SMITH, SYDNEY T., MA. Spacing by Retention Interval Interactions in Retroactive Effects of Memory: The Role of Detecting and Remembering Change. (2021)

Directed by Dr. Christopher Wahlheim. 36 pp.

We have long known that increasing the distance between repeated study opportunities can enhance learning. The magnitude of this spaced repetition effect depends on the retention interval between study and test. The interaction of spacing and retention interval in repetition benefits has been observed in many situations. However, everyday events never repeat exactly, and new events often include repeated and changed features that interfere with memory for earlier events (e.g., when one’s memory for their friend’s maiden name is impaired by the new married name). Although this occurs regularly in daily life, we know little about the role of spacing in such retroactive effects of memory. I address this by examining spacing and retention interval effects in a paired associate learning task including word pairs with repeated cues and changed responses (A-B, A-C). Interference can be reduced in such paradigms when changes are detected and later remembered, so I also examined the role of change processing. Sixty participants completed a continuous paired-associate learning task that varied the spacing between A-B and A-C pairs (lag) and between A-C pairs and test trials (retention interval). On study trials, participants indicated when they detected changed (A-C) pairs. On test trials, participants attempted to recall original responses (B) and indicated which had earlier changed. The results suggest that that the optimal lag for recall of original responses increased as retention interval increased, and such recall depended on how often changes were detected and recollected. These findings add to the growing theoretical framework surrounding the spacing effect and have clear implications for educational practice.

SPACING BY RETENTION INTERVAL INTERACTIONS IN RETROACTIVE EFFECTS OF MEMORY: THE ROLE OF DETECTING AND REMEMBERING CHANGE

by

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A THESIS

Submitted to
the Faculty of The Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Master of Arts

Greensboro

2021

Approved by

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APPROVAL PAGE

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Date of Acceptance by Committee

3/31/21

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I: INTRODUCTION

Learning new information can be enhanced through multiple exposures. Prior research has shown that long-term memory is enhanced when learning events are spaced apart in time, rather than when they are massed in immediate succession. This phenomenon is known as the spacing effect (Ebbinghaus, 1885/1913). Studies on the spacing effect have shown that repetitions can benefit memory to varying degrees, depending on both when the second exposure occurs relative to the first and when testing occurs (Cepeda et al., 2006; 2008; 2009; Kim et al., 2019). Most spacing effect research has focused on the spacing of exact repetitions. But when attempting to learn in a real-world setting, exact repetitions of stimuli almost never occur. Little is known about the effects of spacing and retention interval on original learning when stimuli later change (e.g., Robbins & Bray, 1974). Changed information can either hurt or help memory for original information, depending on whether changes are detected and remembered (Garlitch & Wahlheim, 2020; Jacoby et al., 2015; Wahlheim et al., under review). Detecting and remembering change can enhance memory and prevent interference effects, but the extent to which these benefits vary with spacing and retention interval is unknown.

Here, I propose to address these gaps by examining 1) the effects of spacing changed information and varying retention intervals on memory for original information and 2) the roles of detecting and remembering changes in those effects. In what follows, I will first discuss some relevant studies and theories from the spacing effects literature. Then, I will review studies of retroactive effects of changes on original memories along with an account that attempts to explain the roles of detecting and remembering changes in those effects. I will describe an experiment that I conducted to explore these relationships. Finally, I will discuss the implications of my findings, the limitations of my study, and discuss future directions for this work.

The Spacing Effect

Repeated study, relative to a single study event, has been shown to have overall benefits for memory (for reviews, see Delaney et al., 2010; Maddox, 2016). These benefits depend on the temporal distance, measured either by the number of intervening items or the amount of time between the repetitions (i.e., lag) and between final repetition and final recall (i.e., the retention interval). In an early demonstration of this relationship, Glenberg (1976) set out to define the conditions that influence the effectiveness of restudy. Specifically, he wanted to know how the proportion of correctly recalled items varied in response to changes in lag and retention interval. The first experiment used a continuous paired associate learning paradigm in which participants were shown two presentations of a repeated pair and then given a cued recall test. Importantly, he systematically varied the number of intervening items between presentations (lag interval; 0, 1, 4, 8, 20, or 40) and the number of intervening items between the second presentation and the test (retention interval; 2, 8, 32, or 64). This produced 24 lag × retention interval combinations. The lag function was nonmonotonic for shorter retention intervals (2 and 8 items), with recall accuracy initially decreasing from a lag of 0 to a lag of 1, then increasing from a lag of 1 to a lag of 8, before finally decreasing from a lag of 8 to a lag of 64. For longer retention intervals (32 and 64 items) the lag function was monotonic, with proportion recalled increasing as lag increased. These findings suggest that shorter lags are more beneficial for memory at short retention intervals and longer lags are more beneficial for memory at long retention intervals.

Following this, Cepeda et al. (2008) conducted an experiment to examine how lag and retention interval interact to promote learning and retention over substantially longer time intervals. Specifically, they examined the spacing effect over significant durations, with lags up to 3.5 months and retention intervals up to 1 year. Participants were asked to study 32 obscure, but true facts over two study sessions. During the two study sessions, participants engaged in cued recall retrieval practice and were given feedback. In a third session, participants returned to the lab for a final cued recall test. They found that as study lag increased, subsequent recall initially increased and then decreased for each of the different retention interval conditions, and longer retention intervals were associated with lower recall performance at final test. Additionally, findings from this experiment suggest that the optimal lag between presentations for effective recall depended on the desired length of retention. Overall, these results were consistent with Glenberg's (1976) findings showing that the optimal study lag increased with retention interval.

Cepeda et al. (2009) further examined this relationship between lag and retention interval and investigated whether shorter lags, between 1 and 7 days, are sufficient to produce a pattern similar to the one observed by Cepeda et al. (2008). They investigated the effects of lag duration on subsequent recall for fixed retention intervals of moderate length and were concerned with defining the optimal lag for these retention intervals. In the first experiment, participants learned Swahili-English word pairs in two learning sessions that were spaced apart by either 0, 1, 2, 4, 7, or 14 days. During the first session, participants were asked to study 40 Swahili-English word pairs, complete a cued recall test with feedback. They were cued with Swahili words and asked to type the corresponding English words. Items repeated throughout the test until participants gave a correct response twice. During the second session, participants completed two cued recall tests on the previously studied word pairs and were given feedback. After the second learning session subjects waited 10 days and then completed a final cued recall test without feedback. The second experiment was identical to the first, except it used obscure facts instead of word pairs and the lags were substantially longer (i.e., lags from 20 min to 6 months, and a retention interval of 6 months). Consistent with previous findings, results showed a nonmonotonic lag effect on final recall accuracy showing that accuracy initially increased and then subsequently decreased across lags. Increasing the lag from 0 days to 1 day (Experiment 1, retention interval of 10 days) and from 20 mins to 28 days (Experiment 2, retention interval of 6 months) led to a significant increase in retention. Their findings are consistent with the notion that the optimal lag increases as the retention interval increases. Cepeda et al. (2009) suggested that to promote long-lasting memory in a real-world setting, one should space learning events out over substantial temporal lags (e.g., lags of several months instead of days or weeks).

To test this idea, Kim et al. (2019) examined the spacing effect in a naturalistic setting by analysing longitudinal data from workplace training sessions across five companies. During each training session, employees answered a few questions (either multiple choice, multiple answer, multiple choice with highly detailed feedback, matching, or fill in the blanks format) and received corrective feedback when they answered incorrectly. Employees completed three training sessions separated by 0-210 days. Since the material was not random and some of it was likely to have been previously known by the participant, items that were answered correctly during the first training session were excluded. The authors only included items that had a correct response for the second occurrence of the question, as that demonstrated that the participant had successfully learned the item. Answers to questions during the third training session served as the response variable. The spacing interval corresponded to the time interval between the first and second iteration of a question. The retention interval corresponded to the time interval between the second and third iteration of a question.

Spacing, retention interval, and question format significantly affected the probability of memory accuracy within a training session. Importantly, they found an interaction between spacing interval and retention interval such that at shorter retention intervals (0 and 7 days) the odds of answering correctly decreased as the spacing interval increased, and at longer retention intervals (120, 180, and 210 days) the probability of answering correctly increased as the spacing interval increased. Consistent with previous findings, these results demonstrate that the optimal amount of spacing between an initial learning event and a relearning session varies depending on the length of the retention interval. More specifically, the probability of retaining information in memory for a longer duration (e.g., a month or longer) is higher if the spacing interval is also long (e.g., 11 days or longer). Taken with earlier studies, these findings show clear evidence that the optimal spacing during encoding depends on the retention interval, with shorter lags benefitting memory at short retention intervals and longer lags benefitting memory at long retention intervals. The spacing by retention interval interactions described in the studies above have also been shown across studies using various stimuli. For example, spaced repetition effects have been shown for texts (Rawson & Kintsch, 2005; Verkoeijen et al., 2008; Rawson, 2012), word-pairs (Bahrick & Phelphs, 1987; Küpper-Tetzel & Erdfelder, 2012; Küpper-Tetzel et al., 2014b; Gerbier et al., 2015) and vocabulary words in a classroom setting (Küpper-Tetzel et al., 2014a).

Various mechanisms have been proposed to explain the observed lag by retention interval interactions, including the diminished processing account, encoding variability theory, and the recursive remindings hypothesis (for a review, see Benjamin & Tullis, 2010). The diminished processing account (Bregman, 1967; Cuddy & Jacoby, 1982; Greeno, 1970) proposes that massed presentations and short lags lead to inadequate processing of the second presentation of stimuli. In these cases, the recent encoding of the first presentation decreases the novelty of the second presentation, and therefore less attention is devoted to encoding it. However, the diminished processing account alone cannot fully explain the nonmonotonic lag functions seen at longer retention intervals (e.g., Benjamin & Tullis, 2010).

Lag by retention interval interactions can also be partially explained by the encoding variability theory, which proposes that an item is more likely to be recalled if the associated context during retrieval matches the associated context at encoding (for an in-depth review of the encoding variability theory, see Bray et al., 1976). This theory predicts that as the spacing between presentations of repeated stimuli increases, their representations in memory approach independence. Longer lags between the presentation of repeated stimuli allow for more context change (cf. Estes, 1955), which allows for encoding the same stimuli within different contexts. This in turn allows for a greater proportion of recalled items at longer retention intervals. If any of the contexts present during encoding are reproduced at test, then the studied material is more likely to be recalled. Test contexts are more similar to study contexts at shorter than longer retention intervals. It follows that similar study and test contexts at short retention intervals should boost retrieval relative to less similar study and test contexts at longer retention intervals (Glenberg, 1976). Encoding variability theory can therefore account for the overall benefit of longer lags and shorter retention intervals on memory. But it cannot account for nonmonotonicity in lag by retention interval interactions (e.g., Cepeda et al., 2008, 2009; Glenberg, 1976; Kim et al., 2018).

To explain the mechanisms underlying these nonmonotonic functions, Benjamin and Tullis (2010) also invoked the recursive remindings hypothesis (Hintzman, 2004). While encoding variability theory emphasizes the importance of independence between two presentations, the recursive remindings hypothesis stresses the importance of the interaction, or dependence, between presentations. It proposes that the second presentation of a stimulus can trigger a reminding of the first presentation of that stimulus (i.e., study-phase retrieval), allowing for retrieval practice of the first presentation of that stimulus. Successful retrieval of the first presentation during study of the second presentation allows individuals to encode additional associative information with that stimulus, and therefore allows for more elaborative encoding. Massed presentations do not benefit from study-phase retrieval because the first presentation is still active at the time of the second presentation, and so it is not elaborated upon. Benjamin and Tullis (2010) performed model simulations showing reasonable evidence that some combination of the diminished processing account, encoding variability theory, and the recursive remindings hypothesis provide a general theoretical basis for explaining the effects of repetition and the effects of spacing and retention interval interactions on memory.

More relevant to the current proposal, Benjamin and Tullis also suggested that the mechanisms proposed by these accounts may play a role in lag by retention interval interactions observed when stimuli include features with both repetitions and changes (e.g., Bruce & Weaver, 1973; Robbins & Bray, 1974a, 1974b). In contrast to spaced repetitions, although changed stimulus features can help memory for originally learned information, they more commonly create interference that impairs existing memories. But relatively few studies have examined how spacing and retention intervals moderate these potentially deleterious effects. Most importantly, those studies have not explicitly considered the roles of key retrieval mechanisms operating during both study and test trials, recently shown to moderate such effects (Garlitch & Wahlheim, 2020; Jacoby et al., 2013; Negley et al. 2018; Wahlheim & Jacoby, 2015). In what follows, I will summarize representative studies of spacing and retention interval effects on memory for original information followed by repetitions with changes. Then, I will describe recent studies implicating roles for detecting and recollecting changes in such effects.

Retroactive Effects of Change on Original Memories

Interference theory generally proposes that forgetting occurs in part because memories from differences sources compete with one another (e.g., Underwood, 1957). Retroactive interference (RI) effects occur when later learning hinders one's memory for previously learned material. For example, after changing your phone number, you may have a difficult time remembering your old number. Classic interference theory states that interference will occur between two events from similar contexts because those events will be difficult to differentiate (for a review, see Anderson & Neely, 1996), but other work has shown that there are times when contextually similar events facilitate recall of one another.

As an example of the latter, Barnes and Underwood (1959) used two transfer paradigms to examine retroactive effects in list learning. Their first paradigm used A-B, A-C nonsense syllable and response pairs. B and C responses were low-similarity, two syllable adjectives (e.g., DAX – afraid; DAX – complete), as these normally produce retroactive interference, where learning the C word interferes with one's memory for the previously learned B word. Their second paradigm used A-B, A-B' nonsense syllable and response pairs. B and B' responses were high-similarity, two syllable adjectives (e.g., DAX – afraid; DAX – scared), as these normally produce retroactive facilitation, where learning the high similarity response pair B', enhances one's memory for the previously learned B response (Young, 1955). For both paradigms, participants studied a list of eight A-B word pairs. They then studied a second list of either A-C or A-B' word pairs. List 2 was repeated either 1, 5, 10, or 20 times. Finally, participants were given a written cued recall test where they were tested on their memory for both lists.

For A-B, A-C word pairs, they found that learning a second word pair reduced their memory for the first word pair, and the degree of this interference effect depended on the number of List 2 repetitions. As the number of List 2 repetitions increased, the average of correct responses for List 1 items decreased. Additionally, memory for List 2 A-C pairs was positively correlated with the number of List 2 repetitions. This suggests that A-B associations are weakened by the learning of A-C items. However, for high similarity response pairs (A-B, A-B'), they found that learning a second, related word pair enhanced memory for the first word pair. They attributed this to a mediation mechanism. If one learns an A-B word pair and then sees an A-B’ word pair that is high in similarity, B can act as a mediator for recall of B’. When this occurs, the individual encodes the two word pairs together as A-B-B’. According to this mediation account, learning A-B eases the encoding of A-B’ since words that are high in similarity consequently have a high associative connection. Together these findings suggest that retroactive effects of memory can either be facilitative or interfering, depending on the relationships among stimuli.

In Barnes and Underwood’s experiment, increasing the number of List 2 repetitions consequently increased the spacing between the presentation of A-B items and the test on those items. Seeing that the degree of retroactive interference observed depended on the number of List 2 repetitions in their A-B, A-C paradigm, it is worth considering that the spacing of the presentation of changed stimuli influences the retroactive effects of studying changed information. To examine this, Bruce and Weaver (1973) tested the effects of spacing between A-B and A-C pairs on retroactive effects of memory on short-term retention. Participants studied lists of A-B, A-C and A-B, C-D control word pairs and completed cued recall tests on those lists. During the cued recall test, participants were asked to recall both responses associated with the given cue. The lag between the presentation of A-B, A-C word pairs was systematically varied to be either short, medium, or long (3, 6, or 9 seconds respectively). Their results showed higher recall for B responses for A-B, A-C items than for A-B, C-D items. Like those of Barnes and Underwood, these results show that under certain conditions the presentation of changed information can lead to retroactive facilitation. Additionally, recall for B items was higher for A-B, A-C items with a long lag than those with a short or medium lag. This suggests that retroactive effects of memory are influenced by the spacing of learning changed information.

To explain their findings, Bruce and Weaver amended the rehearsal buffer theory (RBT), proposed by Atkinson and Shiffrin (1968), which proposes that when an item is first presented it enters a limited-capacity rehearsal buffer where it is rehearsed until another item takes its place. The longer an item stays in the buffer, the stronger its memorial representation becomes and the longer it takes for the item to be forgotten. As soon as an item exits the buffer, its memorial strength begins to decrease by a constant proportion for each following item, until the target item is eventually tested. At test, the item is recalled if it is still within the buffer (for short retention intervals) or if its memorial strength is still great enough. When an item is repeated it re-enters the buffer and the strength of the item increases, consequently increasing its probability of recall. However, the extent to which a repeated item strengthens its memorial representation depends on the lag between presentations. According to the RBT, short lags do not allow for the item to be removed from the buffer after its first presentation and, therefore, should show no additional strengthening beyond what can be expected from a longer study duration. However, at longer lags it is more likely that the item will have left the buffer and begun to decrease in memorial strength. If the lag is too long and the item has been forgotten, then the repetition will act as the first presentation of the item. However, if the item has left the buffer and is not yet forgotten, then a repetition allows for exponential strengthening of one’s memory for the item.

Bruce and Weaver proposed an amendment to the RBT to explain the effect of lag and retention interval interactions on retroactive effects of memory when studying changed information. They suggested that if memory of an A-B item is still in the rehearsal buffer at the presentation of the A-C pair, either the A-C pair will force the A-B pair out of the buffer (i.e., retroactive interference) or the A-C pair will serve as a reminder of the A-B pair, increasing its memorial strength (i.e., retroactive facilitation). This theory offers one possible explanation for the findings of Bruce and Weaver and begins to tease apart how retroactive effects of memory are influenced by how one spaces the study of changed information.

Together, findings from Bruce and Weaver and the application of RBT contend that the lag between the presentation of items is the source of the spacing effect. Robbins and Bray (1974a) challenged this idea and examined whether lag and retention interval interact to influence memory for changed information. They conducted an experiment to examine the interaction between lag and retention interval on memory for changed words in a continuous paired-associate task. They had participants study word pairs with tests of those word pairs strategically intermixed. The list consisted of A-B control items, A-B, A-B repetitions, and A-B, A-C changed word pairs. Control items had a retention interval between 5-55 seconds. A-B, A-B repetitions and A-B, A-C changed pairs had lags of either 5, 15, or 25 seconds between presentations and retention intervals of either 5 or 25 seconds between the second presentation and the test.

Consistent with previous studies of spaced repetition effects, their findings showed that memory benefits for A-B, A-C items varied based on spacing and retention interval combinations. Specifically, some combinations led to retroactive interference in which memory for original responses (i.e., memory for B given A as a retrieval cue) was poorer than memory for responses for A-B control items. In contrast, other combinations led to retroactive facilitation in which memory for original responses was better than memory for control items. A-B, A-C items with the shorter retention intervals (5 seconds) showed evidence of retroactive interference at short lags (5 and 15 seconds). However, items with the shorter retention interval and a long lag (25 seconds) showed a proportion of recalled B items that was higher for A-B, A-C items than for repeated controls. At a longer retention interval (25 seconds) and shorter lags (5 or 15 seconds) A-B, A-C recall for the B responses was not significantly different from that of A-B, A-B items.

Robbins and Bray (1974b) extended this work to examine how longer lags and retention intervals interact to influence memory for changed information and to determine if these effects maintain after an additional delay. Their method mirrored that of Robbins and Bray (1974a), with a few minor changes. They included lags and retention intervals of 5, 10, 25, and 50 seconds and had participants complete a delayed recall test after completing the main study and test trials. Their findings showed that when items were paired with a short retention interval (5 or 10 seconds), correct recall of B responses was significantly higher for A-B, A-B items than for A-B, A-C items, demonstrating retroactive interference. They found that this retroactive interference increased as the lag increased, with the longest lags of 25 and 50 seconds producing the lowest recall of B responses and the shortest lag of 5 producing the highest recall for A-B, A-C items in the short retention interval condition. Items in the long retention interval condition (25 or 50 seconds) showed little to no interference, with statistically equivalent proportions of B response recall for A-B, A-C and A-B, A-B items across all the lag variations. Findings from the delayed recall test were similar to those of the immediate recall tests. These findings bolster those of

Robbins and Bray (1974a) and provide further evidence that the nature of retroactive effects of memory are influenced by the interaction between the lag and the retention interval and suggest that these effects last beyond immediate recall.

The works of Bruce and Weaver, and Robbins and Bray were the first to explicitly examine the effect of lag and retention interval interactions on retroactive effects of memory. While Bruce and Weaver’s proposed amendment to the rehearsal buffer theory helps to unravel the mechanisms underlying these effects, it cannot explain the spacing effect observed at substantial lag and retention intervals. Additionally, Bruce and Weaver’s amendment to the rehearsal buffer theory hints at the importance of A-B remindings during A-C study, but no works to my knowledge have explicitly measured the role of retrieval practice during the study of changed information within the context of spacing.

Inspired by Hintzman’s recursive reminding hypothesis, it has been hypothesized that this facilitation is driven in part by the detection of change that involves retrieval of the original information. Jacoby et al. (2015, Experiment 1) examined this hypothesis using an A-B, A-C paradigm in which they manipulated how far back participants were told to monitor for changes when encoding A-C pairs. There were semantic and orthographic relationships between B and C terms, which, based on findings from Barnes and Underwood, should lead to retroactive facilitation. Participants first studied a list of word pairs, followed by an interpolated distractor task. They then studied a second list in which some of the word pairs changed from List 1 and some of the word pairs changed within List 2 only. Before List 2 study, participants were either told to only indicate a change for word pairs that had changed from earlier in List 2, or indicate changes for pairs that had changed from any point in the experiment. After studying List 2, participants were given a cued recall test where they saw the left-hand member of the word pair (A) and were asked to recall the first response (B) that appeared with the cue. The group that was instructed to look back to List 1 during List 2 showed retroactive facilitation in overall recall. In contrast, the group that was instructed to look back only within List 2 did not show facilitated recall. These results suggest that directed remindings of original responses enabled retroactive facilitation partly by enhancing memory through retrieval practice.

Most important to the present investigation of lag and retention interval effects, the paradigm from Jacoby et al. (2015) incidentally included a study lag manipulation. By varying whether A-B, A-C pairs included changes originating from List 1 or List 2, participants encoded each pair at longer (List 1) and shorter (List 2) lags. Consistent with studies of spacing effects, a comparison of original response recall for detected changes showed higher recall for responses appearing at longer than short lags. This finding provides preliminary evidence indicating a lag effect in A-B, A-C learning, comparable to spaced repetition effects shown earlier, that depends on change detection while encoding new information.

Based on the recursive reminding hypothesis (Hintzman, 2011), Jacoby et al. (see also Wahlheim & Jacoby, 2013) proposed a theoretical framework to explain how changes that would typically be predicted to create interference can sometimes improve memory, as in Jacoby et al. (2015) and earlier studies showing retroactive facilitation effects (e.g., Barnes & Underwood, 1959; Bruce & Weaver, 1973). According to the Memory-for-Change (MFC) framework, changed information can interfere with one's ability to recall initial information (i.e., retroactive interference), but such interference can be prevented by detecting changes. The model proposes that change detection during the second presentation of a stimulus (A-C) is enabled when overlapping features (A) trigger retrieval of the first presentation (A-B). These remindings, which are comparable to study-phase retrievals described in the literature on spaced repetition effects (for a review, see Benjamin & Tullis, 2010), increase the accessibility of the first presentation item resulting from retrieval practice, thereby leading to retroactive facilitation. Further, retrieval of original responses when encoding changed responses allows both (B and C) to be held simultaneously in working memory. Such co-activation allows the information from the two presentations to be jointly encoded into one configural (integrated) representation that can further facilitate source memory by supporting recollection of the change between responses. Change recollection occurs when an individual can later remember that a change occurred earlier and can accurately recall the changed response (C). This process is akin to the recursive remindings assumed to occur when participants remember that stimuli earlier appeared as repetitions (Hintzman, 2011).

The MFC explanation of retroactive facilitation proposed by Jacoby et al. (2015) was further examined in an experiment by Negley et al. (2018). Their experiment examined the roles of change detection and recollection in retroactive effects of memory in an A-B, A-C paradigm. Based on the MFC framework, they predicted that spending *more* time with competing information (A-C pairs) would lead to *better* memory for the original information (A-B pairs). This prediction starkly contrasts with the prediction from classic interference theory that more time spent encoding competing information should lead to poorer memory for original information. They tested the hypothesis that extended exposure to associated, competing information should allow for more remindings of and better subsequent memory for the original information. To test this, they manipulated the study time during List 2 so that word pairs were presented for either 1 or 7 seconds. During List 2 study, participants were told to monitor for changes and if they detected a change, they were then asked to output the original, List 1 response. Following List 2, participants were tested on their memory for List 1 items, asked to judge each item as changed or not, and give the List 2 response for changed items (i.e., a change recollection measure). The results showed that longer List 2 study time was associated with greater change detection and retrieval of List 1 responses during List 2, and greater change recollection at test. Importantly, consistent with MFC and contrasting with interference theory, longer List 2 study times also resulted in higher List 1 recall during the final test, which was partly explained by increases in both measures of change processing.

Garlitch and Wahlheim (2020) examined whether these effects would replicate in older and younger adults. Although they did not find improved List 1 recall with longer List 2 study times, as shown by Negley et al. (2018), they also did not show greater retroactive interference effects following longer List 2 study times. Importantly, they did replicate the finding that detection and recollecting changes were associated with facilitation in memory for original responses. Specifically, both age groups showed improved memory for List 1 responses on the final test when changes were detected, and List 1 responses were recalled during List 2 encoding. Change recollection at test also appeared to be associated with a light increase in List 1 recall, and older adults experienced fewer benefits because they recollected change less often than younger adults.

Collectively, these studies indicate a critical role for change detection and change recollection in obtained retroactive facilitation effects. However, as mentioned above, no studies to my knowledge have examined how the spacing between changed pairs and the retention interval between the original presentation and the test of that information, influence moderate retroactive effects of memory associated with detecting and recollecting change.

The Present Experiment

To address this issue, I examined the roles of spacing and retention intervals in retroactive effects of changes on original memories of the sort reported by Jacoby, Wahlheim, and colleagues. To do this, I combined procedures from the repetition effect literature (e.g., Glenberg, 1976) with the procedures from the A-B, A-C retroactive effects studies including overt measures of change processing (e.g., Garlitch & Wahlheim, 2020; Jacoby et al., 2015; Negley et al., 2018). Inspired by Robbins and Bray (1974) and Glenberg (1976), I developed a continuous paired associate A-B, A-C paradigm in which I systematically manipulated combinations of spacing between A-B and A-C pairs and the retention intervals between A-B pairs and cued recall test trials for the original responses (B).

My first goal in this project was to characterize the effects of lag and retention interval combinations using an approach comparable to earlier studies of spaced repetitions (e.g., Cepeda et al., 2008; Glenberg, 1976) and retroactive effects of changes (e.g., Robbins & Bray, 1974). Based on those studies and related studies described above, I expect that the optimal study lag for correct recall of original responses will vary with retention interval such that longer spacing lags will be more beneficial for recall of original responses at longer retention intervals. My second goal was to examine the roles of change detection and recollection in such spacing by retention interval interactions. Since detecting and recollecting change both rely on retrieval processes, I expect that the probabilities of such retrievals will diminish as lags and retention intervals increase, as shown for A-B to A-C lags in Jacoby et al. (2015). Critically, I will also use conditional analyses to determine the extent to which potential retroactive facilitation or interference in overall recall will be associated with whether participants detected and recollected change. Based on the studies above (e.g., Garlitch & Wahlheim, 2020; Negley et al., 2018), I expect to observe retroactive facilitation when changes are detected and recollected and retroactive interference when changes are not detected.

CHAPTER II: METHOD

Participants

Here, I report how I determined sample size, all data exclusions, all manipulations, and all measures in the experiment (Simmons et al., 2012). Sixty adults (45 females) between the ages of 18-30 years (*M* = 18.82, *SD* = 1.87) participated in the experiment. Participants were recruited from the undergraduate participant pool in the Department of Psychology at the University of North Carolina at Greensboro and compensated with partial course credit. A stopping rule was established of 60-75 participants over the course of one academic semester, but with the caveat that if the goal of at least 60 participants could not be reached in one semester, data collection would continue until 60 participants had been tested. I was able to test 60 participants in just over one semester. Results from Cepeda et al. (2006; 2008; 2009), Glenberg (1976), and Kim et al. (2019) suggest a crossover interaction between lag and retention interval such that short lags result in higher recall when paired with a short retention interval, and long lags result in higher recall at longer retention intervals. Based on these results, a sensitivity power analysis was conducted using G*Power 3.1 (Erdfelder et al., 1996) with power set to .80 and alpha = .05, which indicated that a sample size of sixty participants was sufficient to detect a large effect size (Cohen's $f = 0.37$, $\eta p^2 = .12$) of a two-way interaction (3 lag x 3 retention interval). I will discuss the limitations of my study's power to detect lag effects, which can be small, in the Discussion. Any observed effect sizes smaller than those indicated in my sensitivity analysis will be interpreted with caution.

Design

This experiment used a 3×3 within subjects design that included A-B, A-C items, for which lag was manipulated between the first and second presentation of pairs (P1-P2 Lag) and the retention interval was manipulated between the second presentation of those pairs and corresponding test trials (P2-Test Lag). For both lag and retention interval, I included three fully crossed levels: 4, 16, and 48 intervening pairs. This produced nine within-subjects conditions. To examine the effects of presenting A-C pairs following A-B pairs on later recall of A-B pairs, I also included single presentations of pairs that were not followed by A-C pairs prior to test trials (referred to as A-B items). The retention intervals for A-B pairs (i.e., P1-Test Lags) were matched with all A-B, A-C item types. This resulted in six P1-Test Lag control conditions (i.e., 9, 21, 33, 53, 65, or 97 intervening items). The lags for the A-B conditions were the sum of both lag types for each condition plus one to account for the appearance of A-C pairs between A-B and test trials.

Materials

The materials were 255 word pairs that included a cue word with one or two response words (e.g., ball-bounce; ball-park), depending on whether pairs were assigned to be critical or filler items. Critical items (A-B, A-C) contained two response words for every cue word, buffer items contained either one or two responses, depending on if they appeared once (A-B) or twice with a change (A-B, A-C), and filler items only consisted of one response and one cue word (A-B). Of the 255 word pairs, 95 pairs were taken from Wahlheim and Jacoby (2013). The remaining 160 word pairs were taken from the Jacoby (1996) norms and the University of South Florida’s Free Association Norms (Nelson et al., 1998). According to Nelson et al., the strengths of forward associations (*M* = .04, *SD* = .02, range .01-.10) and backward associations (*M* = .02, *SD* = .03, range .00-.10) between B and C words were low on average.

Of the 255 word-pair sets, 150 were critical items, 27 served as primacy buffers, and 78 served as fillers to allow for the even distribution of lag and retention interval spacing throughout the list. There were three buffers for each of the nine within-subjects conditions. These buffers were not included in analyses and the filler items were presented as study items but were not tested throughout the list. The 150 critical items were divided into 15 groups of 10 items that represented each of the different item types equally often across participants (90 A-B, A-C items [9 groups × 10 items] and 60 A-B items [6 groups × 10 items]). The sequence of item appearance within each group was pre-randomized.

Procedure

All participants were tested individually in rooms with a white noise machine running to reduce external distractions. An experimenter remained in the room with the participant for the duration of the test. Once informed consent was obtained, participants completed a computerized demographic questionnaire. All experimental stimuli were administered through E-prime software (Version 3, Psychology Software Tools, Inc) and appeared in white, Arial, size 24 font on a black background. The procedure was a continuous paired associate learning task that included a single list comprising study and test trials. On study trials, word pairs appeared for 6000 ms each followed by a 500 ms interstimulus interval (ISI), during which the screen was blank. They appeared in a fixed random order for all subjects, with the stipulation that no more than two pairs from the same within-subject conditions (i.e., A-B, A-C lag and retention interval combinations) appeared consecutively, and no more than two control pairs from the same retention interval condition appeared consecutively.

Participants were told that when word pairs appeared, they should read those pairs aloud and study them for an upcoming memory test. Participants were also told that some word pairs would change throughout the list (i.e., appear a second time with the same cue word and a new response word, e.g., knee-bone to knee-bend). Participants were instructed to monitor for changed word pairs and press “1” on the keyboard as soon as they noticed that a changed pair had appeared. The text “Changed (1)” was displayed in white underneath each presented word pair. If participants pressed “1” to indicate that they noticed a change, the text “Changed (1)” turned from white to yellow to indicate that their response had been recorded. Participants were told to continue to study the word pairs until they disappeared from the screen. Participants were asked to study all word pairs equally well. They were also aware that they would have to explicitly recall the first response that was paired with each cue and would only be asked to recall the second response if the response had changed.

Periodically throughout the list, participants completed cued recall tests for the responses that appeared on the first presentation of items (i.e., they tried to recall the B terms when given the A terms). Test items counted towards the lag of items that had previously appeared. In other words, the lag for each A-B, A-C item comprised the total number of intervening events between the two presentations (i.e., study and test trials). During test trials, participants were first presented with a cue word and were asked to type the response that first appeared with it. Next, they were asked if the response items that had been paired with this cue had changed throughout the list. Participants were told to press “1” or “0” on the keyboard to indicate that *yes* it changed, or *no* it did not, respectively. Cues appeared in a fixed random order. Participants could advance to the next trial after entering a response, but since the timing of responses varied from person to person (depending on how quickly they typed their responses), test items timed out after 10 s and change classification responses timed out after 4 s. This prevented participants from lingering on test items and varying the spacing of critical items throughout the experiment. I was unable to perfectly equate the serial position of the different A-B, A-C lag-by-retention interval combinations (4-4, 4-16, 4-48, 16-4, 16-16, 16-48, 48-4, 48-16, and 48-48) and each A-B retention intervals (Single-9, Single-21, Single-33, Single-53, Single-65, Single-97) throughout the list, but I did distribute items from each condition as evenly as possible across the list. See table 1 for the average serial positions and standard deviations for each combination of lag and retention interval. Readers can see how this was accomplished by referring to the design and materials spreadsheet provided in https://osf.io/adk37/?view_only=bc21e07028274c9c9ddd1fb9f88b2c2d. See figure 1 for a layout of the structure of the experiment.

Table 1: The mean serial positions and standard deviations for lag and retention interval combinations

	Serial Positions	
Item Type	*M*	*SD*
Lag 4, RI 4	197.90	140.85
Lag 4, RI 16	194.50	124.83
Lag 4, RI 48	211.10	140.70
Lag 16, RI 4	201.10	136.93
Lag 16, RI 16	206.10	149.24
Lag 16, RI 48	199.40	133.00
Lag 48, RI 4	244.40	110.38
Lag 48, RI 16	207.00	127.66
Lag 48, RI 48	182.80	116.73
Single-9	178.70	125.95
Single-21	178.20	130.06
Single-33	182.40	140.20
Single-53	175.60	125.43
Single-65	203.80	127.96
Single-97	193.10	109.92

Note. In the above table, RI refers to the retention interval. Means and standard deviations are calculated from the serial position of the first presention of items (i.e., the first word pair for A-B, A-C items and the only presentation for A-B items), out of the total list length of 468 presentations.

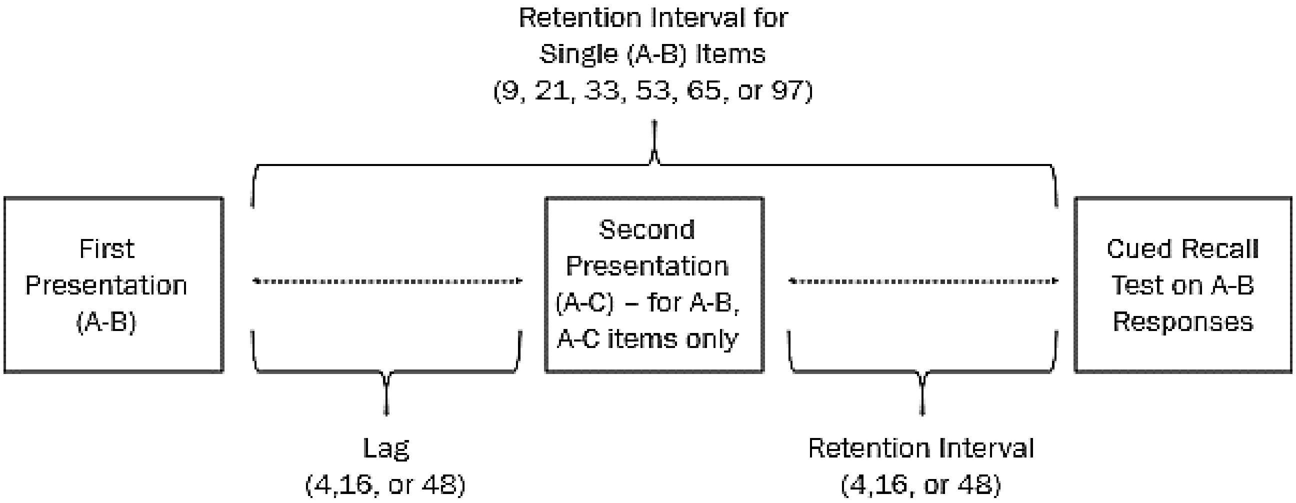

Figure 1: The structure of the present experiment.

Item presentations for each word pair were separated by either 4, 16, or 48 other item presentations. Retention interval is also varied in this way.

CHAPTER III: RESULTS

All analyses were conducted using R (R Core Team, 2014) and figures were produced using the R package, ggplot 2 (Wickham, 2009). The significance level was set at $\alpha = .05$. I conducted hypothesis tests using generalized linear mixed effects models from the *lme4* package (Bates et al., 2015). I chose to use generalized linear mixed effects models as they allowed me to control for both item and subject effects, thus providing more precise population estimates than traditional ANOVAs that only treat either items or subjects as random effects. I conducted posthoc comparisons using the emmeans function from the emmeans (Lenth, 2020) package with the Tukey method to correct for multiple comparisons. To test my hypotheses, I examined the effects of Lag, Retention Interval, and Item Type on the relevant dependent measures of recall performance and change processing. I included those variables as factors in the fixed effects models. I visualized the central tendencies in my data by extracting estimated probabilities and corresponding confidence intervals from the mixed effects models. In what follows, I reiterate the hypotheses described in the Introduction and describe the analyses used to test those hypotheses and the corresponding results.

Hypothesis 1: Longer lags will benefit recall of original responses more at longer retention intervals.

To test this hypothesis, I fit a 3 (Lag) x 3 (Retention Interval) model to compare the probabilities of correct recall of original responses (B terms) across lags (4, 16, & 48) for retention interval pairings (4, 16, & 48) for A-B, A-C items only (see black points in Figure 2). This test revealed a significant main effect of Lag on test accuracy, $\chi^2(2) = 127.25$, $p < .001$, a significant main effect of Retention Interval, $\chi^2(2) = 34.823$, $p < .001$, and a significant Lag × Retention Interval interaction, $\chi^2(4) = 16.51$, $p < .01$. I expected differences in the optimal lag to be most apparent when comparing the most extreme retention intervals (i.e., 4 and 48). Specifically, I expected to observe an interaction indicating that correct recall is highest at a longer lag at retention interval

48 than 4. To examine this, I conducted follow-up pairwise comparisons that only compared A-B, A-C items with a retention interval of 4 or 48. At the shortest retention interval of 4, recall accuracy decreased steadily as lag increased from 4 to 16, *z* ratio = -3.11, *p* < .01, and from 16 to 48, *z* ratio = 5.43, *p* < .001. However, at a retention interval of 48, there was no significant difference in correct recall probabilities between the two shortest lags, *z* ratio = 1.18, *p* = .46. When compared to the longest lag of 48, recall was significantly lower for a lag of 4, *z* ratio = 3.30, *p* < .01, and for a lag of 16, *z* ratio = 4.47, *p* < .001, at a retention interval of 48. This supports the hypothesis that nonmonotonicity of lag functions on recall accuracy is most likely to occur at longer retention intervals.

Contrary to my expectation, there was no significant difference in recall accuracy between retention intervals 4 and 48 at a lag of 48, *z* ratio = 0.73, *p* = .47. However, there was a significant difference in recall accuracy between retention intervals 4 and 48 at the shortest lag of 4, *z* ratio = 5.92, *p* < .001. This offers support for Bruce and Weaver's (1973) amendment to the RBT (Atkinson & Shiffrin, 1968), and shows evidence that, because short lags do not offer as much of a boost to memory strength beyond what is expected from a longer study duration, these items are more likely to have been forgotten after a long retention interval than when paired with a shorter retention interval.

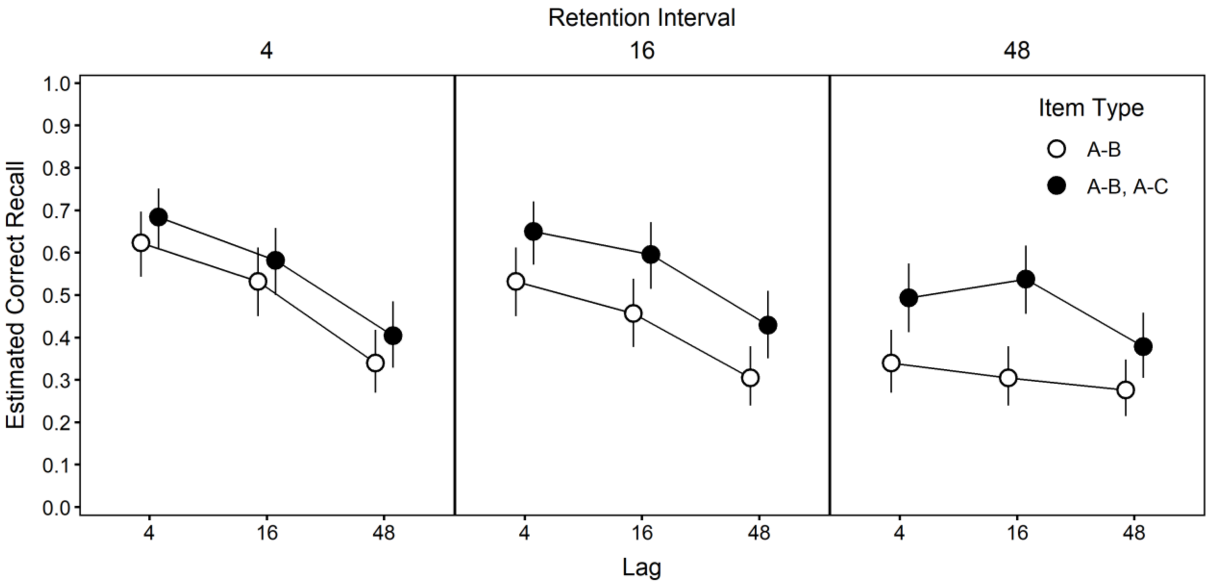

Figure 2: The estimated recall for B responses, as a function of the number of intervening events between the two presentations of a repeated item (lag), and the number of intervening events between the second presentation of an item and its test (retention interval).

Hypothesis 2: Change detection and change recollection should decrease with increasing lags and retention intervals, respectively.

To test this hypothesis, I compared change detection and change recollection probabilities across all combinations of Lag and Retention Interval (see Figure 3). I fit separate 3 (Lag) × 3 (Retention Interval) models to change detection and change recollection. Consistent with previous studies (e.g., Wahlheim et al., 2019), change detection is operationalized as correct classification of A-C pairs as changed during study trials, and change recollection is operationalized as correct classification of A-C pairs as changed during test trials and correct recall of the original response (the B term). Consistent with my hypothesis, the analysis of change detection showed a main effect of lag length, χ^2 (2) = 305.10, *p* < .001, such that change detection decreased as lag length increased from 4 to 16, *z* ratio = -4.60, *p* < .001, and from 16 to 48, *z* ratio = 12.58, *p* < .001.

Likewise, the analysis of change recollection showed a main effect of lag length, $\chi^2(2) = 71.08$, $p < .001$, a main effect of retention interval, $\chi^2(2) = 54.79$, $p < .001$, and a significant Lag × Retention Interval interaction, $\chi^2(4) = 32.71$, $p < .001$. At a lag of 4, there was no significant difference in change recollection rates between the two shortest retention intervals of 4 and 16, *z* ratio = -0.38, $p = .92$, but change recollection rates decreased significantly as retention interval increased from 4 to 48, *z* ratio = 2.77, $p < .001$, and from 16 to 48, *z* ratio = 2.60, $p < .001$. At a lag of 16, there also was no significant difference in change recollection rates between the two shortest retention intervals of 4 and 16, *z* ratio = 0.46, $p = .89$, but change recollection rates decreased significantly as retention interval increased from 4 to 48, *z* ratio = 4.06, $p < .001$, and from 16 to 48, *z* ratio = 4.51, $p < .001$. However, there were no significant differences in change recollection rates between any of the retention intervals when paired with a lag of 48. Change recollection rates decreased as lag increased from 16 to 48 at a retention interval of 4, *z* ratio = 4.52, $p < .001$, and at a retention interval of 16, *z* ratio = 5.62, $p < .001$. Importantly, there were no significant differences in change recollection rates between any of the lags at a retention interval of 48. These findings are consistent with what the RBT (as amended by Bruce and Weaver, 1973) would predict.

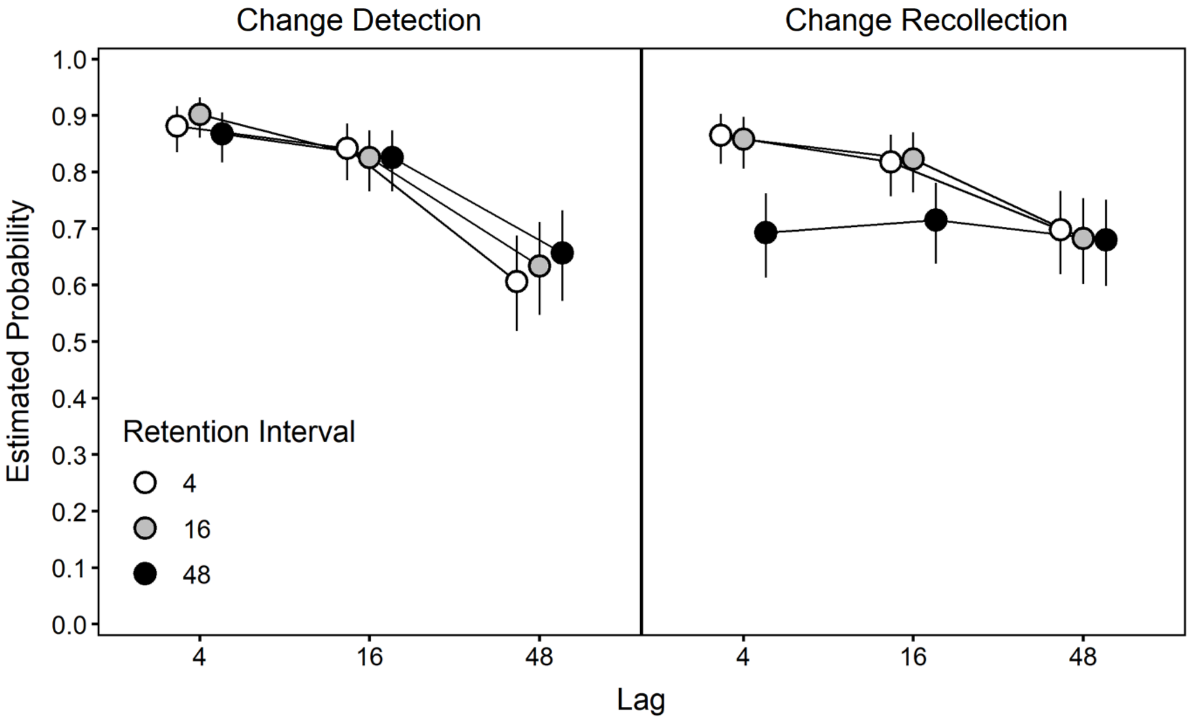

Figure 3: The estimated probability of detecting (left) and recollecting (right) change as a function of the number of intervening events between the two presentations of a repeated item (lag), and the number of intervening events between the second presentation of an item and its test (retention interval).

Hypothesis 3: Detecting and recollecting change should be associated with retroactive facilitation.

To test the third hypothesis, I compared recall accuracy for original responses (B terms) for A-B, A-C items for the following types of Change Classifications (see Figure 4): when changes were both detected and recollected (green points), when changes were detected, but not later recollected (blue points), and when changes were not detected (red points). I fit a 3 (Lag) × 3 (Retention Interval) x 3 (Change Classification) model to correct recall responses. The results showed a significant main effect of change classification on recall accuracy, χ^2 (2) = 851.78, *p* < .001. Recall accuracy was higher for items where change was both detected and recollected compared to those when changes were detected, but not later recollected, *z* ratio = -15.03, *p* < .001, and compared to those when changes were not initially detected, z ratio = 27.15, p < .001.

The results also showed a Lag × Change Classification interaction, χ^2 (2) = 15.47, *p* < .01, on correct recall probabilities. At a lag of 4, detecting and not recollecting change was associated with a greater probability of correct recall than not detecting change, *z* ratio = 2.40, *p* < .05. This was also true for items with a lag of 16. Detecting and not recollecting change was associated with a greater probability of correct recall than not detecting change, *z* ratio = 5.98, *p* < .001. In contrast, at the longest lag of 48, recall probabilities were comparable for instances where change was detected and not recollected vs. where changes were not detected, *z* ratio = 0.77 *p* = .72. These results suggest that instances of change detection and recollection lead to the highest probability or correct recall for original responses. However, the recall benefit of detecting and not recollecting changes depends on the lag and retention interval combination.

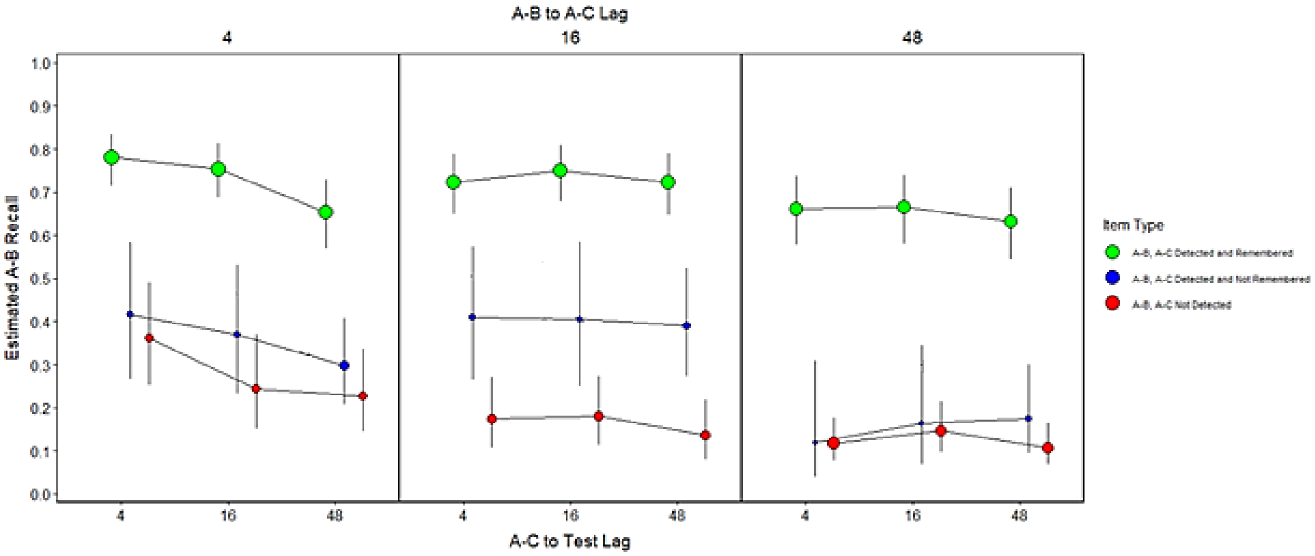

Figure 4: The estimated recall for B responses, as a function of the number of intervening events between the two presentations of a repeated item (lag), and the number of intervening events between the second presentation of an item and its test (retention interval), conditionalized on whether change was detected and recollected.

CHAPTER IV: DISCUSSION

The present experiment examined the roles of varying lags and retention intervals in retroactive effects of changes on original memories. In general, nonmonotonicity of lag functions on recall accuracy was most likely to occur at longer retention intervals (see black points in Figure 2). The results showed that, at the shortest retention interval of 4, recall accuracy decreased steadily as lag increased. However, at a retention interval of 48, there was no significant difference in correct recall probabilities between the two shortest lags, but recall was significantly lower for the lag 48 items. This finding is consistent with much of the previous literature on spacing and retention interval effects on memory (Cepeda et al., 2008, 2009; Glenberg, 1976; Kim et al., 2018), which suggests that shorter lags are more beneficial for memory at short retention intervals and longer lags are more beneficial for memory at long retention intervals. These findings can be partially explained by the encoding variability theory (Glenberg, 1976). which predicts that longer lags between presentations allow for more context change (cf. Estes, 1955), which allows for encoding the same stimuli within different contexts. This in turn allows for a greater proportion of recalled items at longer retention intervals. If any of the contexts present during encoding are reproduced at test, then the studied material is more likely to be recalled. At short retention intervals, the context at retrieval is most similar to that of encoding during the second presentation. When paired with a short lag, there is little context change between the first presentation and the test. However, when paired with a long lag, the second presentation is more likely to be recalled than the first, as its context is more similar to that at retrieval.

The results also showed that, in general, change detection decreased with increasing lags. This is consistent with what the rehearsal buffer theory would predict, i.e., that the memorial strength of an item begins to decrease by a constant proportion for each following item as soon as its presentation is over (Atkinson & Shiffrin, 1968). However, this pattern was different for change recollection rates. At retention intervals 4 and 16, change recollection rates decreased as lag increased. However, there were no significant differences in change recollection rates between any of the lags at a retention interval of 48. At a lag of 4 and at a lag of 16, there were no significant differences in change recollection rates between the two shortest retention intervals of 4 and 16, but change recollection rates were significantly lower at the longest retention interval, 48.

This finding is best explained by applying the RBT (as amended by Bruce and Weaver, 1973). If the A-B pair has not yet been forgotten by the time the A-C pair is presented, then the presentation of the A-C pair can act as a reminder of the A-B pair (indicated by change detection judgements) and increase the memorial strength of the A-B pair (i.e., retroactive facilitation). If the presentation of the A-C pair is successful at reminding participants of the A-B pair, then the memorial strength of the A-B pair once again begins to decrease by a constant proportion for each following item as soon as the A-C presentation is over. According to the RBT, short lags do not allow for the item to be removed from the buffer after its first presentation and, therefore, should show no additional strengthening beyond what can be expected from a longer study duration. Because short lags do not offer as much of a boost to memory strength as longer lags, the item is more likely to have been forgotten at long retention intervals than items paired with a longer lag. This can explain why at test, participants were least likely to recollect change for A-B, A-C items with a short lag (4 and 16) between changes and a long retention interval (48) between the presentation of the change and the test.

The findings from the present experiment extend the literature of the MFC framework (Jacoby & Wahlheim, 2013; Jacoby, 2015), and provide evidence for the applicability of this account across varying paradigms. The MFC framework suggests that the presentation of changed information can create retroactive interference, but this can be prevented by detecting changes. Change detection can serve as a reminder of the original information, which increases its accessibility as a result of retrieval practice, thereby leading to retroactive facilitation. This result is similar to that of a retrieval practice effect (for a review, see Roediger and Karpicke, 2006). Furthermore, retrieval of original responses when encoding changed responses allows both (B and C) to be held simultaneously in working memory. This co-activation allows the information from the two presentations to be integrated into one configural representation, which can further support change recollection. Results from the present experiment showed that recall accuracy was higher for items in which changes were detected, and not recollected than those in which changes were not detected. Additionally, recall accuracy was higher for items where change was both detected and recollected compared to those when changes were detected, but not later recollected.

The novel finding of this experiment was that lag and change classification interact to influence recall accuracy for the B responses of A-B, A-C items. At the two shortest lags of 4 and 16, detecting and not recollecting change was associated with a higher probability of correct recall than not detecting change, and recollecting change was associated with an additional increase in the probability of correct recall. In contrast, at the longest lag of 48, recall probabilities were comparable for instances where change was detected and not recollected vs. where changes were not detected. This provides initial evidence that both the spacing and the ability to detect and recollect change influence memory for information where changes occur.

Limitations of the Present Experiment

Although the results of the current study are supported by what the MFC framework would predict, there are several limitations that should be acknowledged. Though my hypotheses and the observed results hint that lag, retention interval, and change classification could all interact to influence memory, a three way interaction between Lag, Retention Interval, and Change Classification on Recall was not observed. It is likely that if this interaction exists, the effects are small, and this study lacked the necessary power to observe a three way interaction with a small effect. Additionally, due to constraints of the study design, the longest lag length that was included was 48 intervening items. Previous spacing literature suggests that longer lags might be necessary to observe differences in spacing effects on memory (e.g., Cepeda et al., 2008, 2009; Kim et al., 2019). Given these limitations, it is important for future work to apply this or similar paradigms to longer lags and retention intervals, and to power appropriately for the detection of small effects. Before publication, I plan to double the sample size of the current experiment. Additionally, I plan to conduct a follow up study that includes an explicit measure of change remembering by measuring cued recall for A-C items at test. This will allow for more specific conclusions to be drawn about the role that the presentation of changed plays in influencing memory for original information under varying conditions.

Concluding Remarks

In closing, the current experiment is the first to attempt a direct examination of the influence of spacing between changed pairs and the retention interval between the original presentation and the test of that information, on retroactive effects of memory associated with detecting and recollecting change. The findings support previous work on the spacing effect and provide evidence that recall depends on the combination of lag and retention interval used, and showed monotonicity of lag functions at the shorter retention intervals and nonmonotonicity at the longest retention interval. The results also provide evidence that lag influences change detection, and lag and retention interval interact to influence change recollection. Finally, the findings support the MFC framework, showing that the ability to detect and recollect changes influences recall accuracy for original information, and extend the MFC account by suggesting that lag length and the ability to detect and recollect changes interact to influence recall. Future work should continue to examine how varying the lag and retention intervals can influence the processes posited by the MFC account, and should utilize a variety of methods to further test the boundaries of the findings reported here.

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