

# Visual Memory

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### Mechanistic constraints and limitations in the voluntary control of visual long-term memory

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#### **Introduction**

We are constantly bombarded with visual information around us. In many ways, our life hinges on the ability to store this information so that we can later retrieve it when we need to use it. This internal accumulation of visual information is known as visual long-term memory (VLTM), and plays an essential role in carrying out day-to-day operations (e.g., grocery shopping) and forming the building blocks of our identities (e.g., memories of family members). Thus, characterizing the capacity and precision of VLTM is fundamental to the science of the human mind.

At the same time, not all visual information is equal in value for achieving our goals or defining our identities. While some information is directly relevant to a task at hand, other information is irrelevant or even detrimental to the successful completion of the task. Therefore, it is critical to investigate whether and how we can control what gets stored in VLTM.

Relatedly, some visual memories might change in value over time. While some visual memories can become more valuable with time (e.g., experiences with a deceased friend), other memories can become less valuable (e.g., memories of relationships that turned sour). Such changes in mnemonic value motivate us to examine whether and how we can regulate the accessibility and quality of visual information that is already encoded into VLTM.

The last decade or so has been a fascinating era for addressing these questions. As a field, VLTM researchers have made significant strides in elucidating the vast capacity and surprisingly high precision of VLTM (Balaban et al., 2020;

Brady et al., 2008; Brady, Konkle, Alvarez et al., 2013; Brady, Konkle, Gill, et al., 2013; Konkle et al., 2010). In this chapter, we first provide a selective review of recent work that examines the mechanistic constraints that our mind places on the accumulation of visual memories, as well as the nature and extent of our voluntary control over these mechanisms. We then conclude the chapter by raising some fundamental questions that have yet to be answered regarding our ability to modulate our VLTMs.

### **Visual working memory determines the bandwidth of VLTMs encoding**

Despite its vast capacity, not everything that we perceive gets encoded into VLTMs. This suggests that merely perceiving visual information is insufficient for granting access to our virtually unlimited memory store, thus indicating the existence of an encoding bottleneck that limits the “bandwidth” at which we can access this vast storage. The notion of an encoding bottleneck dates back to Atkinson and Shiffrin’s modal model of memory (1968). The model proposed that the short-term memory store—temporary storage for the current contents of the mind—serves as the gateway into long-term memory. Although this model is intuitively appealing, it received a fair amount of criticism due to classic findings that were inconsistent with some of its fundamental assumptions (e.g., Craik & Lockhart, 1972; Ranganath & Blumenfeld, 2005; Shallice & Warrington, 1970). While we do not review this evidence extensively, one of the most critical blows was the doubt concerning the assumed role of temporary memory maintenance in LTM encoding. According to the modal model, durable LTM representations are formed incrementally during temporary maintenance in the short-term memory store. However, later studies demonstrated direct contradictions to this key assumption by manipulating the duration of temporary memory maintenance (e.g., Craik & Lockhart, 1972; Naveh-Benjamin & Jonides, 1984).

For example, Craik and Lockhart (1972) presented a list of words to participants, and they were instructed to rehearse the most recent word that started with the letter “B” (i.e., B-word; e.g., “boy”) until they were presented with the next B-word. This clever manipulation allowed the researchers to control the duration of active maintenance of each B-word by manipulating the lag between B-words. If the modal model’s assumption about the role of maintenance is correct, one would expect that the B-words that were maintained longer would be better remembered than those maintained for a shorter period of time. However, contrary to this prediction, the researchers found no reliable effect of the maintenance duration on LTM encoding. Thus, this finding effectively invalidated the assumed role of temporary maintenance in LTM encoding and led to the development of depth-of-processing perspectives that instead emphasize the nature of encoding processes as the determining factor of LTM encoding (see Craik, 2002 for a review).

While the presumed role of temporary maintenance was invalidated, this does not mean that the temporary memory system (i.e., working memory) plays no

direct role in LTM encoding. Indeed, visual working memory (VWM) may constrain VLTm encoding by limiting the bandwidth of information transfer to VLTm via its severe capacity limit (Forsberg et al., 2020; Fukuda & Vogel, 2019). To test this idea, Fukuda and Vogel (2019) first measured the VWM capacity of healthy young adult participants using a standard color change detection task (Fukuda et al., 2016). Next, participants completed a separate change detection task with pictured arrays of real-world objects. Subsequently, their VLTm for the objects presented during the object change detection task was assessed (Figure 8.1A). If VWM capacity constrains the bandwidth of VLTm encoding, one would expect a robust positive correlation between individuals' VWM capacity and the amount of information encoded into VLTm from the object change detection task. This is precisely what they demonstrated. Across two modes of memory encoding (i.e., incidental encoding and intentional encoding, Figure 8.1B), individuals with higher VWM capacity encoded more objects into their VLTm than those with lower VWM capacity, especially when the number of objects to encode exceeded their VWM capacity (i.e., set size 6).

Although these correlations are consistent with the account that VWM capacity sets the bandwidth for VLTm encoding, correlation does not imply causation. Considering that VWM capacity is robustly correlated with other cognitive abilities involved in VLTm encoding, such as fluid intelligence (e.g., fluid intelligence: Unsworth, 2019; Unsworth et al., 2014) and attention (attention: Adam et al., 2015; deBettencourt et al., 2019; Fukuda et al., 2016), it is entirely possible that the observed correlation between VWM capacity and VLTm encoding reflects shared variance explained by these predictive variables. Thus, to establish a causal role of VWM as a bottleneck for VLTm encoding, one would need to experimentally manipulate VWM encoding success and examine its influence on VLTm encoding. Fukuda and Vogel (2019) did exactly this by interfering with VWM encoding through perceptual masking (e.g., Vogel et al., 2006) and measuring its effect on VLTm encoding. Here, they found that, although the duration of VWM maintenance had a negligible impact on VLTm encoding (e.g., Craik & Lockhart, 1972; Naveh-Benjamin & Jonides, 1984), the parametric corruption of VWM encoding translated into a corresponding impairment in VLTm encoding (Figures 8.1C and 8.1D, see also Cotton & Ricker, 2021). Thus, this result provides direct evidence that the capacity limit for VWM encoding sets the bandwidth on VLTm encoding.

### **Throttling the bandwidth of VLTm encoding**

In the previous section, we reviewed evidence that VLTm encoding is mechanistically constrained by a bandwidth set by VWM capacity. However, we know that VWM performance fluctuates from moment to moment, likely due to temporal fluctuations in attentional control (Adam et al., 2015; deBettencourt et al., 2019; Fukuda et al., 2016). Does this mean that we can voluntarily control VLTm encoding success by throttling its bandwidth? Past studies have examined this possibility by allocating a reward for successfully encoding a given item (Adcock et al., 2006; Gruber & Otten, 2010; Gruber et al., 2013; Miendlarzewska et al., 2016).

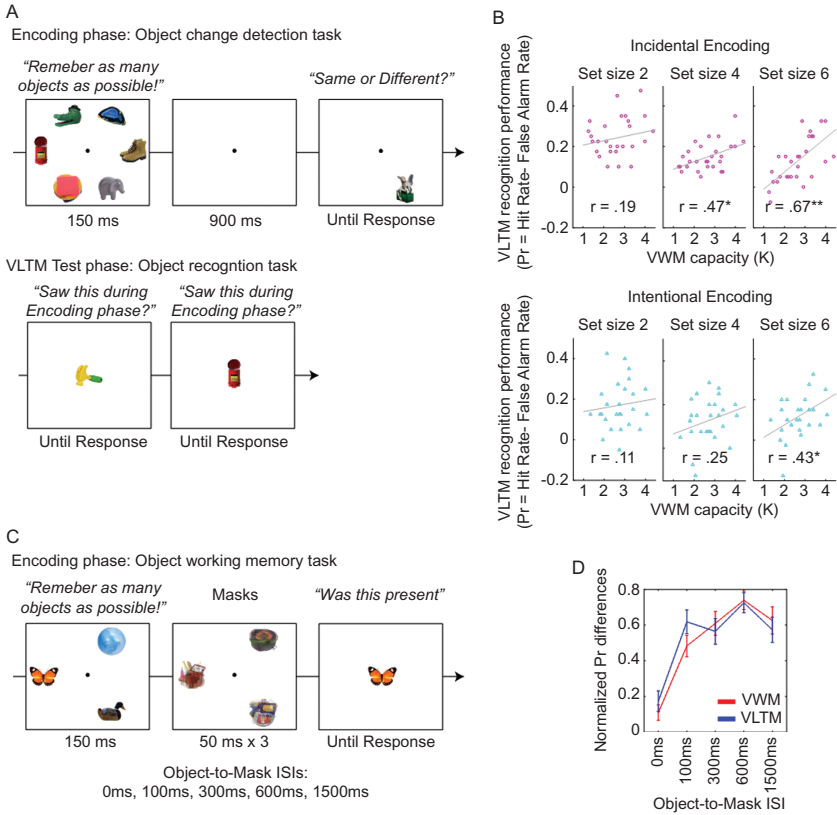


Figure 8.1 VWM determines the “bandwidth” of VLTM encoding. Panel A represents the schematic of Experiments 1a and b in Fukuda and Vogel (2019). In the Encoding phase, participants performed an object change detection task with set sizes 2, 4, or 6 (set size 6 depicted). Participants were briefly (150 ms) presented with an array of objects that they were instructed to remember over a 900 ms-long retention interval. Afterwards, participants saw one test object at one of the locations previously occupied in the preceding array and reported whether or not the test object was the same as the original object at that location. After encoding hundreds of objects during the object change detection task, VLTM for each presented object was assessed using a 2AFC (Old/New) recognition test. As can be seen in Panel B, individuals’ VWM capacity (separately assessed in a standard color change detection task) predicted VLTM recognition performance, especially when encoding set sizes exceeded the conventional VWM capacity limit (e.g., set size 6). This pattern of results was observed regardless of participants’ intentions to encode the objects into their VLTM (incidental encoding; Top row scatter plots; intentional encoding: Bottom row scatter plots). Panel C depicts the object working memory task employed in Experiment 5 of Fukuda and Vogel (2019) to parametrically modulate the quality of VWM representations. Participants were briefly presented with three objects to remember over a brief retention interval. Importantly, after the objects were perceptually attended to for a fixed amount of time (150 ms), three consecutive presentations of mask arrays followed (50 ms/presentation), with each array containing three mask stimuli. The object-to-mask inter-stimulus

(Continued)

Figure 8.1 (Continued)

intervals (ISIs) were manipulated to disrupt VWM encoding in a parametric manner. After the retention interval, one object appeared at the center of the screen, and participants judged whether it was one of the objects in the original array. After encoding hundreds of objects during the object working memory task, participants' VLTm was tested using a 2AFC (Old/New) recognition test. As can be seen in Panel D, the normalized performance on the VLTm recognition task dovetailed the parametric disruption of VWM performance. These findings illustrate the causal role of VWM encoding in VLTm encoding. (Figures adapted from Fukuda and Vogel, 2019.)

These studies have shown that items predicting a future reward result in better VLTm encoding than those that do not. Although such findings are consistent with the idea that we are capable of voluntarily up-regulating memory encoding, it is unclear whether this up-regulation was genuinely voluntary or if it was driven by the external reward.

To address this, more recent studies have simply asked participants to “try harder” to encode a subset of visual stimuli (Sundby et al., 2019; Tozios & Fukuda, 2019). For example, Sundby and colleagues (2019) presented participants with a sequence of pictures of real-world objects that were each preceded by a central fixation cue. A majority of the objects were preceded by a black central fixation cue (baseline cue) that instructed participants to remember the upcoming object. Importantly, for a subset of objects, the preceding fixation cue turned green (up-regulation cue) to instruct participants to “try harder” or to up-regulate memory encoding of the impending stimulus (Figure 8.2A). When their VLTm was subsequently tested, recognition memory performance was reliably higher for objects that were preceded by an up-regulation cue than those preceded by a baseline cue (Figure 8.2B). To examine the neural underpinnings of this voluntary memory up-regulation, the researchers examined EEG signals recorded during encoding. Here, they confirmed that two previously established EEG signals sensitive to memory encoding success, namely frontal positivity (e.g., Friedman & Johnson, 2000; Fukuda & Woodman, 2015) and occipital alpha suppression (e.g., Fukuda & Woodman, 2015; Hanslmayr et al., 2009), were modulated in accordance with the behavioral effect. Specifically, frontal positivity became more positive and occipital alpha power was further suppressed following an up-regulation cue as opposed to a neutral cue (Figure 8.2C).

While the above findings provide compelling evidence of the ability to throttle VLTm encoding, voluntary up-regulation represents only one side of memory regulation that is desirable in our everyday life. We sometimes encounter visual information that we prefer *not* to remember (e.g., a spoiler of a movie that you plan to watch this weekend), and in some cases, remembering such unwanted information can cause a detrimental influence on our everyday functioning (e.g., traumatic scenes from a traffic accident). This raises the question of whether we are also capable of down-regulating memory encoding voluntarily. A large body of literature on the directed forgetting paradigm suggests that it may be possible to intentionally “not remember” specific information (see Anderson & Hanslmayr, 2014 for a

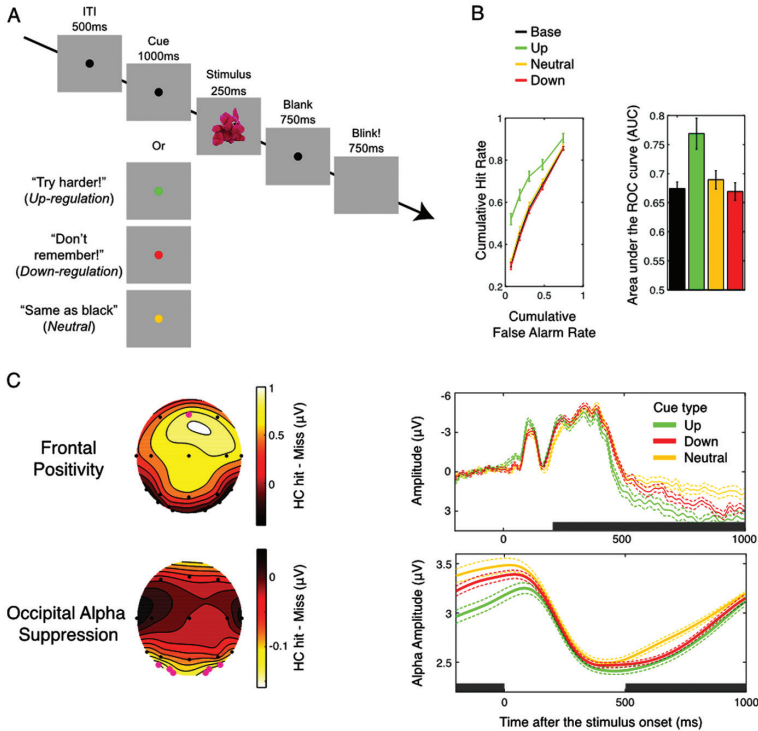


Figure 8.2 Voluntary control of VLTM encoding is asymmetric. Panel A shows the encoding task used in Sundby et al. (2019). Participants were presented with 900 pictures to encode. Critically, 100 pictures were preceded by an up-regulation cue that prompted participants to “try harder” to encode the up-coming picture. Another 100 pictures were preceded by a down-regulation cue that prompted participants to “not encode” the up-coming picture. Another 100 followed a neutral cue that instructed participants to encode them in the same manner as the remaining 600 pictures (baseline). This neutral cue served as a perceptual control for up- and down-regulation conditions. After the encoding phase, participants’ VLTM for each object was assessed by a 6AFC recognition test (*definitely old, probably old, maybe old, maybe new, probably new, definitely new*). As can be seen in Panel B, the results revealed a robust voluntary up-regulation of VLTM encoding ( $AUC_{\text{up-regulation}} > AUC_{\text{neutral}} = AUC_{\text{baseline}}$ ) with no evidence for voluntary down-regulation ( $AUC_{\text{down-regulation}} = AUC_{\text{neutral}} = AUC_{\text{baseline}}$ ). To obtain converging evidence from neural correlates of VLTM encoding success, the researchers examined the consequence of voluntary memory control on two EEG correlates that dovetail subsequent memory effects, namely the frontal positivity and the occipital alpha suppression. Panel C depicts the topographical distributions of the two subsequent memory effects based on the high confidence (HC) hit-miss contrast. The magenta dots show the predetermined channels of interest for the measurement. When we examined the effect of voluntary memory control on the two EEG correlates in predetermined measurement windows (shown in gray bars), we found reliable up-regulation in both the frontal positivity (upper panel) and occipital alpha suppression (lower panel) following the up-regulation cue, but no reliable down-regulation was observed following the down-regulation cue. (Figures adapted from Sundby et al., 2019.)

review). However, since the directed forgetting effect is demonstrated by comparing the memory performance for “cued-to-remember” items to “cued-to-forget” items, it is not clear whether the demonstrated difference in memory performance is driven by down-regulation of memory encoding for “cued-to-forget” items or by up-regulation of memory encoding for “cued-to-remember” items.

To address this, Sundby and colleagues (2019) also presented a cue that instructed participants to “not remember” the impending stimulus (i.e., down-regulation cue, Figure 8.2A). Here, they found that, although cued-to-down-regulate items were recognized more poorly than cued-to-up-regulate items, cued-to-down-regulate items were recognized just as well as the baseline items (Figure 8.2B). The two neural correlates of memory encoding (i.e., frontal positivity and occipital alpha power suppression) corroborated this behavioral effect, demonstrating no evidence of down-regulation of cued-to-down-regulate items compared to baseline items (Figure 8.2C). These results suggest that the directed forgetting effect is a result of voluntary up-regulation of cued-to-remember items rather than voluntary down-regulation of cued-to-forget items, and thus questions our ability to voluntarily and directly down-regulate encoding of VLTMs (Figure 8.2; see also Gao et al., 2016; Zwissler et al., 2015).

### **Indirect, but strategic, down-regulation of VLTMs encoding**

Though recent studies have demonstrated that it is difficult to directly down-regulate the encoding of visual memories, is it entirely impossible to voluntarily not remember unwanted visual information? One possibility is that down-regulation of memory encoding can occur indirectly by biasing attentional allocation away from unwanted information and towards other information that is encoded simultaneously (Desimone & Duncan, 1995; Shapiro & Miller, 2011). To test this, Tozios and Fukuda (2019) presented participants with pairs of real-world objects to remember (Figure 8.3A). Each object pair was preceded by a pair of encoding cues that independently prompted voluntary up- or down-regulation of memory encoding for each object in the impending pair. More precisely, in the baseline condition, both of the items were preceded by black cues, thus instructing participants to remember both objects. In the up-regulation condition, one of the items was preceded by a green cue, thus promoting up-regulation of the cued item, while the accompanying item was preceded by a black baseline cue. In the down-regulation condition, one of the items was preceded by a red cue, thus instructing down-regulation of the specific item, while the accompanying item was preceded by a black baseline cue. In the double-cue condition, one of the stimuli was preceded by a green cue while the other was preceded by a red cue, prompting up- and down-regulation respectively.

When the researchers examined the impact of direct memory control, they replicated the previous findings by Sundby and colleagues (2019): Stimuli preceded by up-regulation cues were better remembered than those preceded by baseline cues. In contrast, stimuli preceded by down-regulation cues were remembered no worse than those preceded by baseline cues. Interestingly, direct up-regulation of



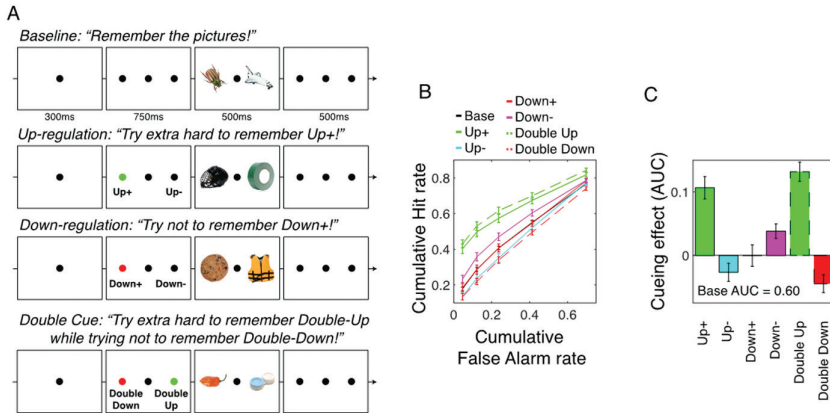


Figure 8.3 Indirect down-regulation of VLM encoding. Panel A represents the encoding task used in Tozios and Fukuda (2019). Participants were presented with a pair of objects to remember. In the up-regulation condition, one of the objects was preceded by an up-regulation cue that prompted participants to “try extra hard” to encode the upcoming object at the cued location. In the down-regulation condition, one of the objects was preceded by a down-regulation cue that prompted participants to “try not” to encode the upcoming object at the cued location. In the double cue condition, participants were presented with both up- and down-regulation cues and followed the corresponding instructions. After encoding hundreds of pictures, participants’ VLM was assessed by a 6AFC recognition test (*definitely old, probably old, maybe old, maybe new, probably new, definitely new*). As can be seen in Panels B and C, asymmetric memory control was observed. Participants demonstrated reliable voluntary up-regulation of memory encoding (i.e., positive cueing effects for Up+ and Double Up conditions). However, no evidence of direct down-regulation of memory encoding was observed (i.e., lack of negative cueing effects for Down+ condition). Interestingly, direct up-regulation of memory encoding resulted in indirect down-regulation of memory encoding for accompanying information (i.e., negative cueing effects for Up- and Double Down conditions). This suggests that memory encoding of unwanted visual information can be indirectly achieved by up-regulating memory encoding of accompanying visual information. (Figures adapted from Tozios and Fukuda, 2019.)

memory encoding for an object inflicted a negative side-effect on the encoding of the accompanying object in the pair. That is, a baseline stimulus that accompanied a cued-to-up-regulate stimulus was remembered worse than a baseline stimulus accompanied by another baseline stimulus. This suggests that voluntary up-regulation of memory encoding in part reflects biased attentional allocation towards cued-to-up-regulate information and away from accompanying information (Desimone & Duncan, 1995; Shapiro & Miller, 2011).

Can individuals take advantage of this biased attentional allocation to indirectly down-regulate the encoding of unwanted memories? If so, memory encoding for a cued-to-down-regulate stimulus should be worse than that for the baseline items when the cued-to-down-regulate stimulus is accompanied by a cued-to-up-

regulate stimulus. This indirect down-regulation was indeed what was found by Tozios and Fukuda (2019; Figures 8.3B and 8.3C). However, this strategic down-regulation was only induced when the memory regulation cues were presented prior to the onset of stimuli. When the cues were provided *after* stimulus offset (i.e., retro-cueing), no evidence of indirect memory suppression was found despite a robust direct up-regulation of memory encoding for cued-to-up-regulate items. This suggests that direct up-regulation of memory encoding is supported by dissociable mechanisms: One that capitalizes on biased allocation of spatial attention during perception and another that leverages sustained attentional processes after encoding. Of note, this dissociable impact of spatial and sustained attention on VLTm encoding has since received additional independent support (deBettencourt et al., 2020). In contrast, the inability to indirectly down-regulate VLTm encoding after VWM encoding reveals a critical window for competition-based down-regulation of VLTm encoding.

### **The impact of retrieval practice on VLTm**

We have described studies illustrating that voluntary control of memory encoding is asymmetric, such that our ability to down-regulate VLTm encoding is rather limited compared to our ability to up-regulate it. Fortunately, previous work has demonstrated that the window of memory control is not limited to encoding and that memories can be modulated through the act of retrieval practice after they are encoded (e.g., Anderson & Hanslmayr, 2014; Nader & Hardt, 2009; Roediger & Butler, 2011; Schacter et al., 2011). Next, we review some recent work that examines the nature and extent of retrieval-based control of VLTm.

Retrieval practice effects, or testing effects, refer to the improved access to LTM representations due to practicing memory retrieval (e.g., Roediger & Butler, 2011). This effect is highly robust and has been documented using a variety of stimuli, including word pairs (e.g., Pyc & Rawson, 2009), picture-word pairs (e.g., Wheeler & Roediger III, 1992), and education-relevant materials (e.g., Roediger & Karpicke, 2006). However, due to the discrete nature of traditional retrieval assessments (e.g., verbal recall tasks, recognition tasks with coarsely sampled foils), it has not been clear whether the benefits of retrieval practice are limited to improved accessibility of VLTm or whether they extend to improved representational fidelity.

To test this, Sutterer and Awh (2016) had participants encode hundreds of colored objects into their VLTm. Object colors were sampled from a well-validated circular distribution (Wilken & Ma, 2004; Zhang & Luck, 2008). Subsequently, half of the objects were presented in a retrieval practice phase, in which a grayscale object was presented and participants estimated its original color on a circular color wheel. Following the retrieval practice phase, participants performed a final recall task in which they estimated the color of all objects with the same estimation procedure as the retrieval practice. When the estimation performance was analyzed using a mixture modeling procedure that allows for the independent estimation of memory accessibility and precision (Suchow et al., 2013; Zhang &

Luck, 2008), they found that although a single opportunity to practice retrieval robustly enhanced the accessibility of a VLTm representation, it did not improve the precision of the representation. A follow-up experiment demonstrated that this retrieval-induced benefit was statistically larger than the benefit obtained by an additional opportunity to re-encode the colored object, thus paralleling the findings established in the verbal memory literature (Roediger & Karpicke, 2006).

In stark contrast to the findings discussed above, related work has illustrated that retrieval practice does not always improve subsequent memory retrieval. For example, retrieval-induced forgetting states that retrieval of a given memory results in the suppression of other memories that are semantically related (Anderson et al., 1994; Storm & Levy, 2012). While retrieval-induced forgetting has traditionally been characterized using recall procedures with verbal stimuli, Maxcey and Woodman (2014) have since extended this work to a recognition memory paradigm with visual stimuli (Recognition-induced forgetting, Chapter 9; Maxcey & Woodman, 2014).

Broadly speaking, the recognition-induced forgetting paradigm is composed of three phases. In the encoding phase, participants encode multiple exemplars of different objects (e.g., pictures of guitar A and guitar B, pictures of teddy bear A and teddy bear B, etc.). In the retrieval practice phase, participants are presented with some of the exemplars from some of the object categories (e.g., a picture of guitar A) as well as new exemplars of the same object (e.g., a picture of guitar C), and have to judge whether or not they have seen the particular exemplars. This makes guitar A a practiced exemplar and guitar B a related exemplar. Importantly, exemplars from some initially encoded object categories (e.g., teddy bears) are never presented during this retrieval practice phase, making them baseline exemplars. Finally, in the recognition phase, participants are presented with all the exemplars from the encoding phase, as well as novel exemplars of the studied objects, and have to judge whether or not the exemplars were displayed during the encoding phase. A typical finding in this paradigm is that, unsurprisingly, practiced exemplars (e.g., guitar A) are better recognized than baseline exemplars (e.g., teddy bears A and B). More critically, however, findings also reveal that the related exemplars (e.g., guitar B) are recognized more poorly than the baseline exemplars. This demonstrates that the visual memories of related exemplars were rendered less accessible through the act of recognizing the practiced exemplars during the retrieval practice phase. This pattern of recognition-induced forgetting has further been demonstrated in multiple developmental cohorts (children: Maxcey & Bostic, 2015; older adults: Maxcey et al., 2016) and is shown to occur with social visual stimuli as well (i.e., human faces, Rugo et al., 2017) (Figure 8.4).

More recent studies have begun to elucidate the underlying cognitive mechanisms of recognition-induced forgetting. First, recognition-induced forgetting is shown to operate by a shared semantic relationship between exemplars as opposed to a shared episodic relationship. That is, recognizing object A triggers the forgetting of object B if A and B are semantically related (e.g., two examples of the same object). However, if the relationship between the two objects is solely defined by episodic co-occurrence (i.e., two different objects that are part of the same epi-

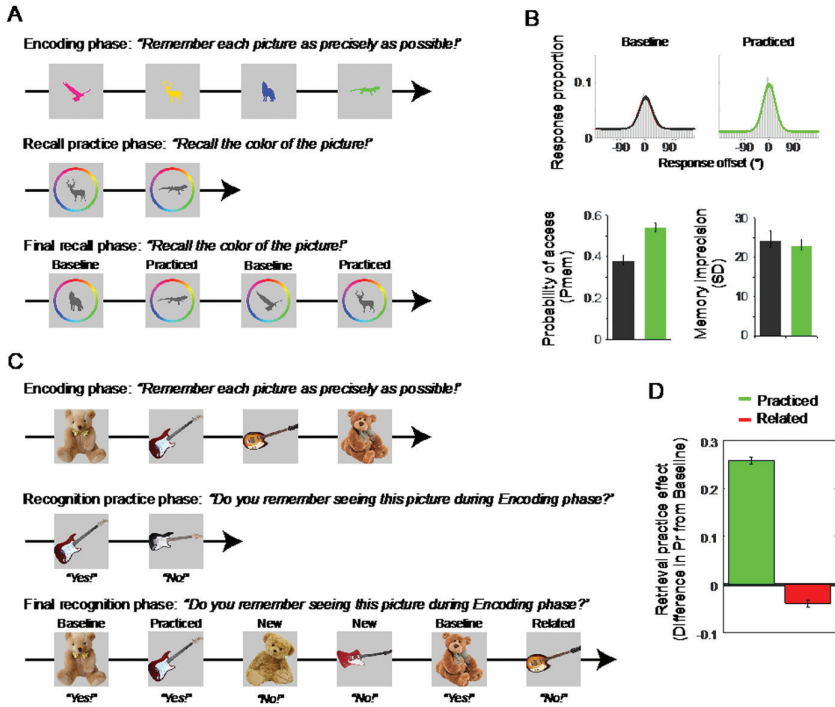


Figure 8.4 Retrieval-based control of VLTm. Panel A shows the schematic of Sutterer and Awh (2016). Participants encoded a series of colored clip art pictures. Subsequently, they practiced recalling the precise color of a subset of the encoded clip art by selecting the encoded color on the color wheel. Finally, participants recalled the precise color of all the clip art in the same manner as the recall practice. Panel B shows the aggregate response offset distributions for the final recall phase for baseline items and practiced items. When the probability of memory access and memory precision were extracted by fitting a standard mixture model (Suchow et al., 2013; Zhang & Luck, 2008), recall practice was found to selectively enhance the probability of memory access while leaving memory precision unchanged. (Figures adapted from Sutterer and Awh, 2016.) Panel C shows an example schematic of the recognition-induced forgetting paradigm used by Maxcey and Woodman (2014). First, participants encoded multiple exemplars of multiple objects (e.g., teddy bears, guitars). A subset of these objects (e.g., guitars) was then subjected to subsequent recognition practice. Notably, only novel exemplars (e.g., black guitar) and a subset of encoded exemplars (e.g., red guitar) were presented during this practice phase. Finally, participants' recognition memory for all the encoded objects (e.g., both guitar and teddy bear exemplars) were assessed. As can be seen in Panel D, practiced exemplars (e.g., red guitar) were better recognized than exemplars in the baseline category (e.g., teddy bear), but related exemplars (e.g., brown guitar) were recognized worse than baseline exemplars, thus demonstrating recognition-induced forgetting.

sode or schema), recognizing object A does not result in the forgetting of object B (Maxcey et al., 2018; Scotti et al., 2020). Second, recognition-induced forgetting does not require re-exposure to previously encoded exemplars during retrieval practice (Fukuda et al., 2020). Specifically, correct rejection of novel exemplars of an encoded object was sufficient to induce forgetting of related exemplars of the same object. This finding effectively demonstrates that it is not just re-exposure of previously encoded exemplars that induces forgetting. Rather, accessing VLTM for correct endorsement as well as rejection of previous encounters causes recognition-induced forgetting. Taken together, both retrieval-practice effects and retrieval-induced forgetting confirm that, in addition to memory encoding, memory retrieval provides additional window for regulating VLTM.

### **Current and future directions**

As we have briefly reviewed in this chapter, the last decade or so has been particularly fruitful for VLTM research. Seminal studies have re-confirmed the massive capacity of VLTM and revealed its surprisingly high representational quality. These scientific advances have enabled researchers to re-evaluate the mechanistic constraints that limit our access to this virtually unlimited store. Furthermore, researchers elucidated the nature and extent of our cognitive control over VLTM by adopting and expanding the theories established by non-visual LTM research. However, we can be confident that the coming years will continue to offer new and exciting discoveries surrounding the rich contributions of VLTM to our everyday cognition. Below, we suggest several research questions that will be critical for guiding this future progress.

### **What happens after VWM encoding?**

Fukuda and Vogel (2019) demonstrated the direct involvement of VWM in determining VLTM encoding success, but not all information that gets encoded into VWM is necessarily granted access to VLTM storage (Forsberg et al., 2020). What variables then determine which VWM representations are successfully stored in VLTM? One possibility is that the likelihood of VLTM encoding success is determined by moment-to-moment fluctuations in the quality of internal processing that each VWM representation goes through (e.g., levels of processing, Craik, 2002). However, recent studies have demonstrated that moment-to-moment fluctuations in internal processing might not be sufficient to fully explain the encoding success of visual memories. Instead, the success of visual memory encoding may in part be determined by stimulus-intrinsic factors (i.e., memorability, Chapter 10; Bainbridge et al., 2017; Bainbridge et al., 2013; Isola et al., 2014). Recent studies have confirmed that this intrinsic memorability of certain stimuli cannot be ascribed to a small set of low-level visual features (e.g., color hue, saturation, value, Isola et al., 2014) and is also dissociable from memory encoding and retrieval success at the neural level (Bainbridge et al., 2017; Bainbridge & Rissman, 2018). Future studies should assess how internal processing interacts with stimulus-driven

factors to determine the successful transfer of VWM representations into VLTm storage (Bainbridge, 2020).

### **Dissociating the up-regulation of VLTm accessibility and precision**

Recent studies have confirmed that we are capable of voluntarily up-regulating VLTm encoding. This ability is composed of at least two attentional control mechanisms: One that down-regulates the encoding of other simultaneously presented information, and another that does not (Tozios & Fukuda, 2019). This dissociation nicely maps onto a recent demonstration of the separable impact of sustained attention and spatial attention on VLTm encoding (deBettencourt et al., 2020). Although these studies provide converging evidence for voluntary up-regulation of VLTm encoding, they do not demonstrate whether voluntary memory up-regulation results from enhanced accessibility or enhanced precision of VLTm. Thus, future studies should aim to tease apart the effect of voluntary up-regulation on these distinct characteristics of VLTm representations.

### **The feasibility and extent of VLTm down-regulation**

In contrast to voluntary up-regulation of VLTm encoding, direct down-regulation of VLTm encoding has not yet been established. This apparent elusiveness of memory encoding down-regulation may be explained by longer durations needed for our brain to implement down-regulatory control of VLTm encoding than to implement up-regulatory control. Such temporal asymmetry in cognitive control is also observed in selective attention. Specifically, to make use of negative attentional templates (i.e., attentional template for to-be-ignored information), individuals need to use the same template consistently across a long run of trials (Cunningham & Egeth, 2016; Moher & Egeth, 2012). This is in stark contrast to more rapid and flexible updating of positive attentional templates (i.e., attentional template for to-be-searched-for information). Given the tight relationship between attentional control and VLTm encoding, future studies should directly manipulate the latency and trial succession of VLTm down-regulation to examine if direct down-regulation of VLTm encoding is possible when down-regulatory control is maintained over time.

Relatedly, memory retrieval provides an ideal opportunity to down-regulate VLTm representations that have already been encoded. Recognition of some visual memories has been shown to impair the subsequent retrieval of related visual memories (e.g., Maxcey & Woodman, 2014). Although this recognition-induced forgetting has been reliably demonstrated, two key questions remain regarding its underlying mechanism. First, does the induced forgetting occur as a result of impaired accessibility or precision in related VLTm representations? Second, does the induced forgetting impact VLTm accessibility and/or precision temporarily in a specific retrieval context or indefinitely across retrieval contexts? Verbal memory literature suggests that retrieval-induced forgetting is best characterized as a temporary inaccessibility of memory rather than permanent memory loss (see Jonker et al., 2013; Storm & Levy, 2012 for example for different theoretical accounts for

the same results). Future studies should directly examine these questions to elucidate the consequence of retrieval-based down-regulation of VLTm.

Lastly, another fruitful approach to down-regulate the negative consequences of unwanted visual memories may be to distort them rather than to render them inaccessible or less precise. Recent studies have demonstrated that visual memories can be biased towards a novel visual input, especially when the visual input is subjectively judged to be similar to the original memory (Fukuda et al., in press). This similarity-induced memory bias was found to be larger than the bias observed when the same stimuli were perceived, but ignored (Saito et al., 2020). This suggests that similarity-induced memory biases cannot be entirely explained by a stimulus-driven perceptual interference (Rademaker et al., 2015; Sun et al., 2017). Instead, explicit engagement in similarity judgments that compare a memory representation to a novel stimulus may causally modulate the magnitude of the bias. This strategy for distorting memories may be particularly efficacious for producing lasting changes to a memory representation, as biases following explicit similarity judgments have been shown to persist up to 24 hours later (Saito et al., 2021). Future studies should examine the extent to which memories can be distorted to avoid the negative consequences of unwanted visual representations.

## References

- Adam, K. C., Mance, I., Fukuda, K., & Vogel, E. K. (2015). The contribution of attentional lapses to individual differences in visual working memory capacity. *Journal of Cognitive Neuroscience*, 27(8), 1601–1616. [https://doi.org/10.1162/jocn\\_a\\_00811](https://doi.org/10.1162/jocn_a_00811)
- Adcock, R. A., Thangavel, A., Whitfield-Gabrieli, S., Knutson, B., & Gabrieli, J. D. (2006). Reward-motivated learning: Mesolimbic activation precedes memory formation. *Neuron*, 50(3), 507–517. <https://doi.org/10.1016/j.neuron.2006.03.036>
- Anderson, M. C., Bjork, R. A., & Bjork, E. L. (1994). Remembering can cause forgetting: Retrieval dynamics in long-term memory. *Journal of Experimental Psychology – Learning Memory and Cognition*, 20(5), 1063–1087.
- Anderson, M. C., & Hanslmayr, S. (2014). Neural mechanisms of motivated forgetting. *Trends in Cognitive Sciences*, 18(6), 279–292. <https://doi.org/10.1016/j.tics.2014.03.002>
- Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation: Advances in Research and theory* (Vol. 2). Cambridge: Academic Press.
- Bainbridge, W. A. (2020). The resiliency of image memorability: A predictor of memory separate from attention and priming. *Neuropsychologia*, 141, 107408. <https://doi.org/10.1016/j.neuropsychologia.2020.107408>
- Bainbridge, W. A., Dilks, D. D., & Oliva, A. (2017). Memorability: A stimulus-driven perceptual neural signature distinctive from memory. *NeuroImage*, 149, 141–152. <https://doi.org/10.1016/j.neuroimage.2017.01.063>
- Bainbridge, W. A., Isola, P., & Oliva, A. (2013). The intrinsic memorability of face photographs. *Journal of Experimental Psychology: General*, 142(4), 1323–1334. <https://doi.org/10.1037/a0033872>
- Bainbridge, W. A., & Rissman, J. (2018). Dissociating neural markers of stimulus memorability and subjective recognition during episodic retrieval. *Scientific Reports*, 8(1), 8679. <https://doi.org/10.1038/s41598-018-26467-5>
- Balaban, H., Assaf, D., Arad Meir, M., & Luria, R. (2020). Different features of real-world objects are represented in a dependent manner in long-term memory. *Journal of Experimental Psychology: General*, 149(7), 1275–1293. <https://doi.org/10.1037/xge0000716>

- Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(38), 14325–14329. <https://doi.org/10.1073/pnas.0803390105>
- Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2013). Real-world objects are not represented as bound units: Independent forgetting of different object details from visual memory. *Journal of Experimental Psychology: General*, *142*(3), 791–808. <https://doi.org/10.1037/a0029649>
- Brady, T. F., Konkle, T., Gill, J., Oliva, A., & Alvarez, G. A. (2013). Visual long-term memory has the same limit on fidelity as visual working memory. *Psychological Science*, *24*(6), 981–990. <https://doi.org/10.1177/0956797612465439>
- Cotton, K., & Ricker, T. J. (2021). Working memory consolidation improves long-term memory recognition. *Journal of Experimental Psychology – Learning Memory and Cognition*, *47*(2), 208–219. <https://doi.org/10.1037/xlm0000954>
- Craik, F. I. M. (2002). Levels of processing: Past, present . . . and future? *Memory*, *10*(5/6), 305–318.
- Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*(6), 671–684. [https://doi.org/10.1016/S0022-5371\(72\)80001-X](https://doi.org/10.1016/S0022-5371(72)80001-X)
- Cunningham, C. A., & Egeth, H. E. (2016). Taming the White Bear: Initial costs and eventual benefits of distractor inhibition. *Psychology Science*, *27*(4), 476–485. <https://doi.org/10.1177/0956797615626564>
- deBettencourt, M. T., Keene, P. A., Awh, E., & Vogel, E. K. (2019). Real-time triggering reveals concurrent lapses of attention and working memory. *Nature Human Behaviour*, *3*(8), 808–816. <https://doi.org/10.1038/s41562-019-0606-6>
- deBettencourt, M. T., Williams, S. D., Vogel, E. K., & Awh, E. (2020). Sustained attention and spatial attention distinctly influence long-term memory encoding. *bioRxiv*. <https://doi.org/10.1101/2020.09.14.297341>
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222. <https://doi.org/10.1146/annurev.ne.18.030195.001205>
- Forsberg, A., Guitard, D., & Cowan, N. (2020). Working memory limits severely constrain long-term retention. *Psychonomic Bulletin and Review*. <https://doi.org/10.3758/s13423-020-01847-z>
- Friedman, D., & Johnson, R. (2000). Event-related potential (ERP) studies of memory encoding and retrieval: A selective review. *Microscopy Research and Technique*, *51*(1), 6–28. [https://doi.org/10.1002/1097-0029\(20001001\)51:1<6::AID-JEMT2>3.0.CO;2-R](https://doi.org/10.1002/1097-0029(20001001)51:1<6::AID-JEMT2>3.0.CO;2-R)
- Fukuda, K., Pall, S., Chen, E., & Maxcey, A. M. (2020). Recognition and rejection each induce forgetting. *Psychonomic Bulletin and Review*. <https://doi.org/10.3758/s13423-020-01714-x>
- Fukuda, K., Pereira, A. E., Saito, J. M., Tang, T., Tsubomi, H., & Bae, G.-Y. (in press). Working memory content is distorted by its use in perceptual comparisons. *Psychological Science*. <https://doi.org/10.1177/09567976211055375>
- Fukuda, K., & Vogel, E. K. (2019). Visual short-term memory capacity predicts the "bandwidth" of visual long-term memory encoding. *Memory and Cognition*. <https://doi.org/10.3758/s13421-019-00954-0>
- Fukuda, K., & Woodman, G. F. (2015). Predicting and improving recognition memory using multiple electrophysiological signals in real time. *Psychology Science*, *26*(7), 1026–1037. <https://doi.org/10.1177/0956797615578122>
- Fukuda, K., Woodman, G. F., & Vogel, E. K. (2016). Individual differences in visual working memory capacity: Contributions of attentional control to storage. In P. Jolicouer, C. Lefebvre & J. Martinez-Trujillo (Eds.), *Mechanisms of sensory working memory: Attention and performance XXV* (Vol. 1). Elsevier.



- Gao, H., Cao, B., Zhang, Q., Qi, M., Li, F., & Li, H. (2016). Intending to forget is not easy: Behavioral and electrophysiological evidence. *International Journal of Psychophysiology*, *104*, 1–9. <https://doi.org/10.1016/j.ijpsycho.2016.03.007>
- Gruber, M. J., & Otten, L. J. (2010). Voluntary control over prestimulus activity related to encoding. *Journal of Neuroscience*, *30*(29), 9793–9800. <https://doi.org/10.1523/JNEUROSCI.0915-10.2010>
- Gruber, M. J., Watrous, A. J., Ekstrom, A. D., Ranganath, C., & Otten, L. J. (2013). Expected reward modulates encoding-related theta activity before an event. *Neuroimage*, *64*, 68–74. <https://doi.org/10.1016/j.neuroimage.2012.07.064>
- Hanslmayr, S., Spitzer, B., & Bäuml, K. H. (2009). Brain oscillations dissociate between semantic and nonsemantic encoding of episodic memories. *Cerebral Cortex*, *19*(7), 1631–1640. <https://doi.org/10.1093/cercor/bhn197>
- Isola, P., Xiao, J., Parikh, D., Torralba, A., & Oliva, A. (2014). What makes a photograph memorable? *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *36*(7), 1469–1482. <https://doi.org/10.1109/TPAMI.2013.200>
- Jonker, T. R., Seli, P., & MacLeod, C. M. (2013). Putting retrieval-induced forgetting in context: An inhibition-free, context-based account. *Psychological Review*, *120*(4), 852–872. <https://doi.org/10.1037/a0034246>
- Konkle, T., Brady, T. F., Alvarez, G. A., & Oliva, A. (2010). Scene memory is more detailed than you think: The role of categories in visual long-term memory. *Psychological Science*, *21*(11), 1551–1556. <https://doi.org/10.1177/0956797610385359>
- Maxcey, A. M., & Bostic, J. (2015). Activating learned exemplars in children impairs memory for related exemplars in visual long-term memory. *Visual Cognition*, *23*(5), 643–658. <https://doi.org/10.1080/13506285.2015.1064052>
- Maxcey, A. M., Bostic, J., & Maldonado, T. (2016). Recognition practice results in a generalizable skill in older adults: Decreased intrusion errors to novel objects belonging to practiced categories. *Applied Cognitive Psychology*, *30*(4), 643–649. <https://doi.org/10.1002/acp.3236>
- Maxcey, A. M., Glenn, H., & Stansberry, E. (2018). Recognition-induced forgetting does not occur for temporally grouped objects unless they are semantically related. *Psychonomic Bulletin and Review*, *25*(3), 1087–1103. <https://doi.org/10.3758/s13423-017-1302-z>
- Maxcey, A. M., & Woodman, G. F. (2014). Forgetting induced by recognition of visual images. *Visual Cognition*, *22*(6), 789–808. <https://doi.org/10.1080/13506285.2014.917134>
- Miendlarzewska, E. A., Bavelier, D., & Schwartz, S. (2016). Influence of reward motivation on human declarative memory. *Neuroscience and Biobehavioral Reviews*, *61*, 156–176. <https://doi.org/10.1016/j.neubiorev.2015.11.015>
- Moher, J., & Egeth, H. E. (2012). The ignoring paradox: Cueing distractor features leads first to selection, then to inhibition of to-be-ignored items. *Attention, Perception and Psychophysics*, *74*(8), 1590–1605. <https://doi.org/10.3758/s13414-012-0358-0>
- Nader, K., & Hardt, O. (2009). A single standard for memory: The case for reconsolidation. *Nature Reviews Neuroscience*, *10*(3), 224–234. <https://doi.org/10.1038/nrn2590>
- Naveh-Benjamin, M., & Jonides, J. (1984). Maintenance Rehearsal: A Two-Component Analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*(3), 369–385. <https://doi.org/10.3758/s13421-018-0835-3>
- Pyc, M. A., & Rawson, K. A. (2009). Testing the retrieval effort hypothesis: Does greater difficulty correctly recalling information lead to higher levels of memory? *Journal of Memory and Language*, *60*(4), 437–447. <https://doi.org/10.1016/j.jml.2009.01.004>
- Rademaker, R. L., Bloem, I. M., De Weerd, P., & Sack, A. T. (2015). The impact of interference on short-term memory for visual orientation. *Journal of Experimental Psychology – Human Perception and Performance*, *41*(6), 1650–1665. <https://doi.org/10.1037/xhp0000110>
- Ranganath, C., & Blumenfeld, R. S. (2005). Doubts about double dissociations between short- and long-term memory. *Trends in Cognitive Sciences*, *9*(8), 374–380. <https://doi.org/10.1016/j.tics.2005.06.009>

- Roediger, H. L., & Butler, A. C. (2011). The critical role of retrieval practice in long-term retention. *Trends in Cognitive Sciences*, 15(1), 20–27. <https://doi.org/10.1016/j.tics.2010.09.003>
- Roediger, H. L., & Karpicke, J. D. (2006). Test-enhanced learning: Taking memory tests improves long-term retention. *Psychology Science*, 17(3), 249–255. <https://doi.org/10.1111/j.1467-9280.2006.01693.x>
- Rugo, K. F., Tamler, K. N., Woodman, G. F., & Maxcey, A. M. (2017). Recognition-induced forgetting of faces in visual long-term memory. *Attention, Perception and Psychophysics*, 79(7), 1878–1885. <https://doi.org/10.3758/s13414-017-1419-1>
- Saito, J. M., Duncan, K., & Fukuda, K. (2021). Comparing visual memories to novel visual input risks lasting memory distortion. *PsychiatryArxiv*. <https://doi.org/10.31234/osf.io/xr4su>
- Saito, J. M., Kolisnyk, M., & Fukuda, K. (2020). Perceptual comparisons modulate memory biases induced by overlapping visual input. *PsychiatryArxiv*. <https://doi.org/10.31234/osf.io/dqng3>
- Schacter, D. L., Guerin, S. A., & St Jacques, P. L. (2011). Memory distortion: An adaptive perspective. *Trends in Cognitive Sciences*, 15(10), 467–474. <https://doi.org/10.1016/j.tics.2011.08.004>
- Scotti, P. S., Janakiefski, L., & Maxcey, A. M. (2020). Recognition-induced forgetting of schematically related pictures. *Psychonomic Bulletin and Review*, 27(2), 357–365. <https://doi.org/10.3758/s13423-019-01693-8>
- Shallice, T., & Warrington, E. K. (1970). Independent functioning of verbal memory stores: A neuropsychological study. *Quarterly Journal of Experimental Psychology*, 22(2), 261–273. <https://doi.org/10.1080/0033557043000203>
- Shapiro, K. L., & Miller, C. E. (2011). The role of biased competition in visual short-term memory. *Neuropsychologia*, 49(6), 1506–1517. <https://doi.org/10.1016/j.neuropsychologia.2011.02.017>
- Storm, B. C., & Levy, B. J. (2012). A progress report on the inhibitory account of retrieval-induced forgetting. *Memory and Cognition*, 40(6), 827–843. <https://doi.org/10.3758/s13421-012-0211-7>
- Suchow, J. W., Brady, T. F., Fougny, D., & Alvarez, G. A. (2013). Modeling visual working memory with the MemToolbox. *Journal of Visualization*, 13(10). <https://doi.org/10.1167/13.10.9>
- Sun, S. Z., Fidalgo, C., Barense, M. D., Lee, A. C. H., Cant, J. S., & Ferber, S. (2017). Erasing and blurring memories: The differential impact of interference on separate aspects of forgetting. *Journal of Experimental Psychology: General*, 146(11), 1606–1630. <https://doi.org/10.1037/xge0000359>
- Sundby, C. S., Woodman, G. F., & Fukuda, K. (2019). Electrophysiological and behavioral evidence for attentional up-regulation, but not down-regulation, when encoding pictures into long-term memory. *Memory and Cognition*, 47(2), 351–364. <https://doi.org/10.3758/s13421-018-0871-z>
- Sutterer, D. W., & Awh, E. (2016). Retrieval practice enhances the accessibility but not the quality of memory. *Psychonomic Bulletin and Review*, 23(3), 831–841. <https://doi.org/10.3758/s13423-015-0937-x>
- Tozios, C. J. I., & Fukuda, K. (2019). Indirect, but not direct, down-regulation of visual long-term memory encoding through strategic biasing of attentional allocation. *Journal of Experimental Psychology: General*. <https://doi.org/10.1037/xge0000712>
- Unsworth, N. (2019). Individual differences in long-term memory. *Psychological Bulletin*, 145(1), 79–139. <https://doi.org/10.1037/bul0000176>
- Unsworth, N., Fukuda, K., Awh, E., & Vogel, E. K. (2014). Working memory and fluid intelligence: Capacity, attention control, and secondary memory retrieval. *Cognitive Psychology*, 71, 1–26. <https://doi.org/10.1016/j.cogpsych.2014.01.003>

- Vogel, E. K., Woodman, G. F., & Luck, S. J. (2006). The time course of consolidation in visual working memory. *Journal of Experimental Psychology – Human Perception and Performance*, 32(6), 1436–1451. <https://doi.org/10.1037/0096-1523.32.6.1436>
- Wheeler, M. A., & Roediger III, H. L. (1992). Disparate effects of repeated testing: Reconciling Ballard's (1913) and Bartlett's (1932) results. *Psychological Science*, 3(4), 240–246. <https://doi.org/10.1111/j.1467-9280.1992.tb00036.x>
- Wilken, P., & Ma, W. J. (2004). A detection theory account of change detection. *Journal of Visualization*, 4(12), 1120–1135. <https://doi.org/10.1167/4.12.11>
- Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, 453(7192), 233–235. <https://doi.org/10.1038/nature06860>
- Zwissler, B., Schindler, S., Fischer, H., Plewnia, C., & Kissler, J. M. (2015). 'Forget me (not)?' – Remembering forget-items versus un-cued items in directed forgetting. *Frontiers in Psychology*, 6, 1741. <https://doi.org/10.3389/fpsyg.2015.01741>