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The Mechanism of Directed Forgetting in Visual Working Memory

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THE MECHANISM OF DIRECTED FORGETTING IN VISUAL WORKING MEMORY

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To my mother, Sandra Mae Bowers:
For teaching me how to read and never letting me give up

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TABLE OF CONTENTS

ABSTRACT

The goal of the current study was to determine if forgetting in visual working memory (VWM) depends on the strength of the memory representations, and to examine different potential mechanisms of directed forgetting in VWM. The strength of memory representations varies depending on factors during encoding and maintenance, which may impact the likelihood of successful forgetting. Experiment 1 manipulated encoding time and cue onset, and utilized eye tracking in order to determine the extent of directed forgetting in VWM. Results support evidence for partial forgetting, and revealed that the strength of memory representations does not impact the likelihood of successful forgetting. Experiment 2 manipulated memory stability and utilized functional magnetic resonance imaging in order to examine different potential mechanisms of directed forgetting. Participants completed a directed forgetting task with faces and buildings. Results from the parahippocampal place area suggest that to-be-remembered buildings elicit higher activation than to-be-forgotten buildings. Finally, dorsolateral prefrontal cortex activation decreased after the cue, suggesting that the cue led to information being dropped from VWM. Overall, results from two experiments suggest that the strength of memory representations does not impact the likelihood of successful forgetting, and the mechanism of directed forgetting in VWM occurs via reduced access.

INTRODUCTION

Visual working memory (VWM) is a capacity-limited memory store (3-4 stimuli, Baddeley, 1992, 2003) that allows for visual information to be manipulated (Fukuda, Awh, & Vogel, 2010) and quickly accessed for a brief period of time (Atkinson & Shiffrin, 1968; Craik & Lockhart, 1972). To efficiently maintain task-relevant information in VWM, encoded information that is no longer relevant to the ongoing task may be forgotten (Williams & Woodman, 2012). The extent and conditions under which complete versus partial forgetting occurs during this process is not well understood. The field is also divided as to the mechanism(s) involved in the forgetting process with research suggesting that information no longer relevant to the current task is either (1) completely removed from memory (Ecker, Lewandowsky, & Oberauer, 2014; Williams, Hong, Kang, Carlisle, & Woodman, 2013; Zhang & Luck, 2009), (2) less accessible than task-relevant information (Dagry & Barrouillet, 2017; Maxcey & Woodman, 2014; Sasin, Morey, & Nieuwenstein, 2017; Schneegans & Bays, 2018; Souza & Oberauer, 2016; Taylor & Hamm, 2016; Zwissler, Schnidler, Fischer, & Kissler, 2015), or (3) actively suppressed (Anderson & Hanslmayr, 2014). However, one research study has not directly compared all of these theories within VWM. Experiment 1 of the current study investigated the extent of forgetting in VWM, and how memory strength impacts forgetting by encouraging increased memory detail and stability. Experiment 2 tested the mechanism of directed forgetting in VWM, and distinguished among sudden death, active suppression, and reduced access with neuroimaging methodologies.

One way to examine how individuals remember or forget information in VWM is with the directed forgetting (DF) paradigm (MacLeod, 1975). In a traditional (array-based) VWM DF

task, participants encode a group of stimuli (typically four stimuli) for a short period of time (typically less than 1000ms). For cue trials, the cue (e.g., an arrow pointing to one side of the display) to maintain a subset of stimuli (i.e., to-be-remembered [TBR] stimuli) is presented during a delay (maintenance) interval, and the other stimuli are no longer relevant to the current task (i.e., to-be-forgotten [TBF] stimuli). For no-cue trials, participants attempt to maintain all of the stimuli. After the delay interval, participants are tested (on TBR stimuli for cue trials and all stimuli for no-cue trials) typically by reporting if a change occurred to the stimuli from the encoding display to the test display (change detection task). Participants have higher accuracy on cue trials than no-cue trials (cuing effect; Gunseli, van Moorselaar, Meeter, & Olivers, 2015; MacLeod, 1975; Van Moorselaar, Olivers, Theeuwus, & Lamme, 2015; Williams & Woodman, 2012; Williams et al., 2013), suggesting that the TBF stimuli were forgotten, and maintaining less information maximized processing efficiency (Anderson et al., 1994; Festini & Reuter-Lorenz, 2014; MacLeod, 1975). The goal of the current study was to determine if forgetting depends on the strength of the memory representations (Experiment 1) and to determine the mechanism of directed forgetting in VWM (Experiment 2).

CHAPTER 1. MEMORY STRENGTH AND DIRECTED FORGETTING

Measuring Forgetting in VWM

Measuring forgetting in VWM is difficult because explicitly testing memory for TBF stimuli results in participants ignoring the instructions to forget some stimuli. Williams and Woodman (2012) examined the DF memory benefit with forget cues that were 100% valid or 90% valid. Participants encoded groups of colored squares, half on each side of the display. After a brief delay, participants were cued to maintain only squares on the left or right half of the display; the other side was TBF. The task was then to detect whether a color change occurred from the first display (all six squares) to the second display (three remaining, TBR squares). With 100% valid cues (e.g., if cued to remember left then left was always tested) participants were more accurate on cue trials than no-cue trials. However, this benefit did not occur when the cue was only valid 90% of the time (e.g., cued to remember left but right was tested 10% of the time); within the first 40 trials, there was no longer a difference between cue and no-cue trials, suggesting that participants were ignoring the cue. This demonstrates the challenge of studying forgetting in VWM. Explicitly testing TBF information in VWM DF paradigms often causes participants to ignore cues and attempt to maintain all stimuli (Gözenman, Tanoue, Metoyer, & Berryhill, 2014; Gunseli et al., 2015; Williams & Woodman, 2012). Experiment 1 utilized a manipulation validated in my previous research (Moen, Pinto, Papesh, & Beck, 2016) to indirectly test memory for TBF stimuli (see Figure 1). Instead of explicitly testing memory for TBF stimuli, I used a TBF stimulus as the changed stimulus (i.e., a TBF stimulus appeared in the location of a TBR stimulus) on some trials (TBF-change trial) to decrease the likelihood that participants will ignore the cue. In a pilot experiment, there was no

difference in new-change trial accuracy when TBF-change trials were present or absent. Thus, TBF-change trials are a reliable, valid way to test memory for TBF information while maintaining cue utilization.

In addition to testing memory for TBF stimuli, including TBF-change trials also allowed for testing the possibility of complete forgetting. If participants completely forgot TBF stimuli, there would be no difference in accuracy when a new stimulus is used as the changed stimulus (new-change trial) versus when a TBF stimulus is used as the change stimulus (TBF-change). However, if partial forgetting occurred, participants may incorrectly report that a change did not occur for TBF-change trials. My previous research suggests that TBF-change trials result in lower accuracy than new-change trials, because participants incorrectly respond "no change," despite a change occurring (Moen et al., 2016). These results suggest that individuals were not completely forgetting TBF information. However, an incorrect no-change response may have occurred because the TBF stimulus seemed familiar, but the memory trace was not strong enough to retrieve the exact location of the stimulus (e.g., stimulus was on the TBF side of the display) or because the object-location binding was never encoded for any stimuli.

In order to accurately utilize a remember cue in a DF task, participants must have encoded the identity of each stimulus and bound the identity to the location of each stimulus. Generally, the remember cue is an arrow that points to one side of the display. The only way to accurately use this cue is to know what stimuli were on each side of the display. On TBF-change trials, the location of a TBF stimulus moves to the location of a TBR stimulus. A participant would inaccurately respond "no change" to these trials if they remembered the identity but not the locations of the stimuli. A participant would accurately respond "change" if they completely

forgot the stimulus or if they remembered both the identity and the location of the stimulus (no forgetting). Overall, it is important to measure object-location binding, in order to ensure that participants encoded and maintained location information before the cue.

Research suggests that stimulus location is not necessarily bound to identity and encoding time impacts the strength of the binding representation (van Lamsweerde & Beck, 2012). Thus, it is possible that the lower accuracy associated with TBF-changes in my previous research was due to participants not encoding or maintaining the bound representations of objects and their locations, rather than partial forgetting following the cue. To determine whether participants encoded bound object-location information, the current study utilized location-change trials in which the two TBR stimuli swapped locations (see Figure 1). Participants' ability to accurately detect these location changes provided an estimate of the strength of object-location binding representations. High accuracy on these trials would suggest that errors on TBF-change trials were not due to a failure to encode or maintain location bindings, but rather a failure to completely forget the TBF information. Furthermore, if accuracy on TBF-changes were only the result of not encoding location information, then there would be no differences between location-change and TBF-change trials in the current study. Overall, by utilizing TBF- and location-change trials, the current study expanded previous research by testing the extent for forgetting in VWM, and determined if what appears to be partial forgetting is actually due to the failure use the cue because the object-location bindings were not encoded or maintained prior to the cue.

Eye tracking may also help measure forgetting in VWM. Previous research suggests that individuals exhibit longer fixations on the changed stimulus than the unchanged stimulus, even

if they do not correctly detect the changed stimulus in a change detection task (Beck, Peterson, Angelone, 2007; Hollingworth, Williams, & Henderson, 2001). In the current study, longer fixations on the TBF stimulus on TBF-change trials may suggest implicit memory for that stimulus. For example, even if accuracy were equivalent for new- and TBF-change trials, participants may look longer at the TBF stimulus than the new stimulus, suggesting that complete forgetting did not occur. The current study recorded eye movements throughout Experiment 1 to measure fixation duration during the post-change display. Overall, it is difficult to measure forgetting within VWM, but the current study utilized several different change types and eye tracking to effectively measure forgetting.

Stages of Memory Tasks That May Differentially Impact Forgetting

Memory tasks can generally be split into three stages: encoding (formation of memory representations), maintenance (rehearsing, keeping memory representations active), and retrieval (active remembering and/or comparing to previous memory representations). Encoding can impact memory performance depending on how long individuals have to form mental representations of the stimuli (Brady, Konkle, Oliva, & Alvarez, 2009). However, no previous research has investigated how encoding time impacts forgetting in an array-based DF task. Additionally, research suggests that longer cue onsets (maintenance; see Figure 1) allow for more time to consolidate information, resulting in more stable VWM representations (Vogel, Woodman, & Luck, 2006), but it is unclear if more stable representations lead to less forgetting of TBF information. The current study did not examine how retrieval impacts forgetting, and instead focused on encoding and maintenance during a DF task. The current

study manipulated factors during encoding and maintenance to examine the impact of durable memory representations on successful forgetting.

Encoding

Longer encoding times lead to more detailed memory representations, and thus improved accuracy on change detection tasks (Brady et al., 2009). Brady and colleagues (2009) had participants encode six real-world objects for a change detection task, and manipulated the presentation time (200ms, 1,000ms or 3,000ms per stimulus) of the pre-change display. They found that change detection accuracy increased as encoding time increased. Although not tested by Brady and colleagues, it is possible that the more detailed representations that are formed after longer encoding times would be less likely to be successfully forgotten once cued as TBF.

My previous work did not manipulate encoding time, but supports the conclusion that more detailed memory representations lead to less complete forgetting (Moen et al., 2016). I have used various stimuli types in order to determine what stimuli are more likely to be forgotten. In one experiment I compared DF accuracy for colored squares and real-world objects, and found that participants were more likely to completely forget colored squares encoded for 100ms than real-world objects encoded for 2,000ms. In a second experiment I compared real-world objects to abstract shapes (both conditions encoded stimuli for 2,000ms), and found that neither stimulus was completely forgotten. The results from my experiment comparing colored squares to real-world objects may have been due to real-world objects leading to more detailed memory representations compared to colored squares. It is possible that real-world objects require participants to remember more detailed information about a

stimulus and decrease the likelihood of successful forgetting, compared to color information. Alternatively, if the memory representations are more durable, it may be easier to utilize the cue and forget TBF information, and it is easier to bind objects to locations (van Lamsweerde & Beck, 2012) than with shorter encoding times. Experiment 1 of the current study examined the impact of detailed representations by manipulating encoding time.

Maintenance

The amount of time participants maintain stimuli before a cue appears (i.e., cue onset) may impact the likelihood of successful forgetting. To my knowledge, the only research examining the impact of cue onset in DF tested long-term memory (LTM) with an item-method DF task (Lee & Lee, 2011). In an item-method DF task, participants are briefly shown (e.g., 2,000ms) stimuli individually, and then receive an immediate cue instructing them to either remember or forget the preceding stimulus. After participants encode several stimuli, and sometimes after an additional delay of several minutes (to ensure information is in LTM), participants complete a recognition memory test on all the stimuli. The benefit of an item-method DF task is that researchers can directly test memory for the TBF stimuli, which is more challenging with an array-based DF task (see above section: Measuring Forgetting in VWM). However, item-method DF tasks primarily test LTM as opposed to VWM, and different memory systems may rely on different mechanisms of directed forgetting (see General Discussion).

Previous research suggests that individuals are less likely to successfully forget a TBF stimulus in an item-method DF task as cue onset increases (Lee & Lee, 2011). A longer cue onset may allow for more stable VWM representations (Vogel et al., 2006), thus making it more difficult to forget TBF information. Vogel and colleagues (2006) examined the time course of

consolidating colored squares in VWM. They presented participants with a varying number of colored squares for 100ms. Participants then maintained those stimuli for 1,000ms before completing a change detection task. A visual mask (multi colored boxes overlaid where the squares were presented) was presented during the delay, and Vogel and colleagues manipulated the amount of time (4ms to 120ms per stimulus) between the pre-change display offset and when the mask appeared (i.e., mask onset). Vogel and colleagues found that accuracy increased as mask onset increased and argued that longer mask onsets allowed for more time to consolidate information, resulting in a more stable VWM representation. Specifically, they found that participants could consolidate information at the rate of 50ms per stimulus. Importantly, the consolidation rate was calculated including the 100ms encoding display. Overall, these results suggest that delays shorter than 50ms per stimulus disrupt VWM consolidation and may impact forgetting due to less stable memory representations.

In Experiment 1 of the current study, a cue to forget may function similarly to the visual mask used by Vogel and colleagues (2006). A visual mask shifts the processing and encoding of visual information, and a cue to maintain a subset of stimuli shifts attention and reassigns task goals to the relevant stimuli. In addition to manipulating encoding time, Experiment 1 examined the impact of cue onset during DF to determine how stable VWM representations impact forgetting. The current study employed a 50ms and 250ms cue onset (not including the encoding display). A 250ms cue onset (62.5ms per stimulus) may allow participants to consolidate the information in VWM, and a 50ms cue onset (12ms per stimulus) may disrupt consolidation, leading to more complete forgetting of TBF stimuli. Previous research from other VWM tasks suggests that real-world objects are fully consolidated in 500ms (Kellie & Shapiro,

2004). In the current study, there may be an interaction between encoding time and cue onset, with larger impacts of cue onset when encoding time is shorter (1,200ms total, 300ms per stimulus), because stimuli will not be completely consolidated after the 1,200ms encoding display.

Experiment 1

Experiment 1 tested three research questions: 1) What is the extent of directed forgetting in VWM? 2) Does forgetting depend on the strength of memory representations? 3) Is what appears to be partial forgetting actually the result of failure to encode or maintain object-location bindings? Experiment 1 focused on factors during encoding and maintenance that may impact the strength of memory representations and subsequent forgetting. Participants viewed stimuli for 1,200ms or 2,000ms in order to manipulate the level of detail encoded into VWM (encoding time). Previous research suggests that longer encoding times lead to more detailed memory representations (Brady et al., 2009), and I predicted that more detailed representations would lead to less successful forgetting (lower accuracy on TBF-change trials). Alternatively, it is possible that more detailed representations would allow participants to more accurately utilize the cue and forget TBF information more effectively. Experiment 1 also manipulated the amount of time participants maintained all stimuli before receiving a cue indicating which stimuli were TBR (cue onset). Previous research suggests that longer cue onsets are associated with less forgetting of TBF information than shorter cue onsets (Lee & Lee, 2011), and may lead to more stable memory representations (Vogel et al., 2006). Alternatively, more stable memory representations may be easier to forget because

participants fully consolidated TBR and TBF information, allowing for more successful cue utilization.

Directly testing memory for TBF information is difficult within the confines of VWM. Thus, Experiment 1 utilized a method that has been validated in my previous research to indirectly test memory for TBF stimuli. Instead of explicitly testing memory for TBF stimuli (presenting a test display with stimuli on the TBF side of the display), I used a TBF stimulus as the changed stimulus (presenting a TBF stimulus on the remember side of the display in place of one of the TBR stimuli) on some trials (TBF-change trial). This method makes the test for TBF stimuli less salient and less likely to be explicitly detected by participants so that they are less likely to ignore the cue. Additionally, this manipulation tests for the possibility of complete forgetting. No differences between new-change and TBF-change trials would indicate support for complete forgetting, because seeing a new stimulus would result in equivalent accuracy to seeing a TBF stimulus.

It is possible that TBF-change trials may result in lower accuracy than new-change trials because individuals remember the identity, but did not successfully encode or maintain where each stimulus was located (identity-bound-to-location). In order to test for this possibility, the current study also implemented location-change trials, where the TBR stimuli swapped locations on the TBR side of the display to provide a measure of how often identity-bound-to-location errors occur for TBR stimuli. Previous research suggests that shorter encoding times lead to less durable object-location bindings (van Lamsweerde & Beck, 2012). Thus, it is important to test for binding errors in the current study in conjunction with the encoding time manipulation.

Hypotheses and Predictions

The goal of Experiment 1 was to determine how the strength of memory representations impacts the likelihood of successful forgetting. First, I predicted that partial forgetting would occur, in that accuracy will be higher for cue trials than no-cue trials, and new-change trials would result in higher accuracy than TBF-change trials. Additionally, I predicted that TBF-change trials would result in longer fixation durations than new-change trials, suggesting implicit memory for TBF stimuli. Second, I predicted that forgetting would be less complete for detailed, stable memory representations (longer encoding time and longer cue onset time), resulting in lower TBF-change accuracy as encoding time and cue onset increase. Finally, I predicted that participants would encode and maintain object-location binding information, resulting in higher accuracy for location-change trials than TBF-change trials. This would suggest that partial forgetting on TBF-change trials is not the result of a failure to encode location information and therefore, an inability to use the cue.

Method

Design. Experiment 1 employed a 2 x 3 x 3 mixed measures design. Encoding time (1,200, 2,000ms) was manipulated between subjects. Cue onset (no-cue, 50ms, 250ms) and change type (new-change, TBF-change, location-change) were manipulated within subjects.

Participants

One hundred sixteen participants completed Experiment 1. Sample size was based on the effect sizes from my previous work (Moen et al., 2016). G*Power was used to calculate the required sample size, by using the effect size from the change type (new-change, TBF-change), stimuli type (shapes, objects), cue type interaction (η_p^2 = .012) Based on the power analysis, 58

participants were required per between subjects condition to achieve an estimated power of .90 (α = .05). Participants were recruited from undergraduate psychology courses at LSU and received partial course credit for participation. Two participants were replaced due to change detection accuracy below 55%, and three participants were replaced due to not finishing the experiment in the allotted time (75 minutes).

Materials. Five hundred real-world, nameable objects were used for the current study. The stimuli were adapted from Brady and colleagues (2013) by Moen and colleagues (2016). All stimuli were converted into gray scale and were 200 x 200 pixels (approximately 3.22 x 3.42 degrees of visual angle). Stimuli were presented 3.5 degrees of visual angle away from the center fixation. Stimuli were presented using a 24-inch Benq monitor with a resolution of 1920 x 1080 pixels. An EyeLink 1000 Plus tracker (SR Research LTD, Canada) was used to detect eye movements. The dominant eye of each participant was tracked throughout the experiment.

Procedure. Before beginning the experiment, participants were randomly assigned to the 1,200 or 2,000ms encoding time condition. Participants completed 288 trials (half cue, half no-cue). Each trial began with a drift correct dot to account for minor shifts in head position during a trial. Participants fixated on the drift correct dot and pressed a button, and then a fixation cross appeared in the center of the display for 500ms. The fixation cross remained on the display throughout the entire trial. After 500ms, participants were presented with four stimuli for 1,200 or 2000ms (depending on the condition). Two stimuli appeared on each side of fixation. Immediately after the stimulus presentation, participants saw a fixation for 50 or 250ms (depending on the cue onset trial type), followed by an arrow pointing to the left or right side of the display, indicating the side of the display that would be tested. The arrow cue

remained on the display for 500ms. Following the cue, a fixation cross remained on the display for 1,650 or 1,450ms (depending on the cue onset trial type) before the post-change display appeared. There was always 2,200ms between the offset of the pre-change display and the onset of the post-change display. The post-change display contained two stimuli on the cued side of the display. The cue was always valid. Participants were instructed to respond if there was any change (different stimuli or stimuli changed locations) from the stimuli presented on that side of the display from the first presentation to the last presentation, and press different buttons to indicate if a change occurred or not (See Figure 1 for the trial sequence).

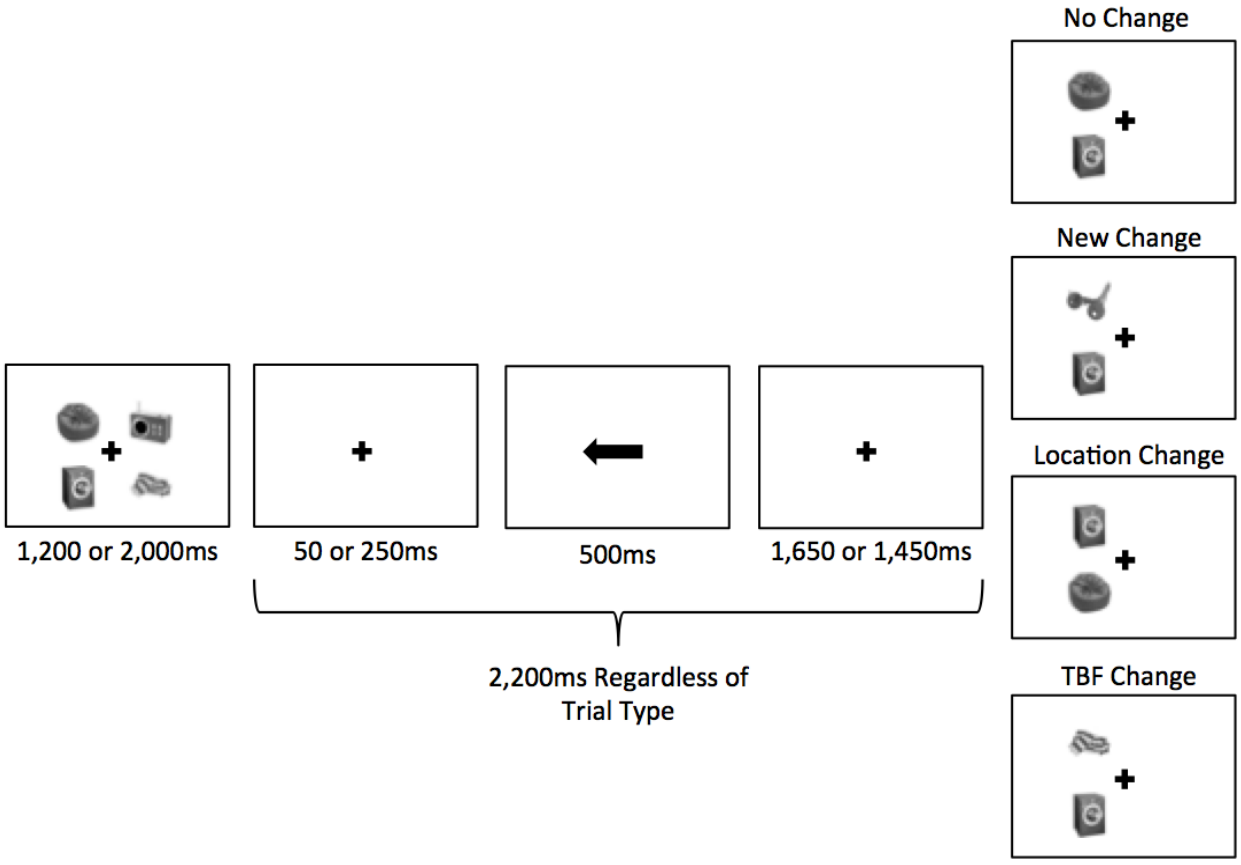

Figure 1. Four types of changes occurred throughout Experiment 1. The stimuli are enlarged to show detail.

Across all blocks, there were four types of post-change displays: no-change, new-change, TBF-change, and location-change. For no-change trials, the exact same cued stimuli appeared on the post-change display. For new-change trials, one of the cued stimuli was replaced with a random stimulus that did not appear in the pre-change display. For TBF-change trials, one of the cued stimuli was replaced with a stimulus from the non-cued side of the display. For example, if participants were instructed to remember stimuli on the left side of the display, a stimulus from the right side of the display was used as the change stimulus. For location-change trials, the two stimuli on the TBR side of the display swapped locations from pre-change to post-change. There were 288 trials total with even numbers of no-change (72), new-change (72), location-change (72), and TBF-change (72). Participants were instructed to indicate if there was any change on the cued side of the display. Participants were given examples of no-change, new-change and location-change trials, but were not informed of the possibility of TBF-changes. Participants completed 12 practice trials with feedback before beginning the experimental trials. Practice trials contained all of the possible trial types with the exception of TBF-change trials, to increase the likelihood that participants utilized the cue. There was no feedback during the experimental trials. After completing all of the experimental trials, participants completed a post experiment questionnaire asking them to report the frequency of each change type, in addition to specific questions such as, “Did you notice images would switch from one side of the display to the other?” The full set of questions can be found in Appendix C.

Experiment 1 Results

Results were analyzed as they pertain to each hypothesis. The omnibus mixed factors ANOVA for accuracy was a 2 (Encoding time: 1,200ms, 2,000ms) x 3 (Change type: new-change, location-change, TBF-change) x 3 (Cue onset: no-cue, 50ms, 250ms) with encoding time as the only between subjects factor (Figure 2), and can be found in Appendix D[1]. Despite 75% of trials being "change" trials, participants were very accurate on no-change trials (*M* = .84, *SD* = .11). No-change accuracy and did not significantly differ from new-change accuracy (*M* = .88, *SD* = .12), $t(115) = 0.70$, $p = .49$.

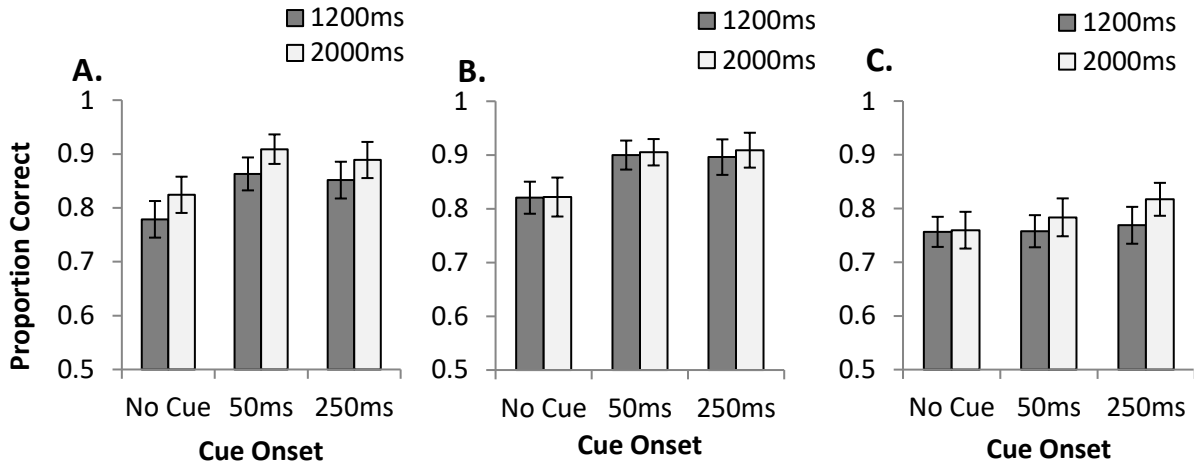

Figure 2. Results from the omnibus ANOVA for (A) new-change trials, (B) location-change trials, and (C) TBF-change trials. Error bars denote 95% confidence intervals.

What is the extent of directed forgetting? First, a paired samples *t*-test was conducted on the proportion correct for new-change (Figure 3) trials, comparing no-cue trials and cue trials (collapsed across cue onset and encoding time). This was done to ensure that participants were utilizing the cue when they were tested on TBR information. Results revealed significantly higher accuracy on cue trials than no-cue trials, $t(115) = 6.95$, $p < .001$. These results replicate

[1] Adding no-change trials to the omnibus ANOVA did not change the pattern of results.

previous VWM DF research (Williams & Woodman, 2012; Williams et al., 2013). Additionally, results from the omnibus ANOVA (see Appendix D) found a main effect of cue onset, $F(2,228) = 56.29$, $p < .001$, $\eta_p^2 = .33$, in that accuracy was lower on no-cue trials than 50ms cue onset trials, $t(115) = 8.70$, $p < .001$, and 250ms cue onset trials, $t(115) = 9.05$, $p < .001$. Overall, these results suggest that some forgetting occurred. Participants were attempting to prioritize TBR information, which resulted in increased accuracy on cue trials.

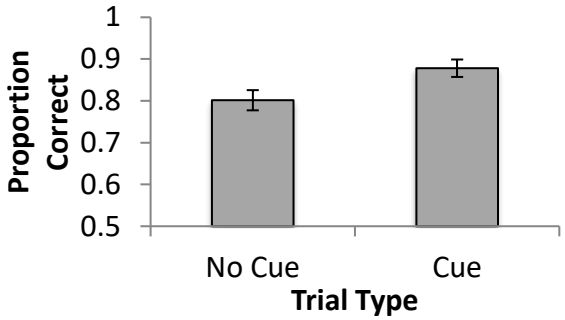

Figure 3. Results from new-change trials, collapsed across cue onset. Error bars denote 95% confidence intervals.

In order to determine if forgetting was partial or complete, a paired samples *t*-test was conducted on cue trials (collapsed across cue onset) for the proportion correct for new-change and TBF-change trials (Figure 4). Results revealed significantly higher accuracy on new-change trials than TBF-change trials, $t(115) = 5.81$, $p < .001$. These results suggest that partial forgetting occurred for TBF information. Participants were more likely to incorrectly respond "no change" for TBF-change trials than new-change trials. These results replicate my previous research demonstrating partial forgetting (Moen et al., 2016).

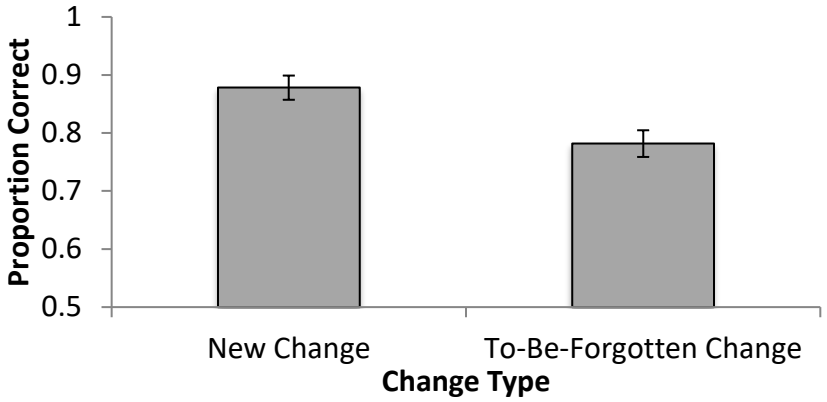

Figure 4. Results from cue trials, collapsed across cue onset, comparing new-change and TBF-change trials. Error bars denote 95% confidence intervals.

To further analyze the extent of directed forgetting, correct and incorrect trials were analyzed separately with 2 x 2 repeated measures ANOVAs examining the average fixation duration on the post-change display to compare the stimulus (changed, unchanged) and the change type (new-change, TBF-change; Figure 5). Eighteen participants were excluded from these analyses because of lack of data[2]. For example, if a participant never answered a new-change trial incorrectly, there would be no eye-tracking data for incorrect, new-change trials.

For correct trials (Figure 5A), there was a significant main effect of stimulus, $F(1,97) = 123.98$, $p < .001$, $\eta_p^2 = .56$, and change type, $F(1,97) = 5.19$, $p = .025$, $\eta_p^2 = .05$, as well as an interaction, $F(1,97) = 9.43$, $p = .003$, $\eta_p^2 = .09$. In order to examine the significant interaction, paired samples *t*-tests were conducted to compare the average fixation duration on new- and TBF-change trials for the changed stimulus and unchanged stimulus separately. Results revealed no differences in fixation duration between new- and TBF-change trials for the changed stimulus, $t(97) = 0.38$, $p = .71$, but participants had significantly longer fixations on the unchanged stimulus for TBF-change trials than new-change trials, $t(97) = 3.43$, $p = .001$. This is

[2] The pattern of results did not change regardless of whether these participants were included.

further evidence that participants responded differently to new- and TBF-change trials, and thus supports partial forgetting.

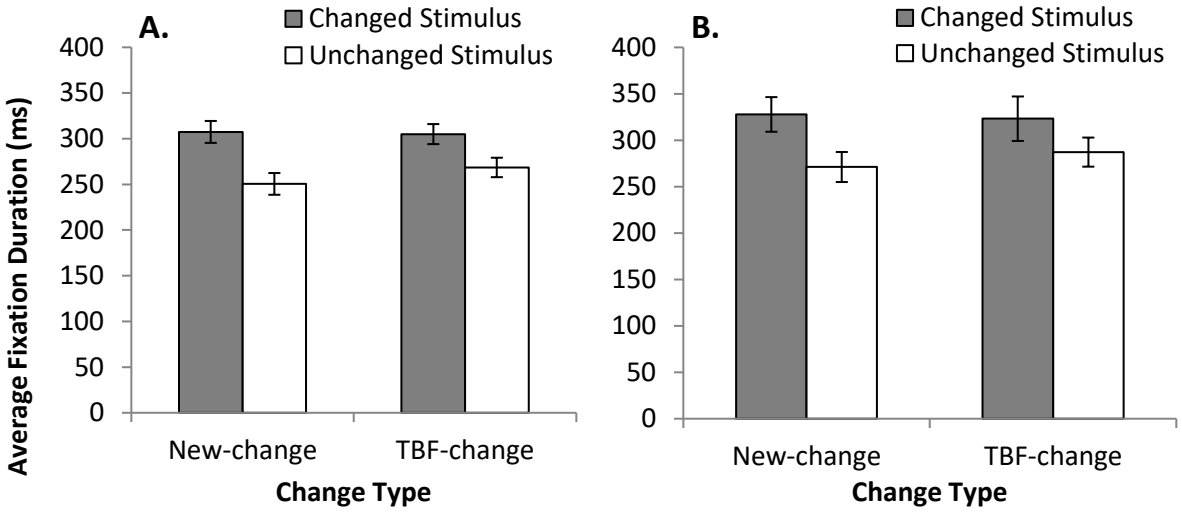

Figure 5. Average fixation duration separated by (A) correct and (B) incorrect change detection accuracy. Error bars denote 95% confidence intervals.

For correct trials (Figure 5A), there was a significant main effect of stimulus, $F(1,97) = 123.98$, $p < .001$, $\eta_p^2 = .56$, and change type, $F(1,97) = 5.19$, $p = .025$, $\eta_p^2 = .05$, as well as an interaction, $F(1,97) = 9.43$, $p = .003$, $\eta_p^2 = .09$. In order to examine the significant interaction, paired samples *t*-tests were conducted to compare the average fixation duration on new- and TBF-change trials for the changed stimulus and unchanged stimulus separately. Results revealed no differences in fixation duration between new- and TBF-change trials for the changed stimulus, $t(97) = 0.38$, $p = .71$, but participants had significantly longer fixations on the unchanged stimulus for TBF-change trials than new-change trials, $t(97) = 3.43$, $p = .001$. This is further evidence that participants responded differently to new- and TBF-change trials, and thus supports partial forgetting.

For incorrect trials (Figure 5B), there was a significant main effect of stimulus, $F(1,97) = 23.10$, $p < .001$, $\eta_p^2 = .19$, but no main effect of change type, $F(1,97) = 0.06$, $p = .80$, $\eta_p^2 = .001$,

and no interaction, $F(1,97) = 2.46$, $p = .12$, $\eta_p^2 = .03$. The main effect of stimulus was due to participants having significantly longer fixations on the changed stimulus than the unchanged stimulus. However, the type of change did not impact this effect. Overall, these results suggest that participants had implicit memory for the changed stimulus, despite responding incorrectly. However, these results do not necessarily support partial forgetting, as there were no differences between new- and TBF-change trials.

Does forgetting depend on the strength of memory representations? A 2 x 3 mixed measures ANOVA was conducted on the proportion correct of TBF-change trials (Figure 2C). Encoding time (1,200 or 2,000ms) was the between subjects variable and cue onset (no-cue, 50ms, or 250ms) was within subjects. Only TBF-change trials were analyzed because those were the only trials when participants were tested on TBF information. There was no main effect of encoding time, $F(1,114) = 1.85$, $p = .18$, $\eta_p^2 = .02$, and no interaction between encoding time and cue onset, $F(2,228) = 1.70$, $p = .19$, $\eta_p^2 = .02$. There was a main effect of cue onset, $F(2,228) = 4.46$, $p < .001$, $\eta_p^2 = .04$, in that accuracy was lower on no-cue trials than 250ms cue onset trials, $t(115) = 3.26$, $p = .001$. This replicates previous directed forgetting research in that DF cues increase accuracy (Moen et al., 2016; Williams & Woodman, 2012; Williams et al., 2013). There were no differences between no-cue trials and 50ms cue onset trials, $t(115) = 1.10$, $p = .27$, which suggests that participants required 250ms in order to effectively utilize the cue. When participants were presented with a cue after 50ms, it was comparable to receiving no cue. However, there was no difference in accuracy between 50ms and 250ms cue onsets, $t(115) = 1.68$, $p = .10$. Overall, these results suggest that increasing the strength of memory representations had a marginal impact on successful forgetting.

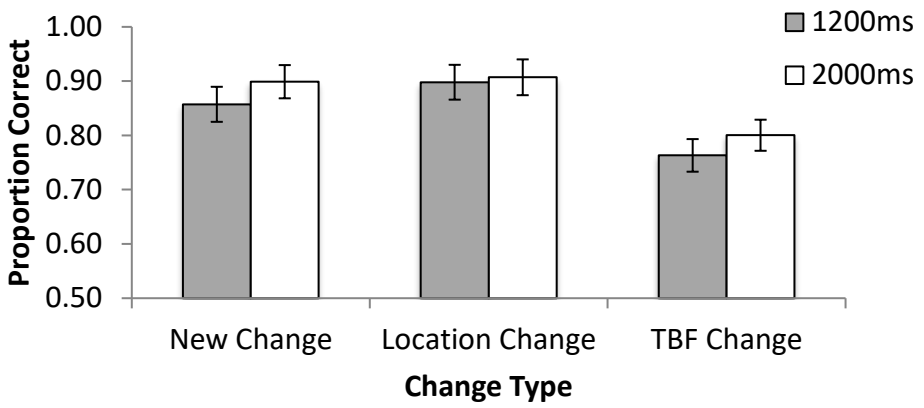

Figure 6. Results from cue trials, collapsed across cue onset, comparing new-change, location-change, and TBF-change trials. Error bars denote 95% confidence intervals.

Is partial forgetting due to a failure to encode or maintain object-location bindings? A 2 x 3 mixed measures ANOVA was conducted to examine the relationship between encoding time (1,200ms, 2,000ms) and change type (new-change, location-change, TBF-change) for cue trials (collapsed across cue onset; Figure 6). Encoding time was manipulated between subjects. Results revealed a significant main effect of change type, $F(2,228) = 36.80$, $p < .001$, $\eta_p^2 = .24$. Accuracy was higher on location-change trials than both new-change trials, $t(115) = 2.54$, $p = .013$, and TBF-change trials, $t(115) = 8.26$, $p < .001$. There was no main effect of encoding time, $F(1,114) = 3.12$, $p = .08$, $\eta_p^2 = .03$, and no interaction between change type and encoding time, $F(2,228) = 0.94$, $p = .39$, $\eta_p^2 = .01$. Overall, these results suggest that participants encoded and maintained stable object-location bindings for TBR information. Additionally, the low TBF-change accuracy observed in the current study and previous research (Moen et al., 2016) was not due to a failure to encode object-location information. Thus, participants were able to effectively utilize the cue. Furthermore, increased encoding time did not impact the success of object-location binding.

Post-experiment questionnaire. Each change type (no-change, new-change, location-change, TBF-change) occurred on 25% of trials. However, participants over-reported the number of new-change trials (*M* = 50.32%, *SD* = 20.48%) and location-change trials (*M* = 36.90%, *SD* = 17.16%). Estimates of TBF-change trials (*M* = 29.01%, *SD* = 17.70%) and no-change trials (*M* = 27.82%, *SD* = 12.00%) were much closer to their actual occurrences. Only 72 participants (approximately 62%)[3] reported that they attempted to only remember the TBR stimuli, but 89 participants (approximately 77%) reported that it was easier to detect a change on cue trials than no-cue trials. A full report of the post-experiment questionnaire responses can be found in Table 1.

Experiment 1 Discussion

The goals of Experiment 1 were to determine 1) the extent of directed forgetting in VWM, 2) if forgetting depends on the strength of memory representations, and 3) if what appeared to be partial forgetting was actually a failure to encode or maintain object-location bindings. The first goal of the current study was to determine the extent of directed forgetting in VWM. Results replicated previous research (Moen et al., 2016) in that participants were prioritizing TBR information (no-cue accuracy < cue accuracy) and partial forgetting occurred for TBF information (new-change accuracy > TBF-change accuracy). Eye movements were also recorded as potential evidence for partial forgetting. However, there were no differences in implicit memory (measured via fixation duration on incorrect trials) between new-change and TBF-change trials. Nevertheless, the strong behavioral results from Experiment 1 suggest that partial forgetting occurred in the current study. However, Experiment 1 did not distinguish

[3] The pattern of results or the significance of individual tests did not change as a result of participants reporting that they only paid attention to TBR stimuli.

Table 1. Post-experiment questionnaire and responses

Question	**Responses**
What button did you press if a new item replaced an old item?	100% Responded “Change”
What button did you press when the two pictures switched locations?	100% Responded “Change”
What button did you press when nothing changed?	100% Responded “No Change”
Did you notice anything strange during the experiment?	Open ended response No participants mentioned TBF-changes
Did you notice that the pictures would move positions?	75.86% Responded “Yes”
Did you notice that a picture would sometimes move from one side of the screen to the other?	89.66% Responded “Yes”
What button did you press if a picture switched sides of the screen?	100% Responded “Change”
What percentage of trials was there no change?	*M* = 27.82%, *SD* = 12.00%
What percentage of trials did a new picture replace the original picture?	*M* = 50.32%, *SD* = 20.48%
What percentage of trials did the two pictures switch locations?	*M* = 36.90%, *SD* = 17.16%
What percentage of trials did a picture move to the other side of the screen?	*M* = 29.01%, *SD* = 17.70%
What did the arrow indicate?	Open ended response 100% Responded Correctly
True/False: The arrow indicated the side of the screen that would be tested.	100% Responded “True”
What did you do when you saw an arrow?	Open ended response 96.55% Reported attempting to remember the TBR stimuli
True/False: I only tried to remember the pictures on the side of the screen the arrow pointed towards.	62% Responded “True”
True/False: I tried to remember all of the pictures even if there was an arrow.	53% Responded “True”
True/False: It was easier to tell if something changed when there was an arrow.	77% Responded “True”
On a scale of 1 (not difficult at all) to 10 (extremely difficult), how difficult was this experiment?	M = 5.68, SD = 1.67
On a scale of 1 (none) to 10 (all of my effort), how much effort did you devote towards this experiment?	M = 8.32, SD = 1.51

between the possible mechanisms of partial forgetting (incomplete active suppression or reduced access), which was tested in Experiment 2.

Second, Experiment 1 focused on factors during encoding and maintenance that may impact the strength of memory representations and subsequent forgetting. Overall, results revealed no impact of the strength of memory representations. Encoding time did not impact memory for TBF information. The lack of an impact of encoding time suggests one of two possibilities. First, it is possible that memory detail does not impact memory for TBF information, and that any exposure to a real-world stimulus is sufficient to form a strong memory representation. The second possibility is that the manipulations of encoding time in the current study were not strong enough to elicit any behavioral differences in performance. It is possible that forgetting may be impacted with significantly longer encoding times (e.g., 6,000ms) as was used by Brady et al. (2009) or significantly shorter encoding times (e.g., 100ms) as was used by Williams and Woodman (2012). Thus, the difference between 1,200ms and 2,000ms in Experiment 1 may not have been sufficient to impact the strength of memory representations.

Another manipulation of memory strength in the current study was cue onset. On cue trials, participants had to maintain all four stimuli for 50ms or 250ms before a cue appeared. Overall, participants were more accurate on cue trials than no-cue trials, but there were no differences between the two cue onset times, with the exception of TBF-change trials. For TBF-change trials, 250ms cue onset trials resulted in higher accuracy than no-cue trials, but there were no differences between 50ms cue onset trials and no-cue trials. Similar to encoding time, these results could be due to memory stability having no impact on forgetting, or because the

manipulations in the current study were not sufficient to impact accuracy. Specifically, in the current study, the encoding time likely contributed to the lack of cue onset differences. Previous research examining consolidation in array-based VWM tasks used very brief stimuli presentation times (100ms total for four stimuli). Thus, in the current study, participants may have fully consolidated the real-world objects within the 1,200ms or 2,000ms encoding display, leading to no impact of cue onset.

The final goal of Experiment 1 was to determine if what appeared to be partial forgetting in VWM was really due to poor encoding or maintenance of object-location bindings. It is possible that participants remembered the TBF stimuli, but never encoded or maintained the stimuli bound to specific locations. If so, the TBF-change trials in the current study could be testing a failure to encode or maintain bindings, rather than memory for TBF information. In order to test for this possibility, the current study utilized location-change trials, where the two TBR stimuli switched locations. Results revealed higher accuracy on location-change trials than new-change and TBF-change trials, which suggests that participants were encoding and maintaining TBR objects bound to specific locations. Importantly, responding “no change” on a TBF-change trial is a binding error. Participants incorrectly responded that a TBF stimulus was on the TBR side of the display. Incorporating location-change trials in the current study allowed me to confirm that 1) participants were encoding objects bound to locations, but 2) that binding information was forgotten after the cue, leading participants to incorrectly respond “no change” for TBF-change trials. Overall, these results suggest that partial forgetting in VWM is not due to a failure to encode location information, but rather location information for TBF stimuli is forgotten after the cue.

The results of Experiment 1 do not distinguish between the possible mechanisms of directed forgetting in VWM. The results suggest that partial forgetting occurs in VWM, but partial forgetting could occur via reduced access to TBF information or active suppression of TBF information that did not result in complete forgetting. Previous research suggests that TBF information is still accessible, albeit less accessible than TBR information, when participants focus their resources on TBR information (reduced access; Zwissler et al., 2015) or actively suppressing TBF information (active suppression; Nowicka et al., 2010). Sudden death is unlikely the mechanism of directed forgetting in VWM, because previous research suggests that sudden death is synonymous with completely forgetting TBF information (Williams et al., 2013). However, it is possible that participants experienced sudden death for one of the two TBF stimuli and remembered the other TBF stimulus, which would result in the behavioral effect that appeared to be partial forgetting.

Neuroimaging is the most useful tool for distinguishing among the possible mechanisms of directed forgetting in VWM. Experiment 2 utilized fMRI in conjunction with neurologically distinct stimuli and increased memory stability on a subset of trials, by using TBF information that had been presented in an earlier portion of Experiment 2.

CHAPTER 2. THE MECHANISM OF DIRECTED FORGETTING

Theories of Directed Forgetting

Studies using the directed forgetting paradigm consistently reveal better long-term memory (LTM) for TBR information than TBF information, which is used as evidence that forgetting occurred (Anderson & Green, 2001; Fawcett, Lawrence, & Taylor, 2016; MacLeod, 1975; Nowicka, Marchewka, Jednorog, Tacikowski, & Brechmann, 2010; Rizio & Dennis, 2013; Wylie, Foxe, & Taylor, 2007; Zwissler et al., 2015). However, the majority of this directed forgetting research has tested LTM, and less is known about forgetting in VWM. Cognitive resources are more limited within VWM compared to LTM (Atkinson & Shiffrin, 1968), thus forgetting may occur differently in VWM compared to LTM. Overall, the mechanisms involved in VWM DF are not well understood. Research generally supports one of three perspectives regarding the mechanism of DF: active suppression, reduced access, or sudden death. Supporters of each perspective agree that individuals focus available cognitive resources on TBR information when presented with a cue. However, the three perspectives differ in how TBF information is "forgotten." The active suppression hypothesis is characterized by actively inhibiting TBF information. Thus, individuals use cognitive resources to both remember TBR information and forget TBF information. According to the active suppression hypothesis, individuals will not be able to remember the TBF information if probed to report it as long as the suppression was successful in eliminating the memory trace (Anderson & Hanslmayr, 2014; Rizio & Dennis, 2013). Reduced access is characterized by focusing all cognitive resources on the TBR information, leading to weaker, but still existent, memory trace for TBF information. Thus, if probed to recall TBF information, individuals may be able to report some information,

but the memory trace to that information would be weak (Dagry & Barrouillet, 2017; Maxcey & Woodman, 2014; Sasin et al., 2017; Schneegans & Bays, 2018; Souza & Oberauer 2016; Taylor & Hamm, 2016; Zwissler et al., 2015). Finally, sudden death is characterized by abrupt, complete removal of TBF information from VWM. Thus, once presented with a cue, individuals completely remove the TBF information from memory, and would not be able to remember TBF information if probed to remember it (Ecker et al., 2014; Williams et al., 2013; Zhang & Luck, 2009). The goal of Experiment 2 was to determine the mechanism of directed forgetting in VWM.

Active Suppression

Active suppression is characterized by actively inhibiting TBF information. According to the active suppression hypothesis, individuals will not remember the TBF information if probed to report it, as long as the suppression was successful. However, research suggests that suppression is not always complete, leading to memory for TBF information (Nowicka et al., 2010; Rizio & Dennis, 2013). The majority of evidence supporting active suppression as the mechanism of directed forgetting comes from item-method DF tasks in long-term memory (LTM; Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie, Foxe, & Taylor, 2007). An item-method DF task involves participants studying stimuli individually for a brief time (e.g., 2,000ms), and then receive an immediate cue instructing them to either remember or forget the preceding stimulus. After participants encode several stimuli, and sometimes after an additional delay of several minutes (to ensure information is in LTM), participants complete a recognition memory test on all of the stimuli. Item-method DF tasks allow for the direct testing of TBF information, which is more challenging with an array-based DF task. However, item-method DF tasks

primarily test LTM as opposed to VWM. With the combination of an item-method DF task and neuroimaging, several studies have found support for the active suppression hypothesis. Behaviorally, TBR stimuli typically result in higher accuracy than TBF stimuli. Neurologically, researchers have found greater prefrontal (middle frontal gyrus and right superior frontal gyrus) and parietal (precuneus and right inferior parietal lobe) activation following a cue to forget compared to a cue to remember. Activation in those brain regions is typically associated with increased effort and cognitive control (Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2007). These neurological findings suggest that forgetting is not a passive process, as proposed by the sudden death or reduced access hypotheses, but rather an active, effortful inhibition of TBF information. However, it is possible that these results are specific to the type of task used in the above research. With an item-method DF task, individuals do not have to bind stimuli to a specific location in order to use the cue effectively because there is only one stimulus preceding the cue. However, with an array-based task, individuals have to remember the identity of stimuli and bind that identity to a specific location, in order to utilize the cue. Thus, an array-based DF task may enroll additional VWM processes compared to item-method DF, possibly leading to a different mechanism of directed forgetting.

Reduced Access

Reduced access is characterized by focusing more cognitive resources on the TBR information than the TBF information, leading to weaker, but still existent, memory traces for TBF information. Thus, if probed to recall TBF information, individuals may be able to report some information, but the memory trace for the TBF information would be weaker than for the TBR information (Dagry & Barrouillet, 2017; Maxcey & Woodman, 2014; Sasin et al., 2017;

Schneegans & Bays, 2018; Souza & Oberauer, 2016; Taylor & Hamm, 2016; Zwissler et al., 2015). Zwissler et al (2015) conducted an experiment using an item-method DF task, but compared performance on "remember" and "forget" cue trials, to trials when participants received no cue to remember or forget (neutral stimuli). They argued that based on the active suppression hypothesis, TBF stimuli would be remembered less accurately than or equivalent to neutral stimuli, because of the purposeful forgetting process. They found the traditional DF effect in that TBR stimuli were remembered with higher accuracy than TBF stimuli, but TBF stimuli were remembered with higher accuracy than neutral stimuli. Zwissler and colleagues argued that their results suggest that participants were selectively rehearsing only the TBR stimuli, and therefore experienced reduced access to the TBF stimuli. Because participants were not actively suppressing nor rehearsing the TBF stimuli, they still had some memory for that information, but not at the level of TBR stimuli (Zwissler et al., 2015). Similarly, other research found memory for TBF stimuli to be stable and above chance, suggesting that TBF information is not purposefully inhibited or removed from memory, but instead is less accessible (Dagry & Barrouillet, 2017). It is possible that when individuals enroll additional VWM processes (e.g., to bind identity to location), such as with an array-based DF task, they may focus their limited resources on maintaining TBR stimuli, leading to reduced access for TBF stimuli.

Sudden Death

Evidence for active suppression and reduced access primarily comes from LTM research, but sudden death has only been documented in VWM. Supporters of the sudden death hypothesis argue that VWM representations are completely dropped from VWM once the

stimulus is labeled as TBF (Ecker et al., 2014; Williams & Woodman, 2012; Zhang & Luck, 2008; 2009). The primary difference between sudden death and active suppression is the effort involved in forgetting. Active suppression classifies complete forgetting as an effortful expulsion of information from memory, whereas sudden death considers complete forgetting to be a byproduct of focusing resources on TBR information. Williams and colleagues (2013) conducted a study to test the sudden death hypothesis in a VWM DF paradigm. Participants completed a precision task in which they encoded the color of one or two colored squares. On 50% of the trials, after participants encoded two stimuli, a cue appeared indicating which stimulus should be maintained (the TBR stimulus). After a 1,500ms delay, participants reported the color of either one or both stimuli, depending on the trial type. Williams and colleagues found that participants provided more precise responses when they only had to maintain one of the two stimuli on the display, as opposed to maintaining both stimuli. Importantly, they also found that encoding one color resulted in equivalent performance to encoding two colors but only maintaining one, suggesting that complete forgetting had occurred for the TBF color (Williams et al., 2013). Additionally, Williams and colleagues (2013) included five invalid trials (testing stimuli that participants were told to forget) to directly test memory for forgotten stimuli. They utilized a maximum likelihood estimation to test the likelihood that the TBF stimulus was still in memory, and found that for the first invalid trial, there was a 1% chance of the TBF stimulus being in memory. The authors attributed these results to the participants having no memory for the forgotten stimuli, thus supporting the sudden death hypothesis.

Interestingly, all of the research supporting the sudden death hypothesis has used simplistic stimuli (e.g., colored squares; Williams & Woodman, 2012; Williams et al., 2013).

Whereas researchers using more detailed stimuli (e.g., real-world scenes) have found support for either reduced access (Zwissler et al., 2015) or active suppression (Nowicka et al., 2010). It is important to note that researchers using simplistic stimuli (e.g., single consonants) have also found support for reduced access (Dagry & Barrouillet, 2017) and active suppression (Rizio & Dennis, 2013), so stimuli type is not the only factor contributing to the mechanism of directed forgetting. However, it is possible that sudden death is more likely to occur when there are very few details associated with the stimulus. With more detailed memory representations, it may be more difficult to completely forget TBF information, possibly leading to reduced access or active suppression of TBF information.

Neural Mechanisms of Directed Forgetting

Neuroimaging is the most efficient way to distinguish between the possible mechanisms of directed forgetting in VWM (active suppression, reduced access, and sudden death). As mentioned above, evidence from item-method DF paradigms reveals greater prefrontal (middle frontal gyrus and right superior frontal gyrus) and parietal (precuneus and right inferior parietal lobe) activation for TBF stimuli compared to TBR stimuli. Activation in those brain regions is typically associated with increased effort and cognitive control (Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2007). One way to distinguish among the possible mechanisms of directed forgetting is to use stimuli that rely on distinct brain regions such as faces and buildings (Beck, Rees, Frith, & Lavie, 2001; Cohen & Tong, 2013; Detre, Natarajan, Gershman, & Norman, 2013; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Schmitz, Cheng, & De Rosa, 2010). Images of human faces are associated with activation in the fusiform face area (FFA) and pictures of buildings and scenes are associated with activation in the parahippocampal place

area (PPA). The FFA is located in the lateral temporal lobe along the ventral stream of the visual pathway, and consistently shows greater activation in response to faces than other stimuli such as buildings or objects (Kanwisher, McDermott, & Chun, 1997). The PPA is located near the hippocampus and is to the posterior side of the FFA, and shows greater activation in response to naturalistic scenes and buildings (Epstein, Harris, Stanley, & Kanwisher, 1999). A number of studies have utilized these areas to investigate a wide variety of research questions and have revealed that while the FFA and PPA are located in close proximity, they are distinct, separable brain regions (Beck et al., 2001; Cohen & Tong, 2013; Detre et al., 2013; Epstein et al., 1999; Gazzaley et al., 2005; Schmitz et al., 2010).

Using neurologically distinct stimuli allowed me to examine the neural mechanisms for TBR and TBF information on the same trial. For example, if participants are presented with one face and one building, and are cued to remember the house, the face is now TBF. Regardless of the hypothesis, participants shift cognitive resources to the TBR stimulus following the cue. Thus, there may be greater activation in the brain region associated with the TBR stimulus than the TBF stimulus on cue trials compared to no-cue trials. However, the predictions for each hypothesis differ depending on the memory stability and dorsolateral prefrontal cortex activation (DLPFC). Active suppression will likely result in increased DLPFC activation after the cue due to the increased cognitive effort associated with purposeful forgetting (Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2007). Reduced access and sudden death will most likely manifest with less activation in the DLPFC, due to a lower VWM load following the cue (Thompson, Waskom, & Gabrieli, 2016). Because the prediction for the reduced access and sudden death hypotheses are similar, the current study also manipulated whether the TBF

information is new information (presented for the first time during the experiment) or old information (previously presented in a different portion of the experiment) in order to test how stable memories are forgotten (TBF status). Old TBF stimuli may result in greater activation overall during the DF task due to increased familiarity (Henson, 2016; Weibert & Andrews, 2015). If the mechanism of directed forgetting is reduced access, the cue would reduce activation for TBF stimulus, but old TBF stimuli may result in more activation than new TBF stimuli. However, if sudden death is the mechanism of directed forgetting, there would be no differences in TBF status (new or old) for cue trials because information would be removed from VWM completely and without effort, regardless of memory stability. Overall, Experiment 2 manipulated memory stability and utilized neurologically distinct stimuli in order to test the mechanism of directed forgetting in VWM.

Experiment 2

The goal of Experiment 2 was to determine the mechanism of directed forgetting in VWM. Previous research suggests that forgetting TBF information in a DF task is due to active suppression (Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2007), reduced access (Dagry & Barrouillet, 2017; Maxcey & Woodman, 2014; Sasin et al., 2017; Schneegans & Bays, 2018; Souza & Oberauer, 2016; Taylor & Hamm, 2016; Zwissler et al., 2015), or sudden death (Williams & Woodman, 2012; Zhang & Luck, 2008; 2009). To date, all of the neurological evidence supports active suppression as the mechanism of directed forgetting, but that research utilized item-method DF in LTM as opposed to VWM. Experiment 2 utilized an array-based DF task to determine the mechanism of directed forgetting. Furthermore, I manipulated whether the TBF information was new information (presented for the first time during the

experiment) or old information (presented in the localizer portion of the experiment) in order to test how stable memories are forgotten (TBF status; Oberauer, Awh, & Sutterer, 2017).

Hypotheses and Predictions

I predicted greater activation in the TBR brain region (e.g., FFA when faces were cued) on cue trials than no-cue trials, because participants will attempt to remember the TBR stimulus, thus increasing activation (see Table 2). Additionally, I predicted less activation in the TBF brain region (e.g., PPA when faces were cued) on cue trials than no-cue trials, because participants will focus only on TBR information. Additionally, in line with both the active suppression and reduced access hypotheses, "new" TBF stimuli may result in less activation than "old" TBF stimuli, but TBF status would not impact brain activation according to the sudden death hypothesis. DLPFC activation would be greater following the cue according to the active suppression hypothesis, due to increased cognitive control and effort to suppress TBF information. DLPFC activation would decrease following the cue according to the reduced access and sudden death hypotheses, due to decreased VWM load.

Table 2. Experiment 2 fMRI Predictions.

	FFA & PPA Activation (TBR/TBF)	FFA & PPA Activation (TBF Status: Old New)	DLPFC Activation
Active Suppression	TBR > TBF	Old ≠ New	Post Cue > Pre Cue
Reduced Access	TBR > TBF	Old ≠ New	Pre Cue > Post Cue
Sudden Death	TBR > TBF	Old = New	Pre Cue > Post Cue

Method

Design. Experiment 2 employed a 2 x 2 within measures design, manipulating cue presence (cue, no-cue) and the TBF relevance (old vs. new TBF stimulus).

Participants. Twenty participants completed Experiment 2. Sample size was based on the effect sizes from my previous work (Moen et al., 2016). G*Power was used to calculate the required sample size, by using Cohen's *d* from the cueing effect (no-cue vs. cue) for new-change trials (*d* = .67). Based on the power analysis, 20 participants were required to achieve an estimated power of .80. The effect sizes used to estimate sample size for Experiment 2 were taken from behavioral data, however, other neuroimaging studies examining change detection with similar stimuli have utilized much smaller sample sizes (e.g., Beck et al., 2001 had 10 participants). Thus, Experiment 2 was sufficiently powered for both the behavioral and neuroimaging data with 20 participants. Participants were recruited from undergraduate psychology courses at LSU and received partial course credit for participation.

Materials. Two hundred fifty Caucasian, female faces and 250 buildings were adapted from various resources for Experiment 2. All stimuli were presented in gray scale. Following the procedure of Cohen and Tong (2013), there was a 250-pixel circle encompassing each stimulus centered on the nose (for faces) or on the center of the building in order to make the stimuli as similar as possible and reduce extraneous details from the face stimuli such as clothing. Eyebrows and the hairline were visible on the faces, in order to equate difficulty with the buildings.

Imaging parameters. FMRI data were collected on a GE 3-T Magnet with a 32 channel MR Instruments head coil at Pennington Biomedical Research Center. Three volumes were trimmed from the functional data and were acquired using a Gradient Echo EPI, echo-planar imaging sequence with the following parameters: repetition time (TR) = 2000 ms; echo time (TE) = 25 ms; flip angle, 90°. The frequency field of view was 22.4 and phase field of view of was 1.0. The structural image was acquired using a three-dimensional magnetization-prepared rapid acquisition gradient (MPRAGE) sequence (TR = 9.252 ms, TE = 3.788 ms, flip angle = 8°, 224 × 256 matrix, phase encoding direction right to left). Functional scans contained 36 slices with a voxel resolution of 3.5 × 3.5 and a slice thickness of 3 mm. Each scan began with four dummy volumes to account for equilibrium effects, and those dummy volumes were discarded from the analyses during preprocessing. The specific number of volumes varied for each portion of the experiment with the localizer task containing 130 volumes and each run of the directed forgetting task containing 160 volumes.

Procedure. Outside of the scanner, participants reviewed and signed the consent form, and were given instructions regarding the scanning process and each task. Participants practiced the DF task outside of the scanner. Once the participant was in the scanner, an anatomical scan (five minutes) was followed by the localizer task (four minutes) and the DF task (35 minutes).

Localizer task. Participants were presented with 36 female faces and 36 places (houses and buildings) individually for 1,500ms, followed by a 1,500ms fixation cross. Participants were told to remember the images for a memory test later on, outside of the scanner. The stimuli were presented in eight blocks (9 stimuli each). Each block only contained one type of stimulus

(faces or buildings), but the order of blocks was randomized for each participant. The localizer task served two purposes: first, it was used to create regions of interest for the FFA and PPA, and a subset of stimuli presented during the localizer task served as the "old" TBF stimuli in the DF task.

Directed forgetting task. Participants were presented with a face on one side of the display and a building on the other side for 1000ms (Figure 7). The pre-change display always contained at least one new stimulus (not presented during the localizer task). The TBF stimulus was either new (50%) or old (50%; presented during the localizer task). Only TBF stimuli could be old. The TBR stimulus was always new. Stimuli on no-cue trials were always both new stimuli. For cue trials (75% of trials), a fixation cross was presented for 1750, 2000, or 2250ms (to avoid predictability and jitter timing for the analyses), followed by an arrow pointing to the left or right side of the display, indicating the side of the display that would be tested. The arrow remained on the display for 1000ms. Following the cue, a fixation cross remained on the display for 1750, 2000, or 2250ms before the post-change display appeared, which contained only one stimulus. For no-cue trials (25% of trials), the fixation cross after the pre-change display remained on the display for 4750, 5000, or 5250ms. Regardless of cue presence, when the post-change display appeared, participants responded whether a change occurred with a button box. The post-change display always contained one stimulus, and it was either identical to the pre-change display (no-change, half of trials) or a new stimulus belonging to the same stimulus group (face presented on left during pre-change, a different face was used post-change). See Figure 7 for an example of the trial sequence. Participants completed a total of six runs, each containing 24 trials. Each run lasted approximately 5.5 minutes.

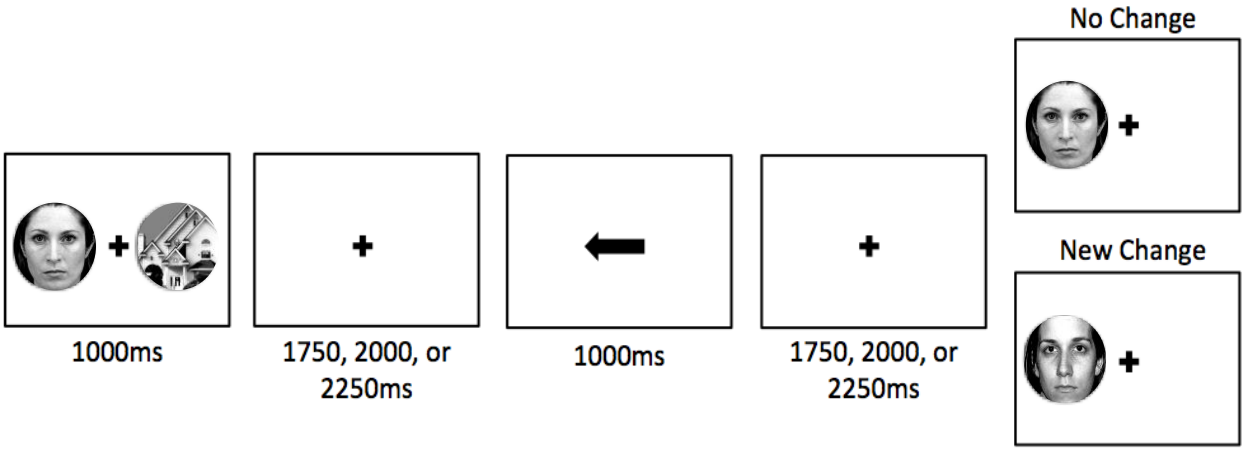

Figure 7. Visual depiction of a typical trial sequence for Experiment 2 with new-change (bottom) and no-change (top) post-change displays. The stimuli are enlarged to show detail.

Experiment 2 Results

fMRI preprocessing and whole-brain univariate analysis. Data were analyzed using FSL software with the standard univariate group level analysis. The standard FSL motion correction was applied. No runs were excluded, because movement for all participants was very low. I used a region of interest (ROI) analysis for the localizer data to extract the FFA and PPA. Those ROIs were used to define the FFA and PPA locations for a group level analysis. Specifically, I looked for activation in the FFA and PPA when there was greater activation on cue trials than no-cue trials. I did this separately for trials when the TBF stimulus was old (previously seen on the localizer) and when the TBF stimulus was new (not previously seen on the localizer). No-cue trials were used to measure baseline activation in the FFA, PPA, and DLPFC.

FMRI data processing was carried out using FEAT (FMRI Expert Analysis Tool) Version 6.00, part of FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). Registration of the functional images to both the high-resolution (T1-weighted) structural image and the standard space image was carried out using FLIRT (Jenkinson, Bannister, Brady, & Smith, 2002; Jenkinson

& Smith, 2001). The following pre-statistics processing was applied: motion correction using MCFLIRT (Jenkinson et al., 2002); slice-timing correction using Fourier-space time-series phase-shifting; non-brain removal using BET (Smith, 2002); spatial smoothing using a Gaussian kernel of FWHM 5mm; high-pass temporal filtering (Gaussian-weighted least-squares straight line fitting, with sigma=50.0s).

The data were analyzed within the General Linear Model using a multi-level repeated measures design. At the single-subject level each run was modeled separately. I used a double-gamma hemodynamic response function (HRF) with which each of the conditions of interest (i.e., TBF status, tested stimulus, cue presence) was combined. I also included several nuisance regressors including six motion correction parameters, and motion censoring regressors for any volume with >0.9mm framewise displacement (Siegel et al., 2014) using the fsl_motion_outliers function. A second-level analysis was performed in order to average each experimental run during the DF task for each participant. This was completed using a fixed effects model, by forcing the random effects variance to zero in FLAME (FMRIB's Local Analysis of Mixed Effects; Beckmann, Jenkinson, & Smith, 2003). Group-level analyses were carried out using FLAME (FMRIB's Local Analysis of Mixed Effects) stage 1 (Beckmann et al., 2003). The resulting *Z* (Gaussianised *T/F*) statistic images were thresholded using clusters determined by $Z > 2.3$ and a (corrected) cluster significance threshold of $p = 0.05$ (Worsley, 2001).

Localizer task. A whole brain analysis was conducted on the localizer task data to examine brain activation in areas that were more active when viewing faces than buildings, and more active for buildings than faces. The criteria for activation on the whole brain analysis was set at an alpha threshold of $p < .01$ at the voxel level and corrected for multiple comparisons at

the cluster level ($p < .05$). Results revealed unilateral (right hemisphere) FFA activation when participants viewed faces, and bilateral PPA activation when participants viewed buildings (Figure 8). In line with previous research, unilateral FFA activation often occurs in the right hemisphere (Cohen et al., 2013). Masks were created of these brain regions in order to examine brain activation in the FFA and PPA during the DF task.

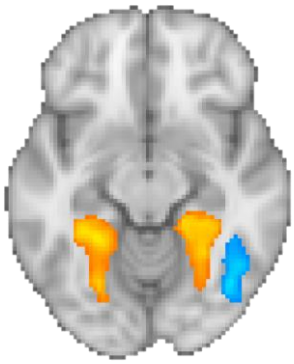

Figure 8. Unilateral FFA (blue) and bilateral PPA activation (orange/yellow) was observed on the localizer task.

Directed Forgetting Task

Behavioral results. Accuracy during the DF task was examined with a 2 x 2 repeated measures ANOVA to compare the tested stimulus (face, building) and TBF status (old, new) for cue trials (Figure 9A). Results revealed a significant main effect of stimulus tested, $F(1,19) = 34.13$, $p<.01$, $\eta_p^2 = .64$, in that accuracy was significantly higher when the face was tested ($M = 92.12\%$, $SD = 11.77\%$) than when the building was tested ($M = 83.64\%$, $SD = 11.87\%$). There was no main effect of TBF status, $F(1,19) = 2.07$, $p = .17$, $\eta_p^2 = .10$, and no interaction, $F(1,19) = 3.20$, $p = .09$, $\eta_p^2 = .14$. The proportion correct for no-cue trials when a face or building was tested (Figure 9B) was compared with a paired samples *t*-test, and revealed higher accuracy when the face was tested than when the building was tested, $t(19) = 3.31$, $p = .004$. Additionally, cue trials

were compared to no-cue trials for each stimulus type and TBF status separately, and revealed no differences between no-cue trials and any of the cue trial types (*p*s > .26). The lack of a difference between cue and no-cue trials do not replicate previous DF research (Moen et al., 2016; Williams & Woodman, 2012; Williams et al., 2013), Overall, these results suggest that faces were remembered more accurately than buildings, and participants did not utilize the cue to increase accuracy. However, it is possible that accuracy was not a sensitive enough measure to detect differences among the various trial types. Thus, neuroimaging data were essential to determine if brain activation changed as a result of stimulus type and TBF status.

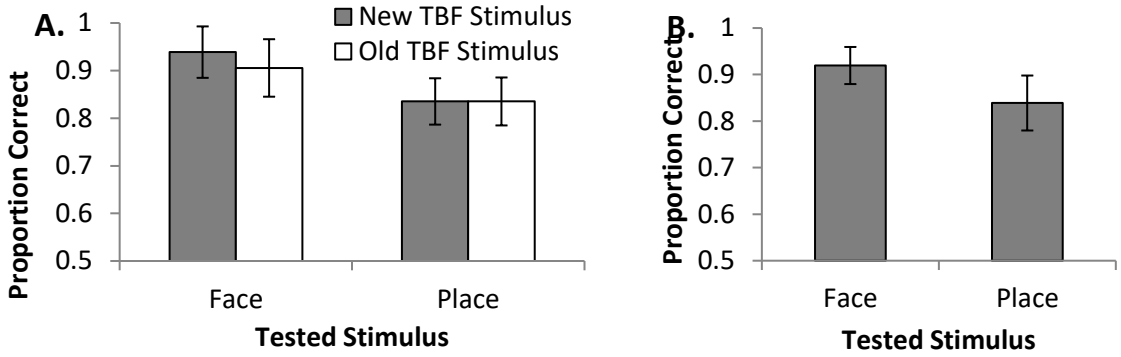

Figure 9. Behavioral results from the directed forgetting task in Experiment 2 for cue trials (A) and no-cue trials (B). Error bars denote 95% confidence intervals.

Neuroimaging results. The data were modeled to separate cue and no-cue trials. Cue trials were further separated into the stimulus that was tested (face, building) and the status of the TBF stimulus (old, new). The dependent variable was percent signal change, which is defined as activation that significantly differed from activation during the non-modeled period (i.e., activation during the inter-trial intervals, when a fixation cross remained on the screen and the participants were instructed to relax and wait for the next trial). For simplicity and succinctness, percent signal change will henceforth be referred to as "activation". For cue trials,

activation in the FFA and PPA was examined from the onset of the pre-change display to the offset of the final fixation cross, immediately before the post-change array onset. For no-cue trials, activation in the FFA and PPA was examined from the onset of the pre-change display to the offset of the fixation cross, immediately before the post-change array onset. This was done to equate the total time frame examined for cue and no-cue trials. Activation during the post-change array was recorded and modeled, so it did not contribute to the non-modeled period, but was not examined in the current study.

FFA activation. FFA activation was analyzed with a 2 x 2 repeated measures ANOVA with face status (face TBR, face TBF) and TBF status (old, new) as the factors (Figure 10). Results revealed no main effect of face status, $F(1,19) = 1.51$, $p = .24$, $\eta_p^2 = .07$ or TBF status, $F(1,19) = 0.02$, $p = .89$, $\eta_p^2 = .001$, but there was a significant interaction between face status and TBF status, $F(1,19) = 10.01$, $p = .005$, $\eta_p^2 = .35$. I conducted paired samples *t*-tests in order to examine the significant interaction. The interaction was driven by greater FFA activation on trials when buildings were cued (TBF faces) than trials when faces were cued (TBR faces), but only when the TBF stimulus was new, $t(19) = 2.86$, $p = .011$. There were no differences in activation between TBR and TBF faces when the TBF stimulus was old, $t(19) = 0.50$, $p = .62$.

I further examined FFA activation by comparing activation on no-cue trials to cue trials. When the TBF stimulus was new, there was significantly higher FFA activation on no-cue trials than trials when faces were cued (TBR faces), $t(19) = 6.50$, $p < .001$, and when buildings were cued (TBF faces), $t(19) = 4.11$, $p = .001$. The same pattern was observed when the TBF stimulus was old, in that no-cue trials resulted in higher FFA activation than trials when faces were cued

(TBR faces), $t(19) = 4.55$, $p < .001$, and when buildings were cued (TBF faces), $t(19) = 4.96$, $p = .001$.

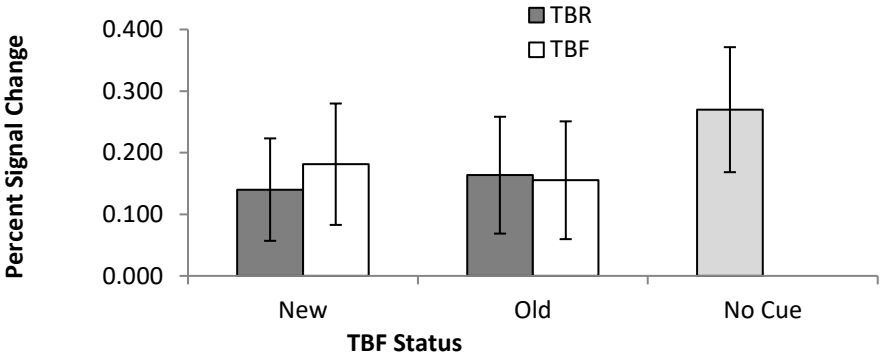

Figure 10. Neuroimaging results from the right FFA when faces were TBR (face cued) or TBF (building cued), and the TBF stimulus was new or old. Activation on no-cue trials is added for comparison. Error bars represent 95% confidence intervals.

Overall, these results suggest that participants were unable to deprioritize faces when buildings were cued. Additionally, no-cue trials consistently resulted in greater FFA activation than cue trials. These results suggest there may be a trade-off in the FFA between constant maintenance of a face (no-cue trials) and a shift to prioritizing the cued stimulus.

PPA activation. PPA activation was analyzed separately for the left and right PPA with a 2 x 2 repeated measures ANOVA with building status (building TBR, building TBF) and TBF status (old, new) as the factors.

Left PPA. Results revealed a main effect of building status, $F(1,19) = 5.76$, $p = .03$, $\eta_p^2 = .23$, no main effect of TBF status, $F(1,19) = 0.03$, $p = .87$, $\eta_p^2 = .001$, but there was a significant interaction between building status and TBF status, $F(1,19) = 6.01$, $p = .03$, $\eta_p^2 = .024$ (Figure 11). I conducted paired samples *t*-tests in order to examine the significant interaction. The interaction was driven by greater left PPA activation on trials when buildings were cued (TBR buildings) than when faces were cued (TBF buildings), but only when the TBF stimulus was new,

$t(19) = 3.63$, $p = .002$. There were no differences between TBR and TBF buildings when the TBF stimulus was old, $t(19) = 0.96$, $p = .35$. These results suggest that when all of the information presented on a given trial is new, participants are able to prioritize the TBR information, and deprioritize the TBF information, leading to a change in PPA activation.

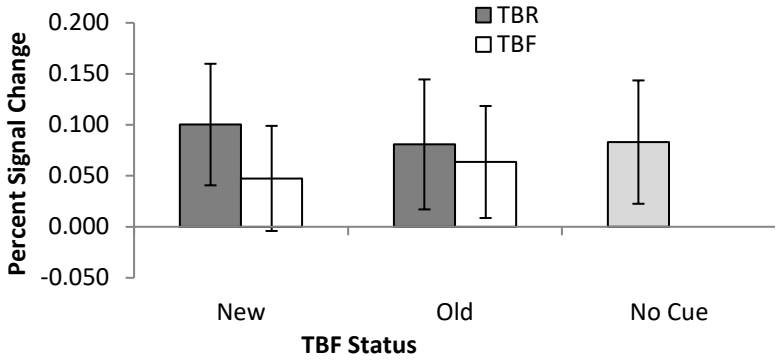

Figure 11. Neuroimaging results from the left PPA when buildings were TBR (building cued) or TBF (face cued), and the TBF stimulus was new or old. Activation on no-cue trials is added for comparison. Error bars represent 95% confidence intervals.

I further examined Left PPA activation by comparing activation on no-cue trials to cue trials, and found that no-cue trials resulted in significantly lower activation than trials when faces were cued (TBF building), but only when the TBF stimulus was new $t(19) = 2.53$, $p = .021$, suggesting that participants were less likely to maintain a new TBF building than the building on no-cue trials. However, TBR buildings did not result in significantly greater activation than buildings on no-cue trials, regardless of if the corresponding TBF stimulus was old, $t(19) = 1.08$, $p = .30$ or new, $t(19) = 0.11$, $p = .91$. There was also no differences in between old TBF buildings and buildings on no-cue trials, $t(19) = 1.22$, $p = .24$.

Overall, these results revealed greater left PPA activation when buildings were cued, than when faces were cued (TBF buildings), but only when the TBF stimulus was new. Participants were less likely to effectively utilize the cue, and prioritize TBR information, when

the TBF stimulus was old. These results suggest that sudden death is not the mechanism of directed forgetting in VWM, because of the differences between new and old TBF stimuli. Sudden death predicts that information is completely dropped from VWM without any effort after the cue, and would thus not be impacted by TBF status. However, these results suggest that more stable memory representations (old TBF stimuli) were less effectively deprioritized compared to less stable memory representations (new TBF stimuli).

Right PPA. Results revealed a main effect of building status, $F(1,19) = 20.16$, $p < .01$, $\eta_p^2 = .52$, and no main effect of TBF status, $F(1,19) = 0.03$, $p = .88$, $\eta_p^2 = .001$, but there was a significant interaction between building status and TBF status, $F(1,19) = 6.27$, $p = .02$, $\eta_p^2 = .025$ (Figure 12). I conducted paired samples *t*-tests in order to examine the significant interaction. The interaction was driven by greater right PPA activation on trials when buildings were cued (TBR buildings) than trials when faces were cued (TBF buildings), regardless of whether the TBF stimulus was new, $t(19) = 5.16$, $p < .001$, or old, $t(19) = 2.37$, $p = .03$. However, the difference between TBR and TBF buildings was significantly larger on trials when the TBF stimulus was new, $t(19) = 2.50$, $p = .022$.

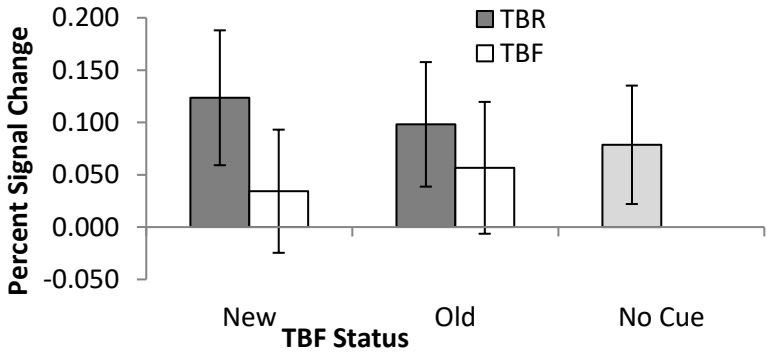

Figure 12. Neuroimaging results from the right PPA when buildings were TBR (building cued) or TBF (face cued), and the TBF stimulus was new or old. Activation on no-cue trials is added for comparison. Error bars represent 95% confidence intervals.

Finally, I compared right PPA activation on cue trials to no-cue trials, and found greater activation for when buildings were cued (TBR buildings), $t(19) = 3.20$, $p = .005$, than no-cue trials, and lower activation when faces were cued (TBF buildings) than no-cue trials, $t(19) = 3.02$, $p = .007$, but only for trials when the TBF stimulus was new. There were no differences in activation between no-cue trials and TBR buildings, $t(19) = 1.18$, $p = .25$, or TBF buildings, $t(19) = 1.48$, $p = .16$, when the TBF stimulus was old.

Overall, these results are similar to the results from the left PPA, and suggest that participants prioritized TBR buildings over TBF buildings. Furthermore, increased memory stability (old TBF stimulus) reduces, but does not eliminate, this prioritization. There was greater right PPA activation when buildings were cued (TBR buildings), than when faces were cued (TBF buildings), but only when the TBF stimulus was new. Participants were less likely to effectively utilize the cue and prioritize TBR information when the TBF stimulus was old. Once again, these results suggest that sudden death is not the mechanism of directed forgetting in VWM.

DLPFC activation. It is essential to examine DLPFC activation in order to distinguish between the active suppression and reduced access hypotheses. The DLPFC was localized with a whole brain analysis comparing activation before and after the cue. Results revealed significant activation in the right DLPFC (Figure 13A). In order to quantify the impact of the cue on DLPFC activation, I conducted a paired-samples *t*-test to compare DLPFC activation before and after the cue (Figure 13B). Results revealed significantly greater DLPFC activation before the cue, than after the cue, $t(19) = 9.40$, $p < .001$. These results suggest that information was

being dropped from VWM after the cue, thus reducing DLPFC activation, and supporting the reduced access hypothesis.

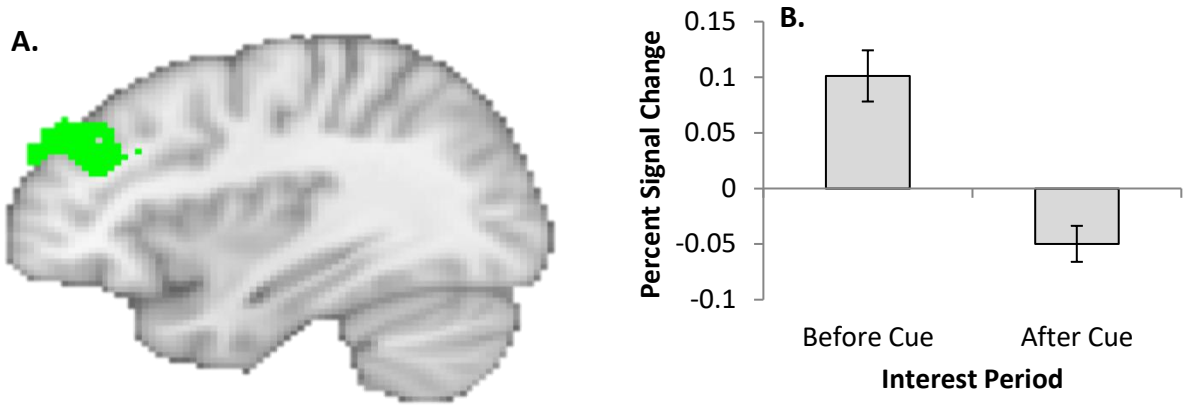

Figure 13. A whole brain analysis revealed significant DLPFC activation in the right hemisphere (A), which was used to create a region of interest mask (green) for the DF task data (B). Error bars represent 95% confidence intervals.

Because of the difference in behavioral results depending on the tested stimulus, and the different pattern of results observed for the FFA and PPA, a post-hoc 2 x 2 x 2 repeated measures ANOVA was conducted to examine the possible impact of stimulus type (face, building), TBF status (old, new), and interest period (before cue, after cue) on DLPFC activation. There was a significant main effect of interest period, in line with the results of the paired samples *t*-test reported above, but no other main effects and no interactions (*p*s > .11). These results suggest that while faces and buildings lead to differences in behavioral performance and FFA/PPA activation, they do not impact the mechanism of directed forgetting in VWM.

Finally, I conducted several correlations to compare DLPFC activation after the cue with activation for the TBF stimulus in the FFA, left PPA, and right PPA. If active suppression occurs, there may be a negative correlation between DLPFC activation and activation in the TBF brain region, with the increased cognitive effort of suppressing TBF information. Alternatively, if reduced access or sudden death occurs, there may be a positive correlation between DLPFC

activation and the TBF brain region as information is dropped from VWM. However, there were no significant correlations between DLPFC activation and activation in any brain region for TBF information regardless of whether the TBF stimulus was old or new, *p*s > .52 (see Table 3).

Table 3. The relationship between DLPFC and the FFA and PPA after the cue

	DLPFC Activation	
	r Value	*p* value
FFA: New TBF Stimulus	-.12	.60
FFA: Old TBF Stimulus	.05	.83
Left PPA: New TBF Stimulus	.07	.78
Left PPA: Old TBF Stimulus	-.06	.80
Right PPA: New TBF Stimulus	-.03	.90
Right PPA: Old TBF Stimulus	-.15	.52

Overall, the results from Experiment 2 suggest forgetting in VWM occurs via the passive process of reduced access to TBF information. Additionally, while stimulus type and TBF status impact behavioral accuracy and activation in the FFA and PPA, these factors do not impact the mechanism of directed forgetting in VWM.

GENERAL DISCUSSION

To date, very little research has investigated forgetting in VWM. Previous research suggests that complete forgetting does take place under certain circumstances (Williams et al., 2013). However, to my knowledge, research has not tested the limits of loss of TBF information, and under what circumstances it is more likely to occur. Additionally, there is disagreement among researchers if the mechanism of directed forgetting in VWM is due to reduced access, sudden death, or active suppression. The current study expanded on previous research in order to determine the mechanism of directed forgetting and how the strength of memory representations impacts forgetting in VWM.

Experiment 1

Experiment 1 replicated previous research in that accuracy was higher on cue trials than no-cue trials (Moen et al., 2016; Williams & Woodman 2012; Williams et al., 2013). These results suggest that participants were utilizing the cue and prioritizing TBR information. Additionally, results from Experiment 1 replicate research suggesting that partial forgetting, opposed to complete forgetting, occurs for objects in VWM (Moen et al., 2016). These results further validate the TBF-change method as a reliable way to measure TBF information in VWM. Furthermore, the current study expanded on my previous research, and determined that partial forgetting in VWM is not due to the failure to encode or maintain location information before the cue.

Representation Strength

The role of detailed VWM representations is essential to understanding how encoding impacts forgetting in VWM. Based on previous research, I predicted that a longer encoding time

would allow participants to encode more detailed memory representations (Brady et al., 2009) leading to less successful forgetting of TBF information. No published research has utilized varying encoding times in DF paradigms in VWM. However, longer encoding times have been shown to lead to more detailed memory representations (Brady et al., 2009). Research supporting complete forgetting has utilized simplistic stimuli with very brief encoding times (e.g., 100ms for four stimuli; Williams et al., 2013). It is possible that complete forgetting only occurs with less detailed memory representations. Results of the current study revealed that partial forgetting occurs regardless of encoding time (1,200ms or 2,000ms). However, the current study does not rule out the possibility that less detailed memory representations would result in more forgetting. It is possible that with even shorter encoding times, memory representations may be forgotten via sudden death. The results of the current study do suggest that 300ms per real-world object is sufficient to encode the stimulus and the representation can only be partially forgotten.

Memory stability may also impact the strength of VWM representations and subsequent forgetting. I predicted that successful forgetting would decrease as cue onset increased. Previous research suggests that longer cue onsets lead to more stable VWM representations (Vogel et al., 2006), which may be more difficult to forget. However, in the current study, cue onset did not impact forgetting in VWM, which may be due to the type of stimuli used in the current study. Previous research examining cue onset and forgetting have utilized item-method DF with verbal stimuli in LTM (Lee & Lee, 2011), and the researchers argued that memory for TBF stimuli increased as cue onset increased due to increased verbal rehearsal. I hypothesized that cue onset would impact forgetting by leading to more stable VWM representations. It is

also possible that participants in the current study used the longer cue onset to verbally rehearse information. However, it is unlikely that a participant could consciously rehearse four stimuli over very short delays (50 or 250ms), participants were likely verbally rehearsing stimuli during the encoding display, which may have continued during the cue onset period. Nevertheless, there was no impact of cue onset in the current study.

One possible limitation of the current study is the amount of time required to encode real-world objects. Previous research demonstrating complete forgetting in VWM has utilized colored squares presented for 100ms (25ms per stimulus; Williams & Woodman, 2012). One benefit of colored stimuli is that color is easily detected in the periphery (Williams & Woodman, 2012; Williams et al., 2013). Real-world objects and non-color based changes are not easily detected in the periphery, and thus require longer encoding times for participants to saccade (make an eye movement) to each stimulus (Moen et al., 2016). In a pilot experiment, I determined that participants required a minimum of 300ms per stimulus in order to fixate on each stimulus. However, in the current study a 1,200ms encoding time may not have been short enough to lead to less detailed memory representations. In my previous research I tested a DF task with shape changes and presented four shapes for 100ms, and accuracy was at chance (50% correct).

The lack of a cue onset effect was likely related to the encoding time manipulation in the current study. Previous research examining consolidation in array-based VWM tasks used very brief stimuli presentation times (100ms total for four stimuli; Vogel et al., 2006). Thus, in the current study, participants may have fully consolidated the real-world objects within the 1,200ms or 2,000ms encoding display, leading to no impact of cue onset. However, previous

research from other VWM tasks suggests that real-world objects are fully consolidated in 500ms (Kellie & Shapiro, 2004), which suggests that full consolidation in the current study would most likely occur in the 2000ms encoding time for 250ms cue onset trials. Future research should experiment with other methods, such as sequential encoding or presenting the stimuli closer to fixation, in order determine the interaction between cue onset and encoding time. Currently, more research is needed to determine if memory detail impacts the extent of directed forgetting in VWM.

Location Binding

One possible explanation for the low performance on TBF-change trials is that participants never encoded object-location binding information, and thus were incorrectly responding "no change" when a TBF-change occurred because they did not encode or maintain location information. Thus, the same pattern of results from the current study would be observed if participants completely ignored the cue, but did not encode objects bound to specific locations. In order to account for this explanation, the current study utilized location-change trials, during which the two TBR stimuli switched locations. This manipulation allowed me to test the possibility that participants never encoded location information. Importantly, the partial forgetting observed in the current study does not appear to be due to a failure to encode object-location binding information, as participants were highly accurate on location-change trials. Instead, it appears that participants encoded and maintained object-location binding information up until the cue, and then forgot location information as part of the partial forgetting process, leading to a higher proportion of incorrect "no change" responses for TBF-change trials.

One limitation of the current study is the nature of location-change trials compared to the other change trials. For new- and TBF-change trials, one stimulus on the TBR side of the display remains unchanged, and one stimulus changed. For location-change trials, both stimuli changed because they both move locations. Because both stimuli changed on location-change trials, participants only had to remember the location of a single TBR stimulus in order to answer correctly. Thus, the high accuracy observed for location-change trials may be due to participants preferentially encoding one stimulus. However, even if participants only encoded a single stimulus, they still would have needed to remember the location of that stimulus in order to respond accurately on location-change trials. Additionally, participants had no way of knowing which side of the display or which of the two stimuli on a given side would change on each trial. Thus, encoding a single stimulus would lead to very low accuracy overall. Nevertheless, future research utilizing location-change trials should use a single stimulus test probe for all trials instead of two stimuli on the tested side of the display.

Overall, the results from Experiment 1 suggest that partial forgetting occurs for real-world objects, regardless of encoding time and cue onset. Additionally, partial forgetting is not due to failure to encode location information. These results also further validate the TBF-change method as a reliable way to measure TBF information in VWM. Future research should continue to use the TBF-change method to examine the extent of partial forgetting in VWM, and find new ways to manipulate memory detail and stability.

Experiment 2

Experiment 2 was the first study to document a mechanism of directed forgetting in VWM. To my knowledge, no research has tested whether DF in VWM is due to active

suppression, reduced access, or sudden death. Furthermore, very little research has examined brain activation associated with DF in VWM. The only research examining neural activation associated with DF has used item-method DF tasks, with verbal stimuli (Anderson & Hanslmayr, 2014; Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2007), and supports the reduced access or active suppression hypotheses. The only research supporting the sudden death hypothesis has utilized simplistic stimuli (colored squares) in an array-based task and did not measure brain activation (Williams & Woodman, 2012; Williams et al., 2013).

Overall, Experiment 2 defined the pattern of brain activation associated with a DF task, and determined that DF in VWM is associated with reduced access to TBF information. The results from the FFA were inconclusive. Participants were unable to prioritize/deprioritize faces after the cue, and instead exhibited greater brain activation to faces on no-cue trials than cue trials. However, results from the PPA suggested that brain activation is higher for TBR than TBF information, and that difference is larger for less stable memory representations (i.e., the TBF stimulus has not been seen before). Previous research suggests that familiar faces elicit greater FFA activation than unfamiliar faces (Weibert & Andrews, 2015), however, this may depend on the delay between presentations and the type of task (Henson, 2016). In the current study, participants were able to more effectively prioritize cued information when the TBF information had no previous memory trace. These results are most likely due to unfamiliar information (new TBF stimuli) leading to less brain activation than familiar information (old TBF stimuli). Additionally, the difference between new and old TBF information suggests that sudden death is not the mechanism of directed forgetting in VWM. If information were dropped from VWM completely and without effort once participants were cued to forget that information, then

having an existing memory representation would not impact the drop from VWM. However, differences between new and old TBF information is consistent with the active suppression and reduced access hypotheses. I distinguished between these hypotheses by comparing brain activation in the DLPFC before and after the cue. The DLPFC has previously been associated with cognitive effort (i.e., trying to actively suppress information) and working memory load (i.e., dropping a stimulus from VWM). Results revealed that DLPFC activation decreased following the cue, suggesting that participants were no longer maintaining the TBF information in VWM. Overall, the results from Experiment 2 suggest that forgetting in VWM is a passive process, characterized by reduced access to TBF information.

One possible limitation of Experiment 2 is the different stimuli types. It is possible that the faces used in Experiment 2 were more salient than the buildings. A pilot study was conducted to norm the faces and buildings used in the current study, and ensure that change detection performance was equivalent. However, results from Experiment 2 revealed significantly higher accuracy when faces were tested than when buildings were tested. Additionally, the pattern of brain activation in the FFA was vastly different than the pattern observed in both hemispheres of the PPA. Previous research suggests that familiar faces result in greater FFA activation than unfamiliar faces (Weibert & Andrews, 2015), but stimulus familiarity does not impact PPA activation (Cohen & Tong, 2013). Additionally, own-race faces elicit higher FFA activation than other-race faces (Golby, Gabrieli, Chiao, & Eberhardt, 2001). Eighteen of the twenty participants from Experiment 2 were Caucasian, as were the faces used in Experiment 2. Indeed, the average FFA activation (M = 0.18) was higher than the average PPA activation (M = 0.08). It is possible that the own-race bias lead to overall increased activation to

faces and contributed to the pattern of results from the FFA in Experiment 2. Future research should account for this possibility and attempt to equate overall activation in the FFA and PPA.

Another limitation of Experiment 2 is the use of fMRI. While neuroimaging was necessary to determine the mechanism of directed forgetting in VWM, there is extensive research documenting the limitations of fMRI as a technique (for review see Logothetis, 2008). The BOLD signal measured via fMRI is a slow process, which does not immediately change as the result of brain activation. Additionally, the magnetic resonance scanner used in the current study recorded BOLD activity every 2-seconds. Thus, there is a limited time period with which to measure brain activation changes. The current study accounted for these issues by analyzing the entire trial period (pre-change onset to post-cue offset) for the FFA and PPA activation. This allowed for 6-seconds (three volumes) with which to acquire data on a given trial. The spatial specificity afforded by fMRI allowed me to localize the FFA, PPA, and DLPFC, in order to determine the mechanism of directed forgetting. However, the mechanism of directed forgetting may also be examined with more temporally specific tools such as event related potentials via electroencephalogram (EGG). Future research should continue to explore the mechanism of directed forgetting in VWM with various neuroimaging techniques, including fMRI and EEG.

Overall, Experiment 2 utilized fMRI and defined the pattern of brain activation associated with a DF task. The results from the PPA revealed that DF in VWM is associated with reduced access to TBF information.

Informing the Unit of Storage in VWM: Slots vs. Resource

There is an extensive debate in the literature regarding the unit of storage of VWM. Researchers generally support one of two perspectives: discrete slots (Zhang & Luck, 2008) or flexible resource (Bays & Husain, 2008). The discrete slot theory argues that individuals can store a fixed number of stimuli (3 or 4) in VWM at one time (Zhang & Luck, 2008), and information is removed from memory as a complete unit (complete forgetting). The flexible resource theory argues that VWM resources can be flexibly allocated to any number of stimuli, but increasing the amount of information held in VWM leads to less detailed memory representations (Bays & Husain, 2008). Additionally, when viewing VWM as a flexible resource, forgetting is not a complete process (partial forgetting). The current study informs this debate and suggests that the unit of storage in VWM is a flexible resource.

The results from Experiment 1 suggest that partial forgetting occurred in the current study. Location-change trials demonstrated that participants encoded and maintained object-location bindings for the TBR stimuli. If VWM were structured as discrete slots, participants would forget object identity and location information for the TBF stimuli. However, results from TBF-change trials suggest that participants had some memory for the TBF stimuli, but did not remember which side of the display the stimuli appeared on. Thus, the results from Experiment 1 suggest that VWM storage is a flexible resource.

The neuroimaging data from Experiment 2 also support the conclusion that VWM storage is a flexible resource. If the unit of storage in VWM were discrete slots, the status of the TBF stimulus would not impact brain activation for the TBR stimulus. That is, information would occupy a single slot in VWM, and would be dropped from that slot, regardless of whether

participants had seen a stimulus in an earlier portion of the experiment. However, results from Experiment 2 suggest that TBF status (old, new) impacted activation in the FFA and PPA. These results suggest that participants may have flexibly allocated resources differently to TBR and TBF stimuli based on the status of the TBF stimulus.

Overall, the current study broadly informs research on VWM storage, and suggests that VWM is a flexible resource, and is not characterized by a fixed number of slots. Future research should further test the flexible resource theory in directed forgetting by manipulating memory detail and utilizing various stimuli types.

Forgetting in VWM vs. LTM

DF is more commonly studied in LTM than VWM (Anderson & Green, 2001; Fawcett, Lawrence, & Taylor, 2016; MacLeod, 1975; Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2007; Zwissler et al., 2015), and I used LTM theories of directed forgetting to motivate the research questions in Experiment 2. The research examining the mechanism of directed forgetting in LTM has found behavioral support for either active suppression (Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2007) or reduced access (Dagry & Barrouillet, 2017; Zwissler et al., 2015). However, the majority of DF research using neuroimaging has found support for active suppression as the mechanism of directed forgetting in LTM (for exception see Experiment 4 in Zwissler et al., 2015).

I chose to rely on LTM theories of directed forgetting in the current study due to the lack of research examining forgetting in VWM. Researchers often segment human memory in VWM and LTM because these types of memory are associated with specific characteristics. VWM is a capacity-limited memory store (3-4 stimuli), that allows for visual information to be

manipulated (Fukuda, Awh, & Vogel, 2010) and quickly accessed for a brief period of time (Atkinson & Shiffrin, 1968; Craik & Lockhart, 1972). Alternatively, LTM has a very large capacity and may be capacity unlimited (Brady, Konkle, Alvarez, & Oliva, 2008; Standing, 1973). Additionally, information in LTM is not active (via continuous rehearsal) prior to the presentation of the appropriate retrieval cue (Atkinson & Shiffrin, 1968). Cognitive resources are more limited within VWM than LTM (Atkinson & Shiffrin, 1968), thus forgetting may occur differently in VWM compared to LTM.

The availability of resources is the critical difference between VWM and LTM when examining the mechanism of directed forgetting. Specifically, active suppression is a cognitively demanding task. Increased DLPFC activation is associated with increased cognitive effort, and is the primary neurological indicator for suppression (Nowicka et al., 2010; Rizio & Dennis, 2013; Wylie et al., 2007). Cognitive resources may be more readily available in LTM, thus allowing for a more active forgetting process, such as suppression. In VWM, however, information must be actively rehearsed to remain active in VWM. When participants receive a cue to maintain only the TBR stimuli, it is advantageous to use a passive forgetting strategy, which is less cognitive demanding because VWM rehearsal is also cognitively demanding.

The current study may inform LTM DF research, specifically for more difficult, cognitively demanding LTM tasks. It is possible that individual differences among participants or various methodologies lead to more cognitively demanding tasks, thus leading some LTM researchers to find support for reduced access as the mechanism of directed forgetting. For example, individuals with small VWM capacities may be more likely to exhibit reduced access as the mechanism of directed forgetting, as opposed to individuals with very large VWM

capacities. Furthermore, some theories argue that VWM and LTM are not completely separate memory systems. Specifically, the three-state model of VWM argues that some information in VWM consists of activated long-term memory (aLTM) representations that are less accessible than some information in VWM, but more accessible than information in LTM (Nee & Jonides, 2011). ALTM may be ideal to study the mechanisms of directed forgetting, because information is more passively maintained than VWM, but more accessible than LTM. Overall, forgetting may operate differently, depending on the structure of memory and various experimental constraints. Future research should continue to explore the mechanism of directed forgetting depending on the relationship between VWM and LTM.

CONCLUSION

The goal of the current study was to determine the mechanism of directed forgetting in visual working memory (VWM) and determine how factors during encoding and maintenance impact forgetting. Results from the current study suggest that shorter encoding times neither increase memory for TBR information, nor decrease the likelihood of forgetting TBF information. Additionally, individuals were able to fully consolidate information from the pre-change display regardless of cue onset. However, the results of Experiment 1 replicate previous research (Moen et al., 2016) in that partial forgetting occurred, and extended previous research by demonstrating that TBF-change errors were not due to a failure to encode object-location bindings. Experiment 2 manipulated memory stability and utilized functional magnetic resonance imaging in order to further determine the mechanism of directed forgetting. Results revealed that the mechanism of directed forgetting in VWM is a passive process, which occurs via reduced access. Overall, results from the current study suggest that directed forgetting occurs different in VWM and LTM. Through a passive forgetting process, individuals are able to prioritize TBR information in VWM, resulting in partial forgetting for TBF information. Future research should continue to explore the mechanisms of forgetting in VWM and LTM, and how the strength of memory representations impacts the likelihood of successful forgetting.

APPENDIX A. EXPERIMENT 1 IRB APPROVAL

ACTION ON EXEMPTION APPROVAL REQUEST

Institutional Review Board
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TO: Katherine Moen
Psychology

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: August 28, 2018

RE: **IRB#** E11161

TITLE: It was a bird! No, it was a plane!

New Protocol/Modification/Continuation: New Protocol

Review Date: 8/28/2018

Approved X **Disapproved**_____

Approval Date: 8/28/2018 **Approval Expiration Date:** 8/27/2021

Exemption Category/Paragraph: 2a

Signed Consent Waived?: No

Re-review frequency: (three years unless otherwise stated)

LSU Proposal Number (if applicable):

By: Dennis Landin, Chairman 

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. **SPECIAL NOTE: When emailing more than one recipient, make sure you use bcc. Approvals will automatically be closed by the IRB on the expiration date unless the PI requests a continuation.**

* *All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

APPENDIX B. EXPERIMENT 2 IRB APPROVAL

ACTION ON PROTOCOL APPROVAL REQUEST

Dr. Dennis Landin, Chair
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TO: Steven Greening
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FROM: Dennis Landin
Chair, Institutional Review Board

DATE: October 29, 2018

RE: **IRB#** 3847

TITLE: Interactions of emotion and cognition

New Protocol/Modification/Continuation: Modification

Brief Modification Description: Add Katherine Moen and Xinrui Jiang. Removed Alex Wandler, Alison Schreckengast, Cade Bourgeois, Cameron Grimball, Justin Le, Mark Maier, Mary Rolfe, Annabeth Madden, and Joshua Owens-French.

Review type: Full ___ Expedited __X___ **Review date:** 10/26/2018

Risk Factor: Minimal _____ Uncertain ____X_____ Greater Than Minimal_____

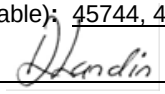
Approved___X____ **Disapproved** _____

Approval Date: 10/27/2018 **Approval Expiration Date:** 2/8/2019

Re-review frequency: (annual unless otherwise stated)

Number of subjects approved: 200

LSU Proposal Number (if applicable)**:** 45744, 47528, 47188

By: Dennis Landin, Chairman 

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. **SPECIAL NOTE: Make sure you use bcc when emailing more than one recipient.**

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

APPENDIX C. POST EXPERIMENT QUESTIONNAIRE

1. What button did you press I f a new item replaced an old item?
2. What button did you press when the two pictures switched locations?
3. What button did you press when nothing changed?
4. Did you notice anything strange during the experiment?
5. Did you notice that the pictures would move positions?
6. Did you notice that a picture would sometimes move from one side of the screen to the other?
7. What button did you press if a picture switched sides of the screen?
8. What percentage of trials was there no change?
9. What percentage of trials did a new picture replace the original picture?
10. What percentage of trials did the two pictures switch locations?
11. What percentage of trials did a picture move to the other side of the screen?
12. What did the arrow indicate?
13. True/False: The arrow indicated the side of the screen that would be tested.
14. What did you do when you saw an arrow?
15. True/False: I only tried to remember the pictures on the side of the screen the arrow pointed towards.
16. True/False: I tried to remember all of the pictures even if there was an arrow.
17. True/False: It was easier to tell if something changed when there was an arrow.
18. On a scale of 1 (not difficult at all) to 10 (extremely difficult), how difficult was this experiment?
19. On a scale of 1 (none) to 10 (all of my effort), how much effort did you devote towards this experiment?

APPENDIX D. OMNIBUS ANOVA FOR EXPERIMENT 1

A 2 x 3 x 3 mixed measures ANOVA was conducted on the proportion correct (Figure 2). Encoding time (1,200 or 2,000ms) was the only between subjects variable. The remaining variables of cue onset (no-cue, 50ms, or 250ms) and change type (new-change, TBF-change, location-change) were within subjects. There was a main effect of cue onset, $F(2,228) = 56.29$, $p < .001$, $\eta_p^2 = .33$, in that accuracy was lower on no-cue trials than 50ms cue onset trials, $t(115) = 8.70$, $p < .001$, or 250ms cue onset trials, $t(115) = 9.05$, $p < .001$. However, there was no difference in accuracy between 50ms and 250ms cue onsets, $t(115)=0.30$, $p=.76$. There was no significant main effect of encoding time, $F(1,114) = 2.20$, $p = .14$, $\eta_p^2 = .02$, but there was a main effect of change type, $F(2,228) = 74.21$, $p < .001$, $\eta_p^2 = .39$, in that accuracy was lower for TBF-changes than new-changes, $t(115) = 10.03$, $p < .001$, and location-changes, $t(115) = 12.57$, $p < .001$. Additionally, location-changes resulted in higher accuracy than new-changes, $t(115) = 2.25$, $p = .03$. There was also an interaction between cue onset and change type, $F(2,456) = 8.94$, $p < .001$, $\eta_p^2 = .07$, but no other significant interactions, ps > .11.

In order to examine the interaction between cue onset and change type, paired samples *t*-tests were conducted to compare cue onsets for each change type separately. For new-change trials (Figure 2A), no-cue trials resulted in lower accuracy than trials with 50ms, $t(115) = 9.10$, $p < .001$, or 250ms cue onsets, $t(115) = 6.95$, $p < .001$, but there were no differences in accuracy between 50ms and 250ms cue onsets, $t(115) = 1.96$, $p = .09$. The same pattern was observed for location-change trials (Figure 2B), with no-cue trials resulted in lower accuracy than trials with 50ms, $t(115) = 8.05$, $p < .001$, and 250ms cue onsets, $t(115) = 8.52$, $p < .001$, but there were no differences in accuracy between the two cue onsets, $t(115) = 0.04$, $p = .97$. For

TBF-change trials (Figure 2C), no-cue trials resulted in lower accuracy than trials with 250ms cue onset, $t(115) = 3.26$, $p = .001$, but there were no differences between no-cue and 50ms cue onset trials, $t(115) = 1.10$, $p = .27$, nor was there a difference between 50ms and 250ms cue onset trials, $t(115) = 1.68$, $p = .10$.

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VITA

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