent for a strong long-term retrieval trace to have formed yet, unless aided by specific strategies at encoding. Another possibility, given that multiple participants reported trying to form word pairs, is that participants expected words 1 and 2 to be paired together, and so on, and thus were expecting to be tested on 5-6, and not on 6-7, leading to greater performance on the former. This seems unlikely given that participants who reported this pair binding strategy demonstrated high performance on both positions 5-6 and 6-7. However, it should be noted that most participants in the unclear strategy condition failed to report a specific strategy but did not report use of no strategy. As such, they may have also been using strategies such as repetition of words in given pairs that they failed to report.

As alluded to previously, the other notable finding of Experiment 2 is that, regardless of strategy, participants show an increase for position 5-6 in the STM condition only. This is in contrast to previous serial position research where recency effects would be maintained over a long RI provided that temporal distinctiveness was maintained. As mentioned above, this may be due to activated long-term memory, rather than the focus of attention, being the factor behind the recency effect for associations. While this would be in line with our original hypothesis, it should be noted that this was not our original prediction. It also does not explain the failure to demonstrate a recency effect in the temporally distinct LTM condition, which is generally predicted by both single and dual-store models. One potential explanation for this may be that the contextual mechanisms theorized to support long-term recency are able to support memory for items, but not bindings. For example, one potential dual-store explanation for long-term recency is contextually guided retrieval (e.g. Glenberg et al., 1983), in which changes in context throughout the experiment serve as retrieval cues, and the increased spacing between presentations allows for more distinct cues, in a manner not unlike temporal oscillator models. If this is the case, it would not be surprising to find that these contextual cues may help retrieve individual items but provide relatively little information about order.

It's unclear why performance was dramatically lower for this experiment compared to Experiment 1. One potential reason may be that the item-position associations were weak enough to be easily disrupted when presented in a recombined format. We designed Experiment 3 to address this issue as well as the issue of the role of activated LTM.

Experiment 3

In order to increase performance in this experiment, we eliminated the yes/no test used in both Experiment 1 and 2 in favor of an item recognition and order reconstruction test, in which participants are presented with all the studied words of a list, as well as an equal number of new words. The participant task would be to select the correct words in the correct order. If the reason for the poor performance in Experiment 2 was because item-position binding information was fragile and disrupted by the presence of incorrect order pairs at test, then we should see improved performance for Experiment 3, as no recombined order pairs are presented.

Based on the results of Experiment 2 in which we see a potential recency effect for STM only, we amended our hypothesis for Experiment 3 to expect for the presence of activated LTM leading to a serial position effect, even if relational memory is stored outside of WM. Instead, we predict differential effects of condition and serial position depending on item vs relational memory. For item memory we predict a serial position effect in both STM, and temporally distinct LTM, but not non-distinct LTM, as has been shown in previous studies. For relational memory we expect a serial position effect in STM only, due to activated LTM traces, but not in the LTM conditions regardless of temporal distinctiveness, as would seem to be indicated by the results of Experiment 2.

Methods

Participants.

66 participants from the University of Missouri participated for course-related credit. 22 were dropped from analysis due to failure to perform over chance level at the

interpolated activity, for a remaining total of 44 (age range: 17-24 [$M = 19.30$, $SD = 1.36$]. Gender distribution: 30 male, 12 female, 2 non-binary).

Design.

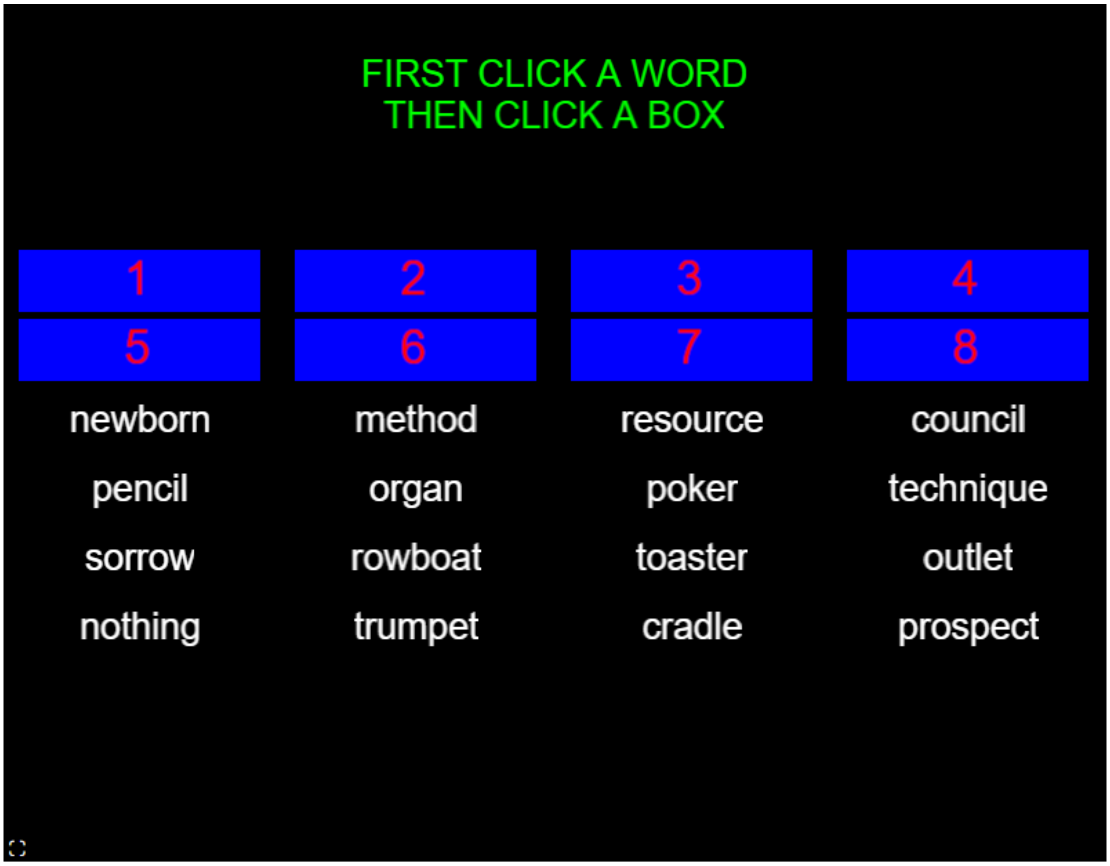
The design of Experiment 3 used the same four levels of the condition variable used in Experiment 1 and 2. However, the position variable was expanded to eight levels, and this 4x8 design was applied to both item recognition as well as memory for item-position binding.

Procedure.

The study phase followed the same basic procedure as in Experiment 2. However, eight words were presented during the study phase, rather than seven. Additionally, in order to prevent ceiling effects for the item recognition element of the test, presentation time of each stimulus was reduced to one second. In the test phase, participants were presented with a 4x4 array of 16 words, eight of which were the original study words, and eight of which were lures. Position of each word in the array was randomized for each participant. To further increase the difficulty of the item recognition test and reduce ceiling effects, in half of the tests the lures would include a 50/50 mix of both never-before-seen words, and words from previous study lists. Pilot testing indicated this increased proactive interference reduced overall item performance but had no effect on position and condition manipulations. Above the word array were eight boxes, labeled 1 through 8 respectively (see Figure 5). Participants were instructed to reconstruct the original study list by clicking first on a word which they had seen presented during the study phase, and then clicking the box that corresponded to the position in the study order where they had seen the words. Upon doing so, the selected word would vanish from the array and appear instead in the selected box.

Figure 5

Experiment 3 – Test Phase



The test phase ended once all eight boxes had been filled. Participants were allowed to fill each box in the order of their choosing. There were six blocks in total consisting of each of the four experimental conditions, with order of conditions randomized between subjects.

Results

Item Analysis.

Participant's correct response data were collected according to two criteria. For item performance, a response was considered correct if participants selected a target item, as opposed to a lure, regardless of their memory position response (for odds ratios see Table 9. For average participant proportion correct data see Table A5, Figure B3).

Table 9

Experiment 3 – Odds Ratios for Item

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8
LTM_TD	4.66	3.95	4.15	5.48	3.75	3.54	3.53	5.30
LTM_TND	5.13	4.92	4.00	2.10	2.73	2.83	2.22	3.70
LTM_UC	8.61	12.57	7.41	5.85	5.65	5.84	4.10	11.05
STM	4.47	5.09	2.35	2.17	3.48	2.66	4.56	9.19

Note. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

For item recognition, model comparison showed strong evidence for all models in comparison to a null model, with the strongest evidence being for the condition + position model (see Table 10).

Table 10

Experiment 3 – Bayes Factor Comparison for Item

	BF
Condition	1.01e+18
Position	5.41e+05
Condition + Position	1.11e+24
Condition + Position + (Condition * Position)	3.09e+15

Note. Comparison is against null hypothesis of random intercept only.

Examining the factors for model inclusion confirmed strong evidence for including the effects of condition + position, but also strong evidence against including the interaction term in the model (see Table 11).

Table 11

Experiment 3 – Bayes Factors for Model Inclusion for Item

	Prior	Posterior	Inclusion BF
Condition	.60	1.00	1.36e+18
Condition + Position	.60	1.00	7.39e+05
Condition + Position + (Condition * Position)	.20	0.00	1.17e-08

Using the condition and position model, the log odds ratio for the random model intercept was 2.34 (*SD* = .65). Log odds ratios of the fixed effects and their 95% HDIs have been transformed into probabilities (see Table 12, Figure 6).

Table 12

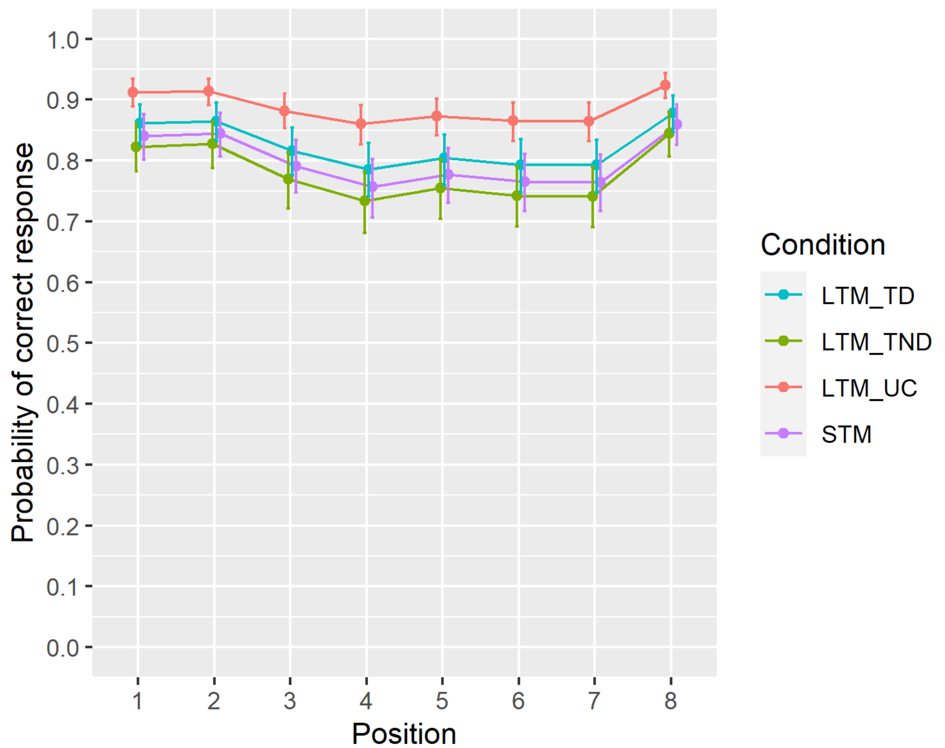
Experiment 3 – Posterior Fixed Effects of Item Model

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8
LTM_TD	.84 (.79 - .89)	.82 (.76 - .87)	.83 (.77 - .87)	.86 (.81 - .9)	.81 (.75 - .86)	.80 (.74 - .85)	.80 (.74 - .85)	.86 (.80 - .90)
LTM_TND	.85 (.80 - .90)	.85 (.79 - .89)	.82 (.76 - .87)	.70 (.63 - .76)	.75 (.68 - .81)	.76 (.69 - .82)	.71 (.64 - .78)	.81 (.75 - .86)
LTM_UC	.91 (.87 - .94)	.94 (.91 - .96)	.90 (.86 - .93)	.87 (.83 - .91)	.86 (.82 - .91)	.87 (.82 - .91)	.82 (.77 - .87)	.93 (.89 - .96)
STM	.84 (.78 - .88)	.85 (.80 - .90)	.72 (.65 - .78)	.70 (.63 - .77)	.79 (.74 - .85)	.74 (.67 - .80)	.84 (.78 - .88)	.91 (.88 - .95)

Note. Posterior fixed effects represented as probabilities. Parentheses represent 95% HDI. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Figure 6

Experiment 3 – Posterior Fixed Effects of Item Model



Note. Posterior fixed effects for item are represented as probabilities. Error bars represent 95% HDI. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

ROPE tests on the item data indicated that participants showed significantly improved probability of success in the long-term memory control condition relative to the other three conditions, with ROPE values < .001 in all cases. Significant decreases in probability of correct response were also seen for middle list conditions compared to both early and late list conditions, indicating both primacy and recency effects (see Table A6).

Order Analysis

For order performance, a response was only considered correct if the participant both selected a correct item and placed the item in the correct memory position, thus requiring an item-position binding (for odds ratios, see Table 13. For average participant proportion correct data Table A7, Figure B4). Both sets of correct/incorrect data were analyzed using the same set of mixed-logit models as in Experiment 1 and 2.

Table 13

Experiment 3 – Odds Ratios for Order

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8
LTM_TD	1.89	1.06	0.70	0.63	0.39	0.48	0.50	0.94
LTM_TND	1.16	0.67	0.55	0.31	0.30	0.26	0.28	0.57
LTM_UC	3.48	2.39	1.70	1.44	1.20	1.08	1.06	2.12
STM	1.27	0.71	0.42	0.33	0.34	0.38	0.71	1.28

Note. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

The order reconstruction data mirrored the same pattern as item recognition data. Comparison against the null model showed strong evidence for all models being preferable to the null, with the strongest evidence being for the condition + position model (see Table 14).

Table 14

Experiment 3 – Bayes Factor Comparison for Order

	BF
Condition	2.98e+105
Position	6.45e+77
Condition + Position	5.12e+189
Condition + Position + (Condition * Position)	5.86e+178

Note. Comparison is against null hypothesis of random intercept only.

However, as with item memory, model inclusion analysis showed strong evidence for both main effect terms, but against the interaction term (see Table 15).

Table 15

Experiment 3 – Bayes Factors for Model Inclusion for Order

	Prior	Posterior	Inclusion BF
Condition	.60	1.00	5.41e+111
Condition + Position	.60	1.00	1.16e+84
Condition + Position + (Condition * Position)	.20	0.00	4.66e-11

Using the condition and position model, the log odds ratio for the random model intercept was 2.34 (*SD* = .65). Log odds ratios of the fixed effects and their 95% HDIs have been transformed into probabilities (see Table 16, Figure 7).

Table 16

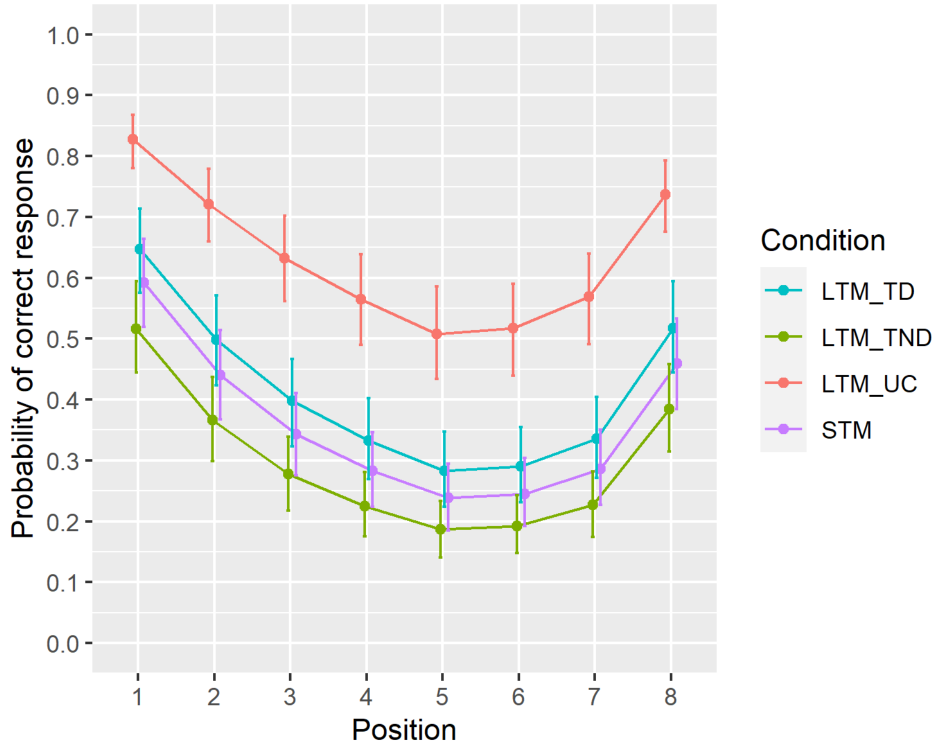
Experiment 3 – Posterior Fixed Effects for Order Model

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8
LTM_TD	.68 (.60 - .76)	.51 (.43 - .60)	.40 (.32 - .49)	.37 (.29 - .45)	.25 (.18 - .32)	.30 (.23 - .38)	.31 (.23 - .39)	.48 (.39 - .57)
LTM_TND	.54 (.45 - .63)	.38 (.30 - .46)	.34 (.26 - .42)	.21 (.15 - .28)	.20 (.14 - .26)	.18 (.12 - .24)	.19 (.13 - .25)	.34 (.26 - .43)
LTM_UC	.80 (.74 - .86)	.73 (.66 - .80)	.64 (.56 - .72)	.61 (.53 - .7)	.55 (.46 - .64)	.52 (.43 - .61)	.52 (.42 - .60)	.71 (.62 - .78)
STM	.57 (.49 - .66)	.40 (.32 - .49)	.27 (.20 - .35)	.22 (.16 - .28)	.22 (.16 - .29)	.24 (.18 - .31)	.40 (.32 - .49)	.57 (.48 - .66)

Note. Posterior fixed effects represented as probabilities. Parentheses represent 95% HDI. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Figure 7

Experiment 3 – Posterior Fixed Effects for Order Model



Note. Posterior fixed effects for order as probabilities. Error bars represent 95% HDI. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

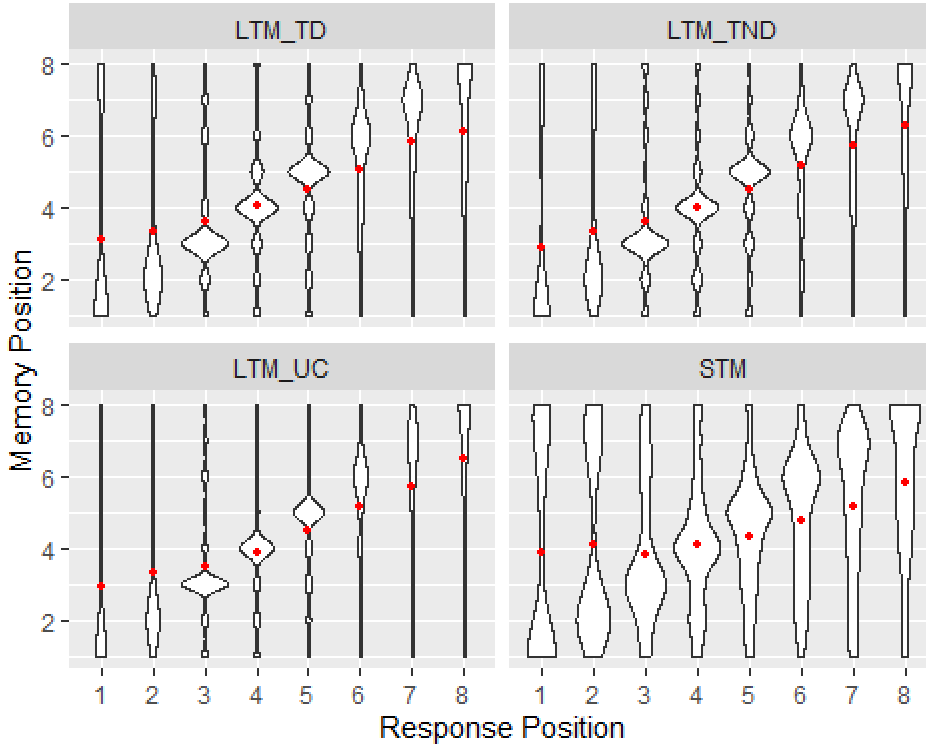
ROPE tests on the order data showed similarly high performance on the long-term memory control condition relative to all other conditions, as well as significantly higher performance in the non-distinct, compared to the temporally distinct long-term memory with ROPE values < .001 in all cases. Likewise, we see similar patterns in comparison of positions for order data as for item data, although with larger primacy effects (see Table A8).

Exploratory Analyses on Output Order.

Given the lack of position by condition effects in the main analysis, we performed multiple exploratory analyses of the data to investigate other potential signs of differential influence of condition across positions. To begin with, we performed an ANOVA to determine if there were any effects of condition on the order in which participants chose to fill each box (output order). This analysis looked at response position (i.e. the first response participants made, their second response, and so on) as a predictor of memory position during encoding (i.e. choice to fill the box corresponding to the first word in the list, the box corresponding to the second word in the list, and so on) across conditions. The interaction between response position and condition was significant, indicating a trend for participants to respond to the memory positions in a different order based on condition, $F(21, 8596) = 23.05$, $p < .001$. In order to clarify the nature of this interaction, we created violin plots to visualize the distribution of memory position responses across each response position and condition (see Figure 8). On this plot bands along the x-axis represent distributions of each response position. Thickness of the band indicates how often each memory position along the y-axis was chosen for that response position. For example, a band that is thick at the top and bottom of the y-axis for the first response position, as we see for the STM condition, indicates that the first box participants attempted to respond to was for either the first or last serial position.

Figure 8

Experiment 3 – Distributions of Memory Position by Response Position



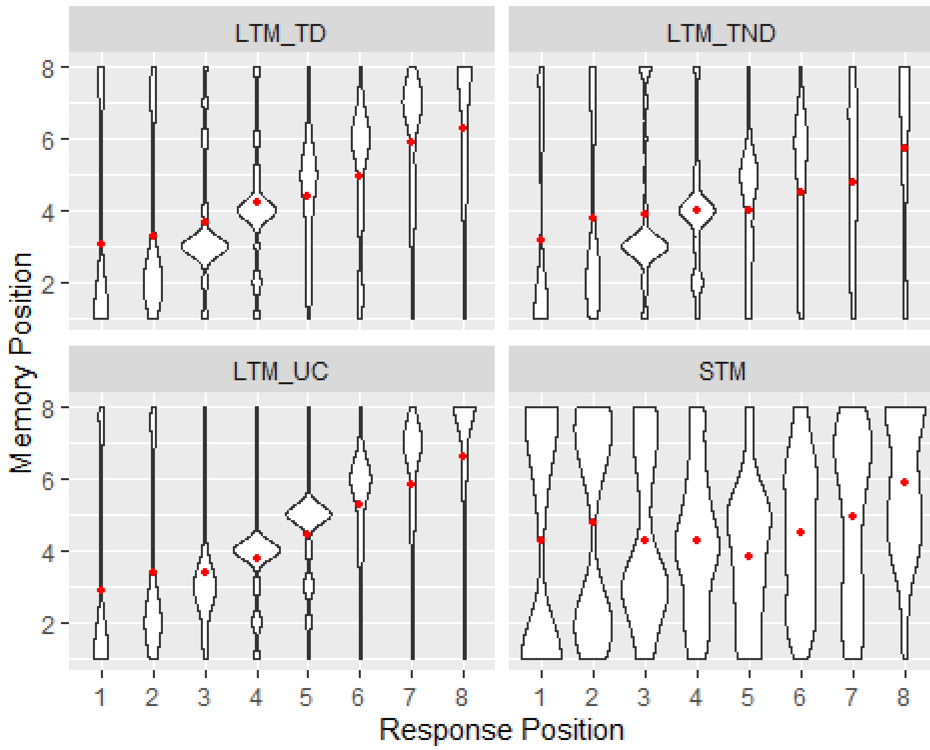
Note. Thickness of the band along the y-axis denotes how many times participants responded with a memory position for each response position. Dot denotes overall mean. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

The violin plots indicate that participants tended to respond in serial order in all LTM conditions but were more likely to deviate from serial order in the STM condition. To test this, we calculated Spearman's rank correlations for each participant and created averages based on the Fisher z-transformation of each result. When transformed back from the z-scale, the long-term control condition showed an average correlation of .64; the long-term temporally non-distinct condition had an average correlation of .67; the long-term temporally distinct condition had an average of .66, and STM had an average of .39. Due to being transformed before averaging, all correlations share the same standard deviation of .17. All z-transformed correlations were statistically significant from zero ($p < .001$). Holm-Bonferroni corrected z-tests on the transformed correlations showed that the average correlation in STM was significantly lower than all other conditions ($p < .05$), though no other correlations were significantly different from each other.

In order to examine if this response order difference impacted accuracy, we created further violin plots examining correct and incorrect order data (see Figure 9 and Figure 10 respectively).

Figure 9

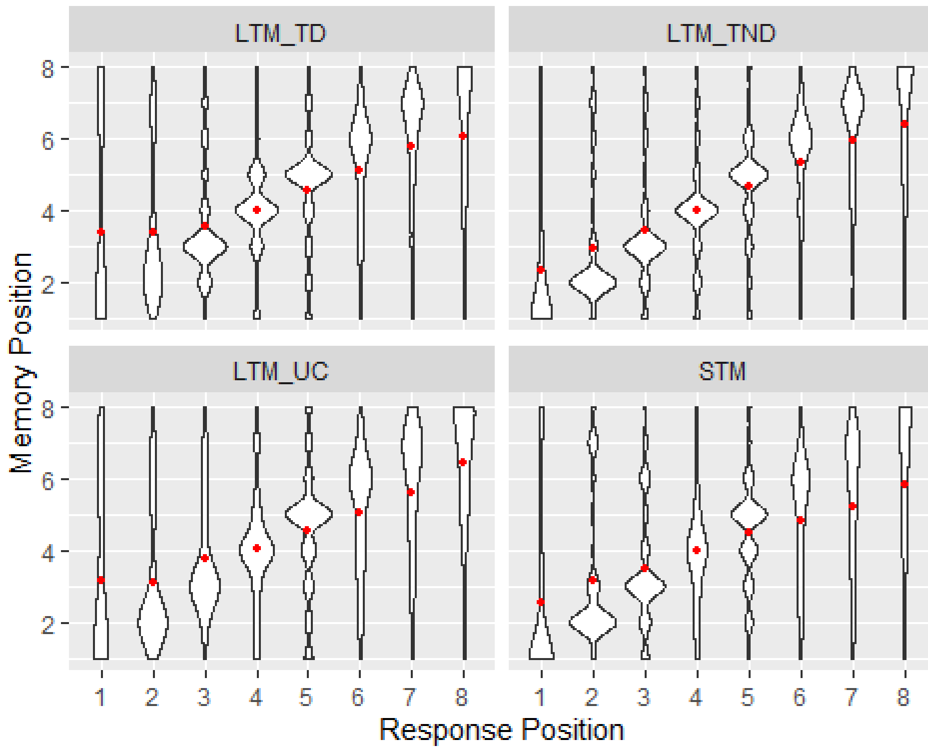
Experiment 3 – Distributions of Correct Memory Positions by Response Position



Note. Thickness of the band along the y-axis denotes how many times participants responded with a memory position for each response position. Dot denotes overall mean. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Figure 10

Experiment 3 – Distributions of Incorrect Memory Position by Response Position



Note. Thickness of the band along the y-axis denotes how many times participants responded with a memory position for each response position. Dot denotes overall mean. STM = short term memory (ISI = 0s, RI = 2s), LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_ND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task).

These plots indicate that, when participants got order information incorrect, they tended to respond in much the same way for the LTM conditions as for the STM condition. However, when participants got order information correct, they were much more likely to respond to memory positions 7 and 8 first. The overall difference between the above correlations in STM and LTM would appear to be due to participants responding in a less sequential manner when they know the correct answer, but only in the STM condition. This is reflected in the patterns of averaged Fisher z-transformed Spearman's rank correlations across participants, which show a moderate correlation for STM that is similar in effect size to the LTM conditions when answering incorrectly, but only a very weak correlation for STM for correct answers (see Table 17). Again, all averaged correlations were significantly greater than zero ($p < .001$). However, Holm-Bonferroni corrected z-tests show no significant declines between incorrect and correct responses, with only the change in the STM condition being near significant at $z = 1.32$, $p = .09$.

Table 17

Experiment 3 – Spearman's R Correlations for Memory Position and Response Position

Condition	Incorrect Response	Correct Response
LTM_UC	.68	.69
LTM_TND	.72	.63
LTM_TD	.66	.69
STM	.55	.30

Note. *SD* .17 for all conditions due to being averaged on z-scale. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Discussion

The results of our planned analysis showed an effect of both condition and position for both item recognition and order reconstruction. In both cases we see a clear recency effect. However, in contrast to our hypothesis, this recency effect was not moderated by condition in either test. Furthermore, this lack of interaction effect does not replicate prior findings that a delay between study and test condition reduces or eliminates the recency effect for items. One potential explanation for this may be due to the relatively short RI used here, which may not have removed study materials from WM before the test. However, this is unlikely to be the case. Howard and Kahana (1999) previously demonstrated that when participants are allowed to recall information in the order of their choosing, they are more likely to recall the last input positions first for an immediate test, compared to a delayed recall test. Examination of response position as a predictor of memory position response shows that we are able to demonstrate the same pattern in the current study, with participants being far more likely to respond to the last memory positions first in STM compared to the three LTM conditions. In addition, even for an RI too short to remove the recency effect, we would still expect to see a moderating influence on the recency effect. Another possible explanation for the lack of a reduction in item recency for the LTM non-distinct condition may be that participants process the item-position bindings in a way that supports recency effects in this condition. We expected that recency effects may be present for item recognition, but that increased recognition wouldn't translate to increased order memory. As a result, Experiment 3 was designed to be able to detect an increase in item performance independent from order performance, but it was not designed to allow for increases in order performance to be independent of item performance. Given it would be difficult for participants to have knowledge of the position an item was in without also knowing the item itself, a recency effect for order information in the temporally non-distinct condition would also explain the same recency effect for item information. Further experiments examining the effects of order reconstruction as an aid to item memory may be warranted, using a more suitable paradigm.

As further evidence against the hypothesis of LTM storage for associations over short delays, our examination of participant response order indicates participants responded uniquely in the STM condition, being far more likely to respond to the last two memory positions first. One could argue that this may reflect participant's use of a response strategy that relies on STM, but not how successful the strategy was. However, examination of correct and incorrect order responses shows that almost all of the difference between STM and LTM response patterns takes place only when participants are able to correctly recall information. While the decline in correlations for serial order responses were not significant, we believe that the decline is likely meaningful, given the correct/incorrect data split removes each response from the context of the trail it was in, making the correlations less reliable. Given that the most likely information to still be in STM during the test phase would be the most recent positions, this seems to indicate that when participants do have order information in WM, they offload that information immediately, but that when order information is not present in STM, they do not change their overall response patterns. This supports the use of STM storage for the relational information linking an item to its serial position.

General Discussion

Across three experiments we examined the storage of relational binding information in both short and long-term memory, as well as the effects of temporal distinctiveness cues on relational bindings. In order to do so, we examined serial position curves across conditions of short-term memory, temporally non-distinct long-term memory, temporally distinct long-term memory, as well as a long-term memory condition controlling for any potential effects of the interpolated activity. In Experiment 1 using item-item bindings, we found a condition by position interaction. However, follow-up tests failed to show meaningful differences in serial position effects across the conditions, nor were we able to observe either primacy or recency effects for any condition. In Experiment 2 we attempted to strengthen serial position effects by having participants form item-position bindings, rather than item-item bindings, thereby enhancing the degree to which position is attended to by participants. However, we failed to show meaningful effects due to floor level performance. In Experiment 3 we changed the method of test from associative recognition to order reconstruction with item recognition, in order to both improve performance and gain a measure of item memory alongside relational binding. Results showed main effects of both condition and position, but no interaction effect, potentially supporting our hypothesis. However, closer examination of participant response strategies indicated the use of a differential response strategy for the STM condition, compared to the LTM conditions, which correlated with increased accuracy on the order reconstruction test. These results would seem to indicate use of different memory systems across short and long RIs, in spite of similarities in overall performance and serial position effects.

While prior studies have shown serial position effects for relational binding (Jones & Oberauer, 2013; Murdock & Hockley, 1989; Tulving & Arbuckle, 1963), we believe we are unique in examining these effects across both temporally distinct and non-distinct LTM.

Reexamination of Hypotheses

Experiments 1 and 2

For Experiments 1 and 2 we hypothesized that there would be no recency effect for STM for relational bindings. This was largely based off the findings of Murdock and Hockley (1989), who show no recency for bindings in recognition memory. While they do show recency effects for bindings in recall tests, they do not attribute this to WM storage, but rather as an artifact of the TODAM2 model. We replicate the lack of a recency effect for relational bindings tested via recognition in Experiment 1, but not Experiment 2. We initially interpreted the findings from Experiment 2 as being due to activated long-term memory but given the evidence for WM storage of relational bindings in the exploratory analysis of Experiment 3, we're forced to consider alternative interpretations. One potential explanation would be that holding relational bindings in WM does lead to a recency effect that is helpful in an associative recognition test, but also increased item familiarity that is harmful in an associative recognition test. In a standard associative recognition test, such as the one performed by Murdock and Hockley (1989) and ourselves in Experiment 1, lures are recombinations of words that appeared during study. This means that the words themselves are highly familiar to the participants, but this familiarity is not useful in determining how to respond. If participants find words that appeared near the end of a list more familiar, due to recency effects, they may interpret this increase in familiarity as evidence that the word pair is a target causing an increase in false alarms. This effect may counteract recency effects for relational bindings, leading to a flat line in the case of associative recognition. In the case of item recognition, increased familiarity would support correct responses. This interpretation then allows for the same effects on memory to be present for both items and bindings but have differential test results. We believe this interpretation is consistent with the results of all three experiments. In Experiment 2, participants were tested on item-order, rather than item-item bindings. If the last one to two items presented at study phase have increased familiarity, and participants are aware that the most familiar objects should be last, then the presentation of a recombined pair can be easily detected, given the more familiar would be first in the pair, rather than second as it should be. This would match, at least tentatively, the Experiment 2 findings. Additionally, for Experiment 3, no recombinations for relational bindings are presented, meaning there is no familiarity detriment to binding memory, which is consistent with our findings of serial position curves in that experiment. However, more research, potentially examining the ROC curves for relational memory at different serial positions, would be needed to verify this interpretation.

Experiment 3

For Experiment 3, we amended our hypotheses based on Experiment 2. Specifically, we predicted that for relational bindings there would be a recency effect for STM based on activated LTM, but that there would be no recency effect in the other conditions. Instead, we see a recency effect in all conditions. For the filled control and temporally distinct LTM conditions, this could be fairly easily explained. For example, it might be the case that the mechanisms which lead to long-term recency in item memory apply to relational bindings as well, and that this was not reflected in Experiment 2 due to low performance. However, the finding of a recency effect even for the temporally non-distinct condition complicates such an assumption. An alternative explanation might be that the RI was not long enough to eliminate the recency effect. However, we do not demonstrate the same memory position and response position correlation shift between incorrect non-distinct responses and correct ones seen in STM, nor does the overall distribution match the response pattern shown in STM, which appears to show evidence of WM storage. One way to potentially make sense of this would be if the RI were long enough to remove relational bindings from the focus of attention, but not long enough to remove them from activated LTM. In this case, activated LTM is not the cause of the STM recency effect, as we originally hypothesized, but potentially is the cause of the temporally non-distinct recency effect observed here. This may be why the distributions of response position for correct non-distinct LTM do not look the same as for STM. For STM, participants offload the contents of the focus of attention first, which will almost always be the items in positions 7 and 8. For non-distinct LTM, participants offload the strongest activations in LTM. These would be the later list items, but the difference in activation strength between those items may not be clear, leading to a much less predictable response order. Further research will be needed to determine if response order characteristics can successfully discriminate information held in the focus of attention from information in activated LTM.

For the item data in Experiment 3, we hypothesized that we would replicate Atkinson & Shiffrin’s (1971) findings that an increase in RI removes the recency effect from item memory, as well as Bjork and Whitten's (1974) findings that increasing the ISI along with the RI returns this recency effect. Instead, we showed no differences in recency across any condition. A potential explanation for this is the shortness of the RI. Even in the LTM conditions the RI was only eight seconds in length, which may not have been enough to remove the recency effect in the temporally non-distinct condition. However, examination of the response distributions shows that response patterns are still quite different compared to STM. Additionally, the difference in performance between the control long-term memory condition and the temporally distinct condition would seem to indicate that our distractor task was at least somewhat effective at preventing rehearsal. Finally, due to the exclusion of participants performing at or below chance level on this distractor task, we can be confident that all participants in the present analysis correctly attended to the distractor task. We believe a more likely explanation is that recency effects for order may have supported item recall. Further research will require more independent item and order conditions to test this.

Related to the original hypotheses, if we assume that activated LTM can support a recency effect in the short-term, and that long-term recency supports both item and binding hypotheses, then the hypotheses no longer make differential predictions. Under both hypotheses we would expect a recency effect for STM, either due to activated LTM or WM, as well as a long-term recency effect in the temporally distinct condition, due to the same mechanism. As such, further tests under these assumptions would require a different methodology.

Interpretation of Findings

One potential explanation for these results may still lie in differential storage for items and relational information in WM. While our results would appear to indicate that relational information is held in the focus of attention, it may be the case that the focus of attention tends to be used to maintain item information (e.g. via rehearsal) but to elaborate on relational information (e.g. actively manipulating information to support binding). This would be partially in line with the findings of Martinez and O'Rourke (2020) that fluid intelligence predicts success on paired associate tasks for participants who tend to use elaborative strategies, while WM capacity predicts success for participants who use non-elaborative strategy. It may be the case that, at least for some participants, WM is occupied with storing items but, rather than storing additional relational information, it is creating elaborations on these items. This may require additional attentional resources, but not additional storage, relative to pure item memory. Other participants may forego use of elaborative strategy and rely on capacity to hold both item and relational information. This would also appear to be in line with the results of Experiment 2, which likewise showed dramatically different performance based on strategy. Unfortunately, for Experiment 3 most participants reported use of multiple different strategies, and 35 of the 44 participants reported use of repetition at least in part, making it difficult to categorize participants as having primarily used elaborative or non-elaborative processes, and hence preventing the use of a similar split analysis by strategy used in Experiment 2. However, it is worth noting that the increase in performance for the control LTM condition, relative to the STM condition especially, reflects a major advantage for increased elaboration and/or rehearsal time. We discuss potential avenues by which to test this hypothesis in the Future Directions section.

Potential Issues

Some potential issues with the reported experiments include the use of online only participants. Due to the COVID-19 pandemic, we were unable to run participants in-person. As such, participants were not able to be tested in a controlled environment. While care was taken to make sure that we only analyzed data from participants who passed attentional checks and performed above chance level on the interpolated activity, there's still a possibility that participants were not as attentive as in lab conditions. Additionally, we were not able to use the more common cued recall type design for these experiments. Our experimental software for online research was not capable of recording audio, and based on prior work, we did not believe that participants would be able to type with sufficient speed to recall words in a working memory test by typing them. Furthermore, such typing could result in issues related to scoring misspellings and typographical errors.

In addition, given that use of recognition over recall for item-item bindings has altered serial position effects in at least some studies (Murdock & Hockley, 1989), it is likely that this affected our Experiment 1 data. It's less clear if use of recognition, rather than recall, affects serial position for item-order bindings, such as those tested for in Experiment 2. Order reconstruction tasks have previously shown serial position curves similar to recall (Healy et al., 2000), but it remains unclear if our findings on recency and temporal distinctiveness would transfer to a cued recall paradigm of associative memory, or if there are unique effects of order reconstruction.

An additional issue with the reported research may have been the use of relatively short RIs in Experiments 2 and 3. In order to allow for comparison to Experiment 1, we wished to keep the factors of RI and ISI as similar as possible for the following experiments. However, for Experiment 1, participants were presented with word pairs, while they were only presented with single words in the following experiments. In order to maintain the ratio of ISI per word, we thus had to half the ISI and, in order to maintain temporal distinctiveness in the relevant conditions, the RI as well. This resulted in a relatively short RI for the long-term memory conditions. As noted above, we believe that this may have affected the temporally non-distinct long-term memory condition in Experiment 3, though we still think it was at least partially effective in its function as a test of LTM. Still, further experiments examining longer RIs may be advisable.

Finally, we wish to note that our ultimate conclusions are taken from a post-hoc analysis of the data that was not part of the original hypothesis. We believe this is a valid interpretation for the present study as, while the planned analysis for Experiment 3 would appear to confirm the original hypothesis, the lack of the predicted decline in recency for the non-distinct LTM condition necessitated further analysis in order to prevent spurious conclusions based on the planned analysis alone. However, further research should be conducted using a-priori analysis to replicate or extend these results before we can make definitive claims. Additionally, while we believe we do show a difference in response pattern between STM and LTM, which we believe reflects working memory, the difference in correlation between incorrect and correct responses is not significant. Based on the shapes of the distributions, we still believe this difference is meaningful, though obscured by the use of non-optional metrics to evaluate it. While a-priori testing should always be conducted to verify post-hoc findings, we believe the need for verification using a paradigm designed to test this finding is doubly important here.

Future Directions

In order to correct the potential issues with the current studies, we recommend that future research re-examine this topic using recall, rather than recognition or reconstruction tests. Additionally, given the findings of Experiment 3, in which encoding for order potentially supported item memory, we would recommend that more independent tests of item vs relational binding be used in order to verify the existence of a differential effect of increased RI for relational vs item memory.

Additionally, given the potential distinction between how WM handles relational and item memory noted above, further examination of this hypothesis is a ripe ground for future research. If WM does primarily use elaborative methods to form effective relational binds, we would expect that continuous divided attention may disrupt that process. In the current experiment, while there are filled RIs and ISIs, depending on condition, there is no secondary task at encoding itself. Use of a distractor task, in a different modality from the memoranda, should reduce general attention enough to interfere with elaboration, while not reducing storage itself. It has already been shown that manipulations on general attention affect relational binding (Elsley & Parmentier, 2009), but it remains unknown how this interacts with serial position effects.

Final Conclusions

The present findings further explore the topic of relational bindings in a short-term memory context, and present multiple possibilities for further research. The results of Experiment 1 provide further evidence that recency effects for relational bindings are not present in recognition tests. The results of Experiment 3 additionally show that, while WM storage may not provide a boost over LTM storage for relational bindings, there is evidence for separate processes that predict success in STM that do not appear to do so for LTM.

References

Antonov, I., Antonova, I., Kandel, E. R., & Hawkins, R. D. (2003). activity-dependent presynaptic facilitation and hebbian LTP are both required and interact during classical conditioning in aplysia. *Neuron*, *37*(1), 135–147. https://doi.org/10.1016/S0896-6273(02)01129-7

Artuso, C., & Palladino, P. (2014). Binding and content updating in working memory tasks. *British Journal of Psychology*, *105*(2), 226–242. https://doi.org/10.1111/bjop.12024

Atkinson, R. C., & Crothers, E. J. (1964). A comparison of paired-associate learning models having different acquisition and retention axioms. *Journal of Mathematical Psychology*, *1*(2), 285–315. https://doi.org/10.1016/0022-2496(64)90005-7

Atkinson, R. C., & Shiffrin, R. M. (1971). The control of short-term memory. *Scientific American*, *225*(2), 82–91.

Aue, W. R., Criss, A. H., & Fischetti, N. W. (2012). Associative information in memory: Evidence from cued recall. *Journal of Memory and Language*, *66*(1), 109–122. Scopus. https://doi.org/10.1016/j.jml.2011.08.002

Baddeley, A., Allen, R., & Vargha-Khadem, F. (2010). Is the hippocampus necessary for visual and verbal binding in working memory? *Neuropsychologia*, *48*(4), 1089–1095. https://doi.org/10.1016/j.neuropsychologia.2009.12.009

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 8, pp. 47–89). Academic Press. https://doi.org/10.1016/S0079-7421(08)60452-1

Bergmann, H. C., Rijpkema, M., Fernández, G., & Kessels, R. P. C. (2012). Distinct neural correlates of associative working memory and long-term memory encoding in the medial temporal lobe. *NeuroImage*, *63*(2), 989–997. https://doi.org/10.1016/j.neuroimage.2012.03.047

Bjork, R. A., & Whitten, W. B. (1974). Recency-sensitive retrieval processes in long-term free recall. *Cognitive Psychology*, *6*(2), 173–189. https://doi.org/10.1016/0010-0285(74)90009-7

Bourassa, D. C., & Besner, D. (1994). Beyond the articulatory loop: A semantic contribution to serial order recall of subspan lists. *Psychonomic Bulletin & Review*, *1*(1), 122–125. https://doi.org/10.3758/BF03200768

Brodie, D. A., & Murdock, B. B. (1977). Effect of presentation time on nominal and functional serial-position curves of free recall. *Journal of Verbal Learning and Verbal Behavior*, *16*(2), 185–200. https://doi.org/10.1016/S0022-5371(77)80046-7

Brown, G. D. A., Preece, T., & Hulme, C. (2000). Oscillator-based memory for serial order. *Psychological Review*, *107*(1), 127–181. https://doi.org/10.1037/0033-295X.107.1.127

Brown, G., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review*, *114*, 539–576. https://doi.org/10.1037/0033-295X.114.3.539

Brown, J. (1958). Some tests of the decay theory of immediate memory. *Quarterly Journal of Experimental Psychology*, *10*(1), 12–21. https://doi.org/10.1080/17470215808416249

Calfee, R. C., & Atkinson, R. C. (1965). Paired-associate models and the effects of list length. *Journal of Mathematical Psychology*, *2*(2), 254–265. https://doi.org/10.1016/0022-2496(65)90004-0

Capitani, E., Della Sala, S., Logie, R. H., & Spinnler, H. (1992). Recency, primacy, and memory: Reappraising and standardising the serial position curve. *Cortex*, *28*(3), 315–342. https://doi.org/10.1016/S0010-9452(13)80143-8

Cave, C. B., & Squire, L. R. (1992). Intact verbal and nonverbal short-term memory following damage to the human hippocampus. *Hippocampus*, *2*(2), 151–163. https://doi.org/10.1002/hipo.450020207

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin*, *104*(2), 163–191. https://doi.org/10.1037/0033-2909.104.2.163

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87–114. https://doi.org/10.1017/S0140525X01003922

Cowan, N. (2019). Short-term memory based on activated long-term memory: A review in response to Norris (2017). *Psychological Bulletin*, *145*(8), 822–847. https://doi.org/10.1037/bul0000199

Crites, S. L., Devine, J. V., Lozano, D. I., & Moreno, S. (1998). Event-related potentials and serial position effects in a visual probe recognition task. *Psychophysiology*, *35*(3), 293–304. https://doi.org/10.1017/S0048577298970457

Crowder, R. G. (1976). Principles of learning and memory. Lawrence Erlbaum.

Davachi, L. (2006). Item, context and relational episodic encoding in humans. *Current Opinion in Neurobiology*, *16*(6), 693–700. https://doi.org/10.1016/j.conb.2006.10.012

Davelaar, E. J., Goshen-Gottstein, Y., Ashkenazi, A., Haarmann, H. J., & Usher, M. (2005). The demise of short-term memory revisited: empirical and computational investigations of recency effects. *Psychological Review*, *112*(1), 3–42. https://doi.org/10.1037/0033-295X.112.1.3

Ecker, U. K. H., Maybery, M., & Zimmer, H. D. (2013). Binding of intrinsic and extrinsic features in working memory. *Journal of Experimental Psychology: General*, *142*(1), 218–234. https://doi.org/10.1037/a0028732

Elsley, J. V., & Parmentier, F. B. R. (2009). Short article: Is verbal–spatial binding in working memory impaired by a concurrent memory load? *Quarterly Journal of Experimental Psychology*, *62*(9), 1696–1705. https://doi.org/10.1080/17470210902811231

Forsberg, A., Guitard, D., & Cowan, N. (2021). Working memory limits severely constrain long-term retention. *Psychonomic Bulletin & Review*, *28*(2), 537–547. https://doi.org/10.3758/s13423-020-01847-z

Glanzer, M., & Cunitz, A. R. (1966). Two storage mechanisms in free recall. *Journal of Verbal Learning and Verbal Behavior*, *5*(4), 351–360. https://doi.org/10.1016/S0022-5371(66)80044-0

Glenberg, A. M., Bradley, M. M., Kraus, T. A., & Renzaglia, G. J. (1983). Studies of the long-term recency effect: Support for a contextually guided retrieval hypothesis.

Journal of Experimental Psychology: Learning, Memory, and Cognition, *9*(2), 231–255. https://doi.org/10.1037/0278-7393.9.2.231

Goodwin, D. W., Powell, B., Bremer, D., Hoine, H., & Stern, J. (1969). Alcohol and recall: State-dependent effects in man. *Science*, *163*(3873), 1358–1360. https://doi.org/10.1126/science.163.3873.1358

Greeno, J. G. (1967). Paired-associate learning with short-term retention: Mathematical analysis and data regarding identification of parameters. *Journal of Mathematical Psychology*, *4*(3), 430–472. https://doi.org/10.1016/0022-2496(67)90033-8

Guitard, D., Saint-Aubin, J., & Cowan, N. (2022). Tradeoffs between item and order information in short-term memory. *Journal of Memory and Language*, *122*, 104300. https://doi.org/10.1016/j.jml.2021.104300

Hannula, D. E., & Ranganath, C. (2008). Medial Temporal Lobe Activity Predicts Successful Relational Memory Binding. *Journal of Neuroscience*, *28*(1), 116–124. https://doi.org/10.1523/JNEUROSCI.3086-07.2008

Hartley, T., Hurlstone, M. J., & Hitch, G. J. (2016). Effects of rhythm on memory for spoken sequences: A model and tests of its stimulus-driven mechanism. *Cognitive Psychology*, *87*, 135–178. https://doi.org/10.1016/j.cogpsych.2016.05.001

Hartshorne, J. K., & Makovski, T. (2019). The effect of working memory maintenance on long-term memory. *Memory and Cognition*, *47*(4), 749–763. https://doi.org/10.3758/s13421-019-00908-6

Healy, A. F., Havas, D. A., & Parker, J. T. (2000). Comparing serial position effects in semantic and episodic memory using reconstruction of order tasks. *Journal of Memory and Language*, *42*(2), 147–167. https://doi.org/10.1006/jmla.1999.2671

Hebb, D. O. (1949). *The organization of behavior; a neuropsychological theory* (pp. xix, 335). Wiley.

Hintzman, D. L. (1984). MINERVA 2: A simulation model of human memory. *Behavior Research Methods, Instruments, &amp Computers*, *16*(2), 96–101. https://doi.org/10.3758/BF03202365

Hockley, W. E., Ahmad, F. N., & Nicholson, R. (2016). Intentional and incidental encoding of item and associative information in the directed forgetting procedure. *Memory and Cognition*, *44*(2), 220–228. Scopus. https://doi.org/10.3758/s13421-015-0557-8

Hockley, W. E., & Cristi, C. (1996). Tests of encoding tradeoffs between item and associative information. *Memory & Cognition*, *24*(2), 202–216. https://doi.org/10.3758/BF03200881

Howard, M. W., & Kahana, M. J. (1999). *Contextual variability and serial position effects in free recall*.

Huber, D. E., Tomlinson, T. D., Jang, Y., & Hopper, W. J. (2015). The Search of Associative Memory with Recovery Interference (SAM-RI) memory model and its application to retrieval practice paradigms. In *Cognitive modeling in perception and memory: A festschrift for Richard M. Shiffrin* (pp. 81–98). Psychology Press.

Hulme, C., Maughan, S., & Brown, G. D. A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language*, *30*(6), 685–701. https://doi.org/10.1016/0749-596X(91)90032-F

Jones, T., & Oberauer, K. (2013). Serial-position effects for items and relations in short-term memory. *Memory*, *21*(3), 347–365. https://doi.org/10.1080/09658211.2012.726629

Jonin, P.-Y., Calia, C., Muratot, S., Belliard, S., Duché, Q., Barbeau, E. J., & Parra, M. A. (2019). Refining understanding of working memory buffers through the construct of binding: Evidence from a single case informs theory and clinical practise. *Cortex*, *112*, 37–57. https://doi.org/10.1016/j.cortex.2018.08.011

Kahana, M. J., Howard, M. W., & Polyn, S. M. (2008). Associative retrieval processes in episodic memory. In *Learning and Memory: A Comprehensive Reference* (pp. 1–24). Elsevier. https://doi.org/10.1016/B978-012370509-9.00185-6

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review*, *9*(4), 637–671. https://doi.org/10.3758/BF03196323

Kelley, R., & Wixted, J. T. (2001). On the nature of associative information in recognition memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*(3), 701–722. https://doi.org/10.1037/0278-7393.27.3.701

Kruschke, J. K., & Liddell, T. M. (2018). The Bayesian new statistics: Hypothesis testing, estimation, meta-analysis, and power analysis from a Bayesian perspective. *Psychonomic Bulletin & Review*, *25*(1), 178–206. https://doi.org/10.3758/s13423-016-1221-4

Lewis-Peacock, J. A., & Postle, B. R. (2008). Temporary activation of long-term memory supports working memory. *Journal of Neuroscience*, *28*(35), 8765–8771. https://doi.org/10.1523/JNEUROSCI.1953-08.2008

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

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281. https://doi.org/10.1038/36846

Makowski, D., Ben-Shachar, M. S., Chen, S. H. A., & Lüdecke, D. (2019). indices of effect existence and significance in the Bayesian framework. *Frontiers in Psychology*, *10*, 2767. https://doi.org/10.3389/fpsyg.2019.02767

Maratos, E. J., Dolan, R. J., Morris, J. S., Henson, R. N. A., & Rugg, M. D. (2001). Neural activity associated with episodic memory for emotional context. *Neuropsychologia*, *39*(9), 910–920. https://doi.org/10.1016/S0028-3932(01)00025-2

Martinez, D., & O'Rourke, P. (2020). Differential involvement of working memory capacity and fluid intelligence in verbal associative learning as a possible function of strategy use. *The American Journal of Psychology*, *133*(4), 427–451. https://doi.org/10.5406/amerjpsyc.133.4.0427

McElree, B. (2006). Accessing recent events. In *Psychology of Learning and Motivation* (Vol. 46, pp. 155–200). Academic Press. https://doi.org/10.1016/S0079-7421(06)46005-9

Monsell, S. (1978). Recency, immediate recognition memory, and reaction time. *Cognitive Psychology*, *10*(4), 465–501. https://doi.org/10.1016/0010-0285(78)90008-7

Moscovitch, M., & Craik, F. I. M. (1976). Depth of processing, retrieval cues, and uniqueness of encoding as factors in recall. *Journal of Verbal Learning and Verbal Behavior*, *15*(4), 447–458. https://doi.org/10.1016/S0022-5371(76)90040-2

Murdock, B. (1999). Item and associative interactions in short-term memory: Multiple memory systems? *International Journal of Psychology*, *34*(5–6), 427–433. https://doi.org/10.1080/002075999399783

Murdock, B. B. (1995). Developing TODAM: Three models for serial-order information. *Memory & Cognition*, *23*(5), 631–645. https://doi.org/10.3758/BF03197264

Murdock, B. B., & Hockley, W. E. (1989). Short-term memory for associations. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 24, pp. 71–108). Academic Press. https://doi.org/10.1016/S0079-7421(08)60535-6

Murdock Jr., B. B. (1962). The serial position effect of free recall. *Journal of Experimental Psychology*, *64*(5), 482–488. https://doi.org/10.1037/h0045106

Murre, J. M. J., Wolters, G., & Raffone, A. (2006). Binding in working memory: Towards an integrated model. In H. D. Zimmer, A. Mecklinger, & U. Lindenberger (Eds.), *Handbook of Binding and Memory: Perspectives from Cognitive Neuroscience*. Oxford University Press.

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: Tests of an associative deficit hypothesis. *Journal of Experimental Psychology: Learning*

Memory and Cognition, *26*(5), 1170–1187. https://doi.org/10.1037/0278-7393.26.5.1170

Naveh-Benjamin, M., & Kilb, A. (2014). Age-related differences in associative memory: The role of sensory decline. *Psychology and Aging*, *29*(3), 672–683. https://doi.org/10.1037/a0037138

Neath, I. (1993). Distinctiveness and serial position effects in recognition. *Memory & Cognition*, *21*(5), 689–698. https://doi.org/10.3758/BF03197199

Neath, I., & Brown, G. D. A. (2006). SIMPLE: Further applications of a local distinctiveness model of memory. In B. H. Ross (Ed.), *The psychology of learning and motivation: Advances in research and theory., Vol. 46.* (2008-16279-006; Vol. 46, pp. 201–243). Elsevier Academic Press. https://doi.org/10.1016/S0079-7421(06)46006-0

Nee, D. E., Berman, M. G., Moore, K. S., & Jonides, J. (2008). neuroscientific evidence about the distinction between short- and long-term memory. *Current Directions in Psychological Science*, *17*(2), 102–106. https://doi.org/10.1111/j.1467-8721.2008.00557.x

Old, S. R., & Naveh-Benjamin, M. (2008). Differential effects of age on item and associative measures of memory: A meta-analysis. *Psychology and Aging*, *23*(1), 104–118. https://doi.org/10.1037/0882-7974.23.1.104

Olson, I. R., Moore, K. S., Stark, M., & Chatterjee, A. (2006). Visual working memory is impaired when the medial temporal lobe is damaged. *Journal of Cognitive Neuroscience*, *18*(7), 1087–1097. https://doi.org/10.1162/jocn.2006.18.7.1087

Olson, I. R., Page, K., Moore, K. S., Chatterjee, A., & Verfaellie, M. (2006). Working memory for conjunctions relies on the medial temporal lobe. *Journal of Neuroscience*, *26*(17), 4596–4601. https://doi.org/10.1523/JNEUROSCI.1923-05.2006

Parra, M. A., Fabi, K., Luzzi, S., Cubelli, R., Hernandez Valdez, M., & Della Sala, S. (2015). Relational and conjunctive binding functions dissociate in short-term memory. *Neurocase*, *21*(1), 56–66. https://doi.org/10.1080/13554794.2013.860177

Peterson, D. J., Decker, R., & Naveh-Benjamin, M. (2019a). Further studies on the role of attention and stimulus repetition in item–item binding processes in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(1), 56–70. https://doi.org/10.1037/xlm0000577

Peterson, D. J., Decker, R., & Naveh-Benjamin, M. (2019b). The effects of divided attention and of stimulus repetition on item–item binding in verbal working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(11), 1955–1969. https://doi.org/10.1037/xlm0000698

Peterson, D. J., Schmidt, N. E., & Naveh-Benjamin, M. (2017). The role of schematic support in age-related associative deficits in short-term and long-term memory. *Journal of Memory and Language*, *92*, 79–97. https://doi.org/10.1016/j.jml.2016.05.007

Peterson, L. R., Saltzman, D., Hillner, K., & Land, V. (1962). Recency and frequency in paired-associate learning. *Journal of Experimental Psychology*, *63*(4), 396–403. https://doi.org/10.1037/h0043571

Postman, L., & Phillips, L. W. (1965). Short-term temporal changes in free recall. *Quarterly Journal of Experimental Psychology*, *17*(2), 132–138. https://doi.org/10.1080/17470216508416422

Raaijmakers, J. G., & Shiffrin, R. M. (1981). Search of associative memory. *Psychological Review*, *88*(2), 93–134. https://doi.org/10.1037/0033-295X.88.2.93

Schacter, D. L., Guerin, S. A., & St. Jacques, P. L. (2011). Memory distortion: An adaptive perspective. *Trends in Cognitive Sciences*, *15*(10), 467–474. https://doi.org/10.1016/j.tics.2011.08.004

Scoville, W. B., & Milner, B. (1957). Loss of recent memory after bilateral hippocampal lesions. *Journal of Neurology, Neurosurgery, and Psychiatry*, *20*(1), 11–21.

Shing, Y. L., Werkle-Bergner, M., Li, S. C., & Lindenberger, U. (2008). Associative and Strategic Components of Episodic Memory: A Life-Span Dissociation. *Journal of Experimental Psychology: General*, *137*(3), 495–513. https://doi.org/10.1037/0096-3445.137.3.495

Shrager, Y., Levy, D. A., Hopkins, R. O., & Squire, L. R. (2008). Working memory and the organization of brain systems. *Journal of Neuroscience*, *28*(18), 4818–4822. https://doi.org/10.1523/JNEUROSCI.0710-08.2008

Stoet, G. (2010). PsyToolkit: A software package for programming psychological experiments using Linux. *Behavior Research Methods*, *42*(4), 1096–1104. https://doi.org/10.3758/BRM.42.4.1096

Stoet, G. (2017). PsyToolkit: A novel web-based method for running online questionnaires and reaction-time experiments. *Teaching of Psychology*, *44*(1), 24–31. https://doi.org/10.1177/0098628316677643

Talmi, D., Grady, C. L., Goshen-Gottstein, Y., & Moscovitch, M. (2005). Neuroimaging the serial position curve: A test of single-store versus dual-store models. *Psychological Science*, *16*(9), 716–723. https://doi.org/10.1111/j.1467-9280.2005.01601.x

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

Tulving, E. (1972). Episodic and semantic memory. In *Organization of memory* (pp. xiii, 423–xiii, 423). Academic Press.

Tulving, E., & Arbuckle, T. Y. (1963). Sources of intratrial interference in immediate recall of paired associates. *Journal of Verbal Learning and Verbal Behavior*, *1*(5), 321–334. https://doi.org/10.1016/S0022-5371(63)80012-2

Tulving, E., & Madigan, S. A. (1970). Memory and verbal learning. *Annual Review of Psychology*, *21*, 437–484. https://doi.org/10.1146/annurev.ps.21.020170.002253

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review*, *80*(5), 352–373. https://doi.org/10.1037/h0020071

Underwood, B. J. (1969). Attributes of memory. *Psychological Review*, *76*(6), 559–573. https://doi.org/10.1037/h0028143

Underwood, B. J., Runquist, W. N., & Schulz, R. W. (1959). Response learning in paired-associate lists as a function of intralist similarity. *Journal of Experimental Psychology*, *58*(1), 70–78. https://doi.org/10.1037/h0044866

Visser, P. J., Krabbendam, L., Verhey, F. R. J., Hofman, P. A. M., Verhoeven, W. M. A., Tuinier, S., Wester, A., Van Den Berg, Y. W. M. M., Goessens, L. F. M., Van Der Werf, Y. D., & Jolles, J. (1999). Brain correlates of memory dysfunction in alcoholic Korsakoff's syndrome. *Journal of Neurology, Neurosurgery & Psychiatry*, *67*(6), 774–778. https://doi.org/10.1136/jnnp.67.6.774

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

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General*, *131*(1), 48–64. https://doi.org/10.1037/0096-3445.131.1.48

Wilson, B. A., Baddeley, A. D., & Kapur, N. (1995). Dense amnesia in a professional musician following herpes simplex virus encephalitis. *Journal of Clinical and Experimental Neuropsychology*, *17*(5), 668–681. https://doi.org/10.1080/01688639508405157

Yang, J., Zhu, Z., Mecklinger, A., Fang, Z., & Li, H. (2013). Memory Asymmetry of Forward and Backward Associations in Recognition Tasks. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *39*(1), 253–269. https://doi.org/10.1037/a0028875

Zola-Morgan, S., Squire, L. R., & Amaralt, G. (1986). Human amnesia and the medial temporal region: Enduring memory impairment following a bilateral lesion limited to field CA1 of the hippocampus. *The Journal of Neuroscience*, *6*(10), 18.

Appendix A

Table A1

Experiment 1 – Proportion Correct

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6
LTM_TD	.70 (.04)	.64 (.04)	.68 (.03)	.66 (.03)	.72 (.03)	.76 (.03)
LTM_TND	.64 (.04)	.59 (.04)	.68 (.03)	.68 (.04)	.70 (.03)	.65 (.02)
LTM_UC	.74 (.03)	.66 (.03)	.71 (.03)	.76 (.03)	.76 (.03)	.76 (.03)
STM_ND	.67 (.03)	.71 (.04)	.72 (.04)	.68 (.03)	.68 (.03)	.72 (.03)

Note. SE in parentheses. LTM_TD = temporally distinct long-term memory (ISI = 16s, RI = 16s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 16s), LTM_UC = unfilled control long-term memory (ISI = 16s, RI = 16s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Table A2

Experiment 2 – Proportion Correct

	Position 1-2	Position 2-3	Position 3-4	Position 4-5	Position 5-6	Position 6-7
LTM_TD	.43 (.04)	.57 (.04)	.50 (.04)	.55 (.04)	.49 (.04)	.61 (.04)
LTM_TND	.55 (.04)	.56 (.04)	.62 (.04)	.53 (.04)	.60 (.04)	.59 (.04)
LTM_UC	.64 (.04)	.45 (.04)	.56 (.04)	.57 (.04)	.56 (.04)	.61 (.04)
STM	.49 (.04)	.49 (.04)	.51 (.04)	.57 (.04)	.74 (.04)	.56 (.04)

Note. SE in parentheses. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Table A3

Experiment 2 – Posterior Fixed Effects for Deep Level Strategy

	Position 1-2	Position 2-3	Position 3-4	Position 4-5	Position 5-6	Position 6-7
LTM_TD	.54 (.38 - .71)	.57 (.39 - .73)	.46 (.29 - .64)	.57 (.39 - .72)	.55 (.37 - .71)	.63 (.46 - .78)
LTM_TND	.63 (.46 - .78)	.59 (.41 - .74)	.77 (.6 - .88)	.52 (.35 - .69)	.61 (.45 - .77)	.59 (.42 - .74)
LTM_UC	.72 (.55 - .85)	.52 (.34 - .69)	.61 (.44 - .78)	.64 (.46 - .79)	.62 (.44 - .77)	.63 (.46 - .78)
STM	.54 (.37 - .72)	.52 (.35 - .7)	.64 (.45 - .79)	.57 (.39 - .73)	.79 (.64 - .9)	.77 (.6 - .88)

Note. SE in parentheses. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Table A4

Experiment 2 – Posterior Fixed Effects for Shallow Level Strategy

	Position 1-2	Position 2-3	Position 3-4	Position 4-5	Position 5-6	Position 6-7
LTM_TD	.37 (.28 - .48)	.58 (.48 - .68)	.52 (.41 - .62)	.55 (.44 - .64)	.46 (.36 - .57)	.60 (.50 - .70)
LTM_TND	.51 (.41 - .62)	.55 (.45 - .66)	.56 (.45 - .66)	.54 (.43 - .64)	.60 (.50 - .70)	.59 (.49 - .69)
LTM_UC	.60 (.50 - .70)	.41 (.31 - .51)	.54 (.43 - .65)	.54 (.43 - .63)	.54 (.44 - .63)	.61 (.51 - .71)
STM	.46 (.36 - .56)	.48 (.38 - .59)	.45 (.36 - .56)	.57 (.46 - .67)	.73 (.63 - .81)	.47 (.37 - .57)

Note. SE in parentheses. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Table A5

Experiment 3 – Proportion Correct for Item

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8
LTM_TD	.82 (.02)	.80 (.02)	.81 (.02)	.85 (.02)	.79 (.03)	.78 (.03)	.78 (.03)	.84 (.02)
LTM_TND	.84 (.02)	.83 (.02)	.80 (.02)	.68 (.03)	.73 (.03)	.74 (.03)	.69 (.03)	.79 (.03)
LTM_UC	.90 (.02)	.93 (.02)	.88 (.02)	.85 (.02)	.85 (.02)	.85 (.02)	.8 (.02)	.92 (.02)
STM	.82 (.02)	.84 (.02)	.70 (.03)	.68 (.03)	.78 (.03)	.73 (.03)	.82 (.02)	.90 (.02)

Note. SE in parentheses. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Table A6

Experiment 3 – Significant ROPE Comparisons for Item

Parameter	Inside ROPE
1 - 4	.00
1 - 5	.02
1 - 6	.00
1 - 7	.00
2 - 4	.00
2 - 5	.01
2 - 6	.00
2 - 7	.00
3 - 8	.01
4 - 8	.00
5 - 8	.00
6 - 8	.00
7 - 8	.00

Table A7

Experiment 3 – Proportion Correct for Order

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8
LTM_TD	.65 (.03)	.51 (.03)	.41 (.03)	.39 (.03)	.28 (.03)	.32 (.03)	.33 (.03)	.48 (.03)
LTM_TND	.54 (.03)	.40 (.03)	.36 (.03)	.24 (.03)	.23 (.03)	.21 (.02)	.22 (.03)	.36 (.03)
LTM_UC	.78 (.03)	.71 (.03)	.63 (.03)	.59 (.03)	.55 (.03)	.52 (.03)	.52 (.03)	.68 (.03)
STM	.56 (.03)	.42 (.03)	.3 (.03)	.25 (.03)	.25 (.03)	.27 (.03)	.42 (.03)	.56 (.03)

Note. SE in parentheses. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Table A8

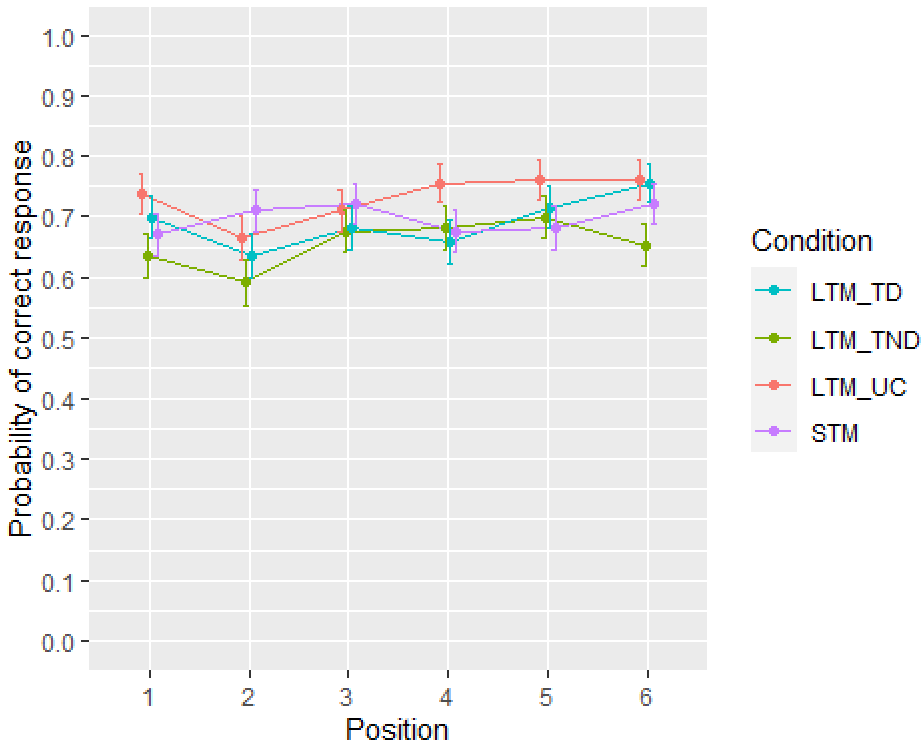
Experiment 3 – Significant ROPE Comparisons for Order

Parameter	Inside ROPE
1 - 2	.00
1 - 3	.00
1 - 4	.00
1 - 5	.00
1 - 6	.00
1 - 7	.00
1 - 8	.00
2 - 3	.01
2 - 4	.00
2 - 5	.00
2 - 6	.00
2 - 7	.00
3 - 5	.00
3 - 6	.00
3 - 8	.00
4 - 8	.00
5 - 8	.00
6 - 8	.00
7 - 8	.00

Appendix B

Figure B1

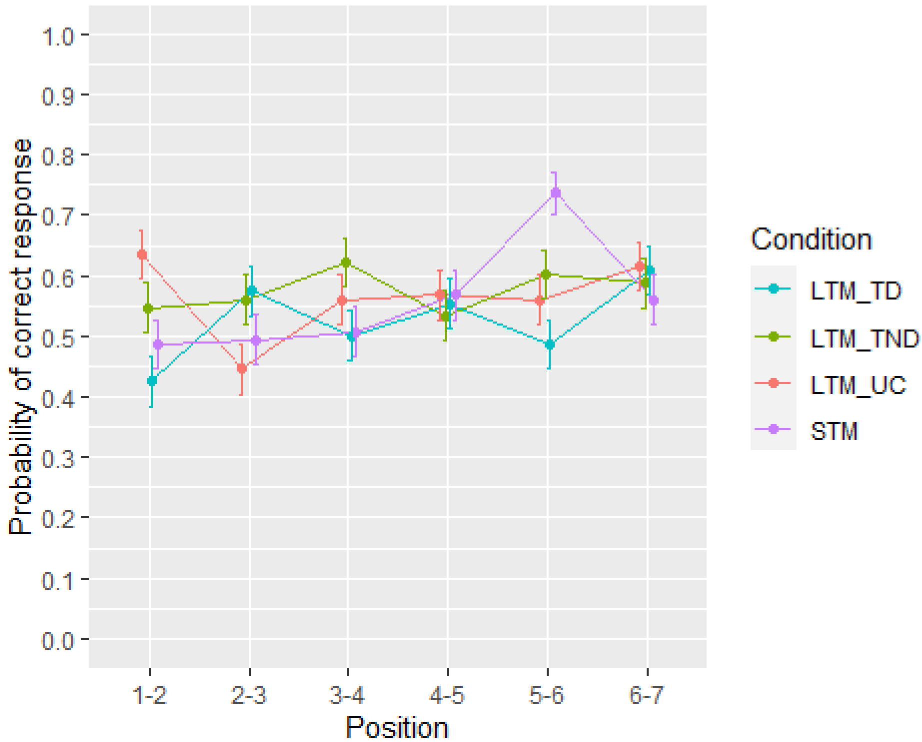
Experiment 1 – Proportion Correct



Note. Error bars represent SE. LTM_TD = temporally distinct long-term memory (ISI = 16s, RI = 16s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 16s), LTM_UC = unfilled control long-term memory (ISI = 16s, RI = 16s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Figure B2

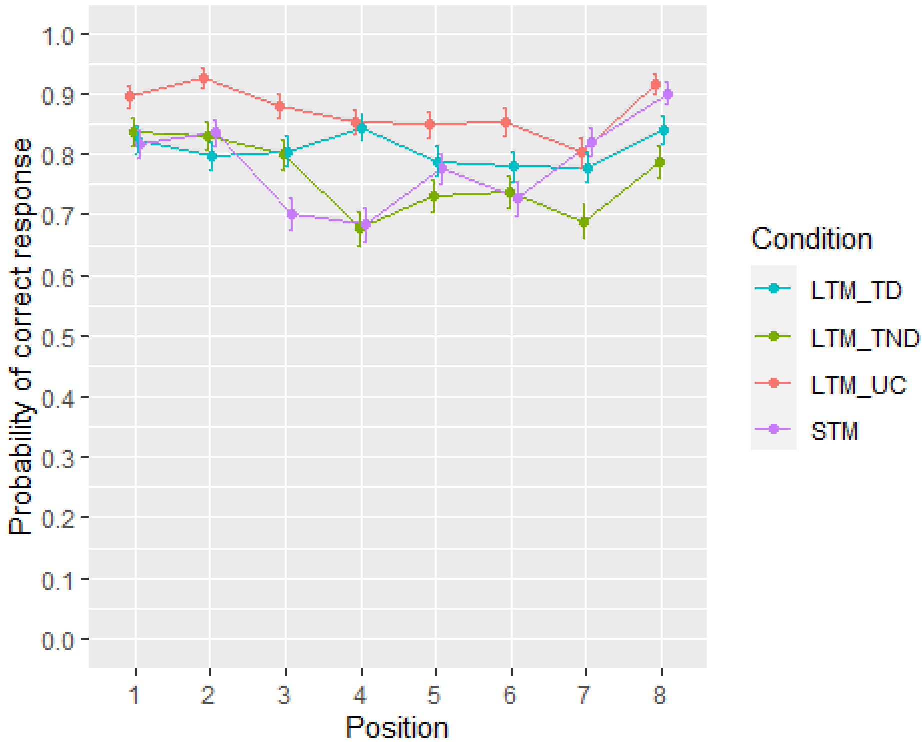
Experiment 2 – Proportion Correct



Note. Error bars represent SE. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Figure B3

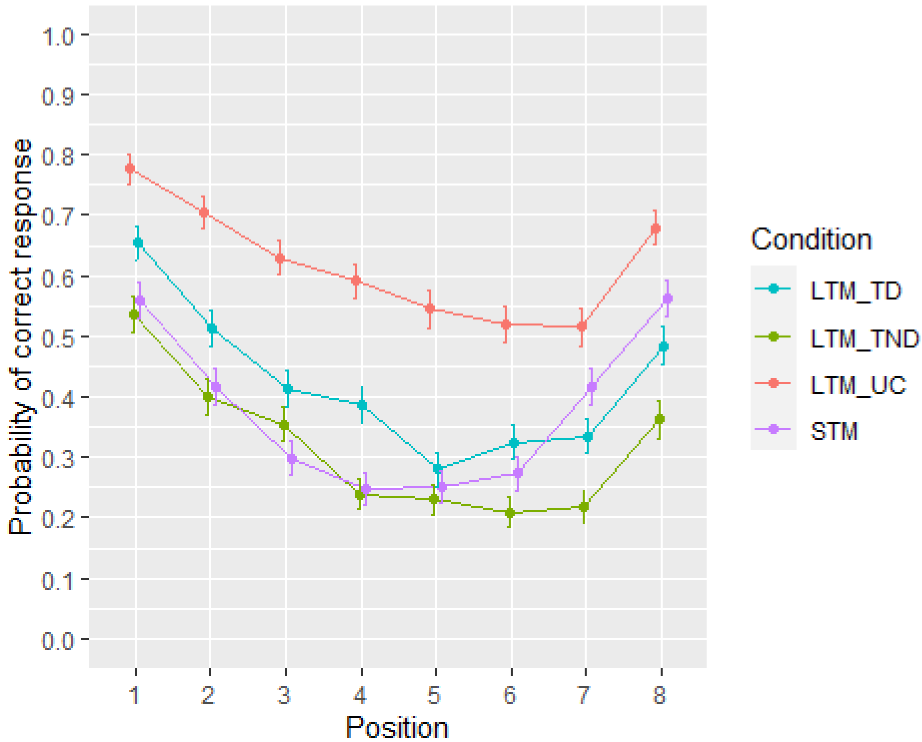
Experiment 3 – Proportion Correct for Item



Note. Error bars represent SE. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

Figure B4

Experiment 3 – Proportion Correct for Order



Note. Error bars represent SE. LTM_TD = temporally distinct long-term memory (ISI = 8s, RI = 8s), LTM_TND = temporally non-distinct long-term memory (ISI = 0s, RI = 8s), LTM_UC = unfilled control long-term memory (ISI = 8s, RI = 8s, no secondary task), STM = short term memory (ISI = 0s, RI = 2s).

VITA

Reed Decker was born in Kansas City on July 14th, 1992. He was given secular homeschooling by his parents and began enrolling in classes at the Metropolitan Community College – Maple Woods Campus in 2007 before graduating with an Associate in Arts degree in December of 2010. He then transferred to Truman State University in Kirksville and graduated Summa Cum Laude in May 2013 with a Bachelor of Science in Psychology. He entered the University of Missouri – Columbia as a graduate student in August of 2016 and completed his Master's in Cognitive Psychology in 2019.