Cognition 238 (2023) 105489

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Tracing the emergence of the memorability benefit

Greer Gillies [a,b,c], Hyun Park [a,c], Jason Woo [a], Dirk B. Walther [c], Jonathan S. Cant [b,c], Keisuke Fukuda [a,c,*]

[a] University of Toronto, Mississauga, Canada
[b] University of Toronto, Scarborough, Canada
[c] University of Toronto, Canada

A R T I C L E I N F O

Keywords:
Visual working memory
Memorability
Visual long-term memory

A B S T R A C T

Some visual stimuli are consistently better remembered than others across individuals, due to variations in memorability (the stimulus-intrinsic property that determines ease of encoding into visual long-term memory (VLTM)). However, it remains unclear what cognitive processes give rise to this mnemonic benefit. One possibility is that this benefit is imbued within the capacity-limited bottleneck of VLTM encoding, namely visual working memory (VWM). More precisely, memorable stimuli may be preferentially encoded into VLTM because fewer cognitive resources are required to store them in VWM (efficiency hypothesis). Alternatively, memorable stimuli may be more competitive in obtaining cognitive resources than forgettable stimuli, leading to more successful storage in VWM (competitiveness hypothesis). Additionally, the memorability benefit might emerge post-VWM, specifically, if memorable stimuli are less prone to be forgotten (i.e., are “stickier”) than forgettable stimuli after they pass through the encoding bottleneck (stickiness hypothesis). To test this, we conducted two experiments to examine how memorability benefits emerge by manipulating the stimulus memorability, set size, and degree of competition among stimuli as participants encoded them in the context of a working memory task. Subsequently, their memory for the encoded stimuli was tested in a VLTM task. In the VWM task, performance was better for memorable stimuli compared to forgettable stimuli, supporting the efficiency hypothesis. In addition, we found that when in direct competition, memorable stimuli were also better at attracting limited VWM resources than forgettable stimuli, supporting the competitiveness hypothesis. However, only the efficiency advantage translated to a performance benefit in VLTM. Lastly, we found that memorable stimuli were less likely to be forgotten after they passed through the encoding bottleneck imposed by VWM, supporting the “stickiness” hypothesis. Thus, our results demonstrate that the memorability benefit develops across multiple cognitive processes.

1. Tracing the emergence of the memorability benefit

Humans have a remarkable ability to store large numbers of images in visual long-term memory (VLTM), in high detail and often only after a single exposure (Brady, Konkle, Alvarez, & Oliva, 2008; Standing, 1973). Despite this, not all visual information is remembered equally well (Fukuda & Woodman, 2015; Sundby, Woodman, & Fukuda, 2019; Tozios & Fukuda, 2020). This variability in VLTM encoding success has traditionally been studied using a subject-centric framework, characterizing the efficacy of the types and quality of the memory encoding processes each individual performs (Craik & Lockhart, 1972; Fukuda & Woodman, 2015; Ovalle-Fresa, Uslu, & Rothen, 2021). However, this subject-centric approach only captures a part of the variability in VLTM encoding success, as it ignores stimulus-intrinsic factors that influence memory encoding success consistently across individuals (e.g., Bainbridge, Dilks, & Oliva, 2017; Bainbridge, Isola, & Oliva, 2013; Isola, Xiao, Torralba, & Oliva, 2011). Recent studies have demonstrated that some stimuli are more likely to be remembered than other stimuli across different individuals despite idiosyncratic differences in the types and quality of VLTM encoding processes each individual may experience. This inter-individual consistency in VLTM encoding success has been used to demonstrate the existence of stimulus-intrinsic properties that renders an image memorable or forgettable (e.g., Isola et al., 2011; Bainbridge et al., 2013; Bainbridge et al., 2017; Bainbridge et al., 2022). As such, some stimuli are more memorable (have a higher probability to be recognized on a memory test post-encoding) than other stimuli.

* Corresponding author at: Dept. of Psychology, University of Toronto Mississauga, 3359 Mississauga Rd, Ontario L5L 1C, Canada.
E-mail address: keisuke.fukuda@utoronto.ca (K. Fukuda).

https://doi.org/10.1016/j.cognition.2023.105489
Received 27 April 2022; Received in revised form 10 April 2023; Accepted 3 May 2023
Available online 8 May 2023

2. What contributes to stimulus memorability?

What makes a stimulus memorable or forgettable? Work by Isola et al. (2011, 2013) demonstrated that memorability cannot be deduced to a simple set of perceptual, social, and semantic features. More precisely, when controlling for low-level features such as colour and spatial frequency or high-level properties like emotion, attractiveness, or scene content, differences in memorability continue to persist (Bainbridge et al., 2017). For images of faces, a combination of social and personality attributes (e.g., facial attractiveness, trustworthiness) can only explain around 25% of the overall variance in memory performance (Bainbridge et al., 2013). Memorability is also separable from cognitive phenomena shown to influence memory, such as attentional capture. More precisely, memorable stimuli do not automatically capture attention, as they do not "pop out" in a visual search task more than forgettable stimuli (Bainbridge, 2020). This finding argues against a hypothesis that memorability can be explained by the perceptual salience of stimuli.

Voluntary memory control also fails to explain stimulus memorability. That is, the effect of encoding instructions (e.g., remember or forget the stimulus) does not interact with the effect of stimulus memorability (Bainbridge, 2020). In other words, memorable stimuli are not stimuli that observers "try to encode" voluntarily.

Memorability's impact on VLTM encoding success does not seem to entirely rely on the low or high-level features that make up the stimulus, nor on bottom-up or top-down attentional control. If so, then at what cognitive processes is the memorability benefit imbued?

3. How does the memorability benefit emerge?

Although memorability has been documented across a wide range of stimuli (e.g., Bainbridge et al., 2013; Isola et al., 2011; Saito, Kolisnyk, & Fukuda, 2021), no study thus far has examined how the benefit of memorability (or the cost of "forgettability") is imbued to a memory representation of a stimulus as it is encoded into and maintained within VLTM. In other words, at what stage of VLTM encoding do memory representations of memorable stimuli become distinguishable from their forgettable counterparts? To answer this question, we need to consider the processes through which visual information is encoded into VLTM and monitor through which processes the difference in memory performance emerges between memorable and forgettable stimuli. According to prominent memory encoding models, VLTM encoding is gated by the capacity-limited visual working memory (VWM) system. In other words, VWM capacity sets the bandwidth for VLTM encoding (Atkinson & Shiffrin, 1968; Cotton & Ricker, 2001; Forsberg, Guitard, & Cowan, 2020; Fukuda & Vogel, 2019). This model has been validated by demonstrating that performance variations in a VWM task within and across individuals can predict subsequent VLTM performance for stimuli encoded during the VWM task. More precisely, individuals with high VWM capacities recognized stimuli that were encoded during a VWM task better than low-capacity individuals (Forsberg et al., 2020; Fukuda & Vogel, 2019). Furthermore, parametric disruption of VWM encoding with post-perceptual masks has a directly transferable impact on subsequent VLTM performance for the corresponding stimuli (Cotton & Ricker, 2021; Fukuda & Vogel, 2019).

Given this relationship between VWM and VLTM, there are two non-mutually exclusive mechanisms through which the memorability benefit may emerge as stimuli go through this capacity-limited VWM gateway. First, memorable stimuli might be more efficiently represented in VWM because they require less cognitive resources to process than forgettable stimuli (i.e., efficiency hypothesis). As a result, more memorable stimuli could be maintained in VWM at a given time and thus pass through the gateway to VLTM compared to forgettable stimuli. Second, the memorable stimuli may have a competitive edge in obtaining the cognitive resources required to be represented in VWM compared to forgettable stimuli (i.e., competitiveness hypothesis). In this case, memorable stimuli would have a higher chance of being represented within VWM than forgettable stimuli, especially when memorable and forgettable stimuli are in direct competition to be represented within VWM.

If VWM is where all memorability benefits emerge, then the performance benefit accrued within VWM should "lock in" the memorability benefit, and there should be no additional benefit imbued to memorable stimuli over forgettable stimuli after they pass through the VWM bottleneck. Alternatively, the memorability benefit may continue to develop after visual information passes through the capacity-limited gateway of VWM. Specifically, memorable stimuli may be less prone to forgetting than forgettable stimuli, thus making memorable stimuli "stickier" in VLTM (i.e., stickiness hypothesis). If so, even after equating the differences in VWM performance, memorable stimuli may be better retained in VLTM than forgettable stimuli.

4. Current study

In the current study, we examined how the memorability benefit emerges by quantifying how much visual information passes through VWM and "sticks" in VLTM. To see if the manner in which the benefit emerges generalizes across different types of stimuli, participants encoded human faces in Experiment 1, and real-world objects in Experiment 2 into their VLTM. Participants encoded memorable and forgettable stimuli and then performed a VWM recognition task. To test the efficiency hypothesis, participants encoded either memorable *or* forgettable stimuli at different set sizes (Pure 3 Memorable, Pure 3 Forgettable, Pure 6 Memorable, Pure 6 Forgettable). To examine competition between memorable and forgettable stimuli, participants also encoded memorable *and* forgettable stimuli within the same trial (Mixed Memorable and Mixed Forgettable, both conditions were composed of three memorable *and* three forgettable stimuli). After a VWM recognition task, participants then performed a VLTM recognition task for the stimuli encoded in the VWM task.

To preview our results, we found support for both the efficiency and competitiveness hypotheses, as memorable stimuli were not only maintained more efficiently in VWM (participants recognized more memorable stimuli compared to forgettable) but were also more competitive in attracting cognitive resources for VWM maintenance (memorable stimuli had an advantage when competing with forgettable stimuli for cognitive resources). However, only the efficiency benefit, but not the competitiveness benefit, was translated to VLTM performance. This suggests that the memorability benefit in VLTM is mainly driven by the improved efficiency that memorable stimuli enjoy in VWM maintenance. Additionally, we also found support for the stickiness hypothesis, showing that memorability is not entirely imbued within VWM, but continues to develop after VWM, with memorable stimuli being more resistant to forgetting or interference (i.e., were "stickier") than forgettable stimuli.

5. Method

5.1. Participants

For Experiment 1, we recruited 156 psychology students from the University of Toronto Mississauga (mean age = 19.61 years, SD = 3.645, 105 females). Each participant provided electronic consent to the protocol approved by the Research Ethics Board of the University of Toronto prior to participation and received a course credit in a partial fulfilment of a requirement for an undergraduate psychology course. All participants reported fluency in English, normal or corrected-to-normal vision, no colour blindness, no history of head injury, and no history of mental illness/condition.

For Experiment 2, we used Prolific (Prolific, 2021) to recruit 156 young adults (mean age = 24.35 years; SD = 3.521; 92 females) who resided in the U.S. or Canada at the time of the experiment. Each participant provided electronic consent to the protocol approved by the Research Ethics Board of the University of Toronto prior to participation and received monetary compensation for their participation (7.50 pounds/h). All participants reported fluency in English, normal or corrected-to-normal vision, no colour blindness, no history of head injury, no history of mental illness/condition, and no cognitive impairment/Dementia. Additionally, all participants had to have successfully completed 90% or more of the studies that they had participated in on prolific (i.e., Approval rate > 90%). This means that the individuals who took part in our study had completed multiple other studies on Prolific and had very rarely been rejected (< 10%) from other studies.

We did not exclude any participants from either Experiment (i.e., no participant was excluded because they were not following task instructions and were responding randomly, and all participants performed above chance in at least the VWM task). The performance in the VWM task for both experiments was comparable to previous studies that were conducted in-person in the laboratory (e.g., Fukuda & Vogel, 2019).

5.2. Stimuli

For Experiment 1, we first selected the top 468 memorable face images and the top 468 forgettable face images from Bainbridge et al. (2013) (see Fig. 1). The memorability for each image was operationalized as the mean difference in the hit rate and the false alarm rate. Here, hit rate is defined as the probability of saying “old” when being shown a previously seen (old) stimulus. False alarm rate is defined as the probability of saying “old” when being shown a never-before-seen (new) stimulus. Consequently, miss rate is defined as the probability of saying

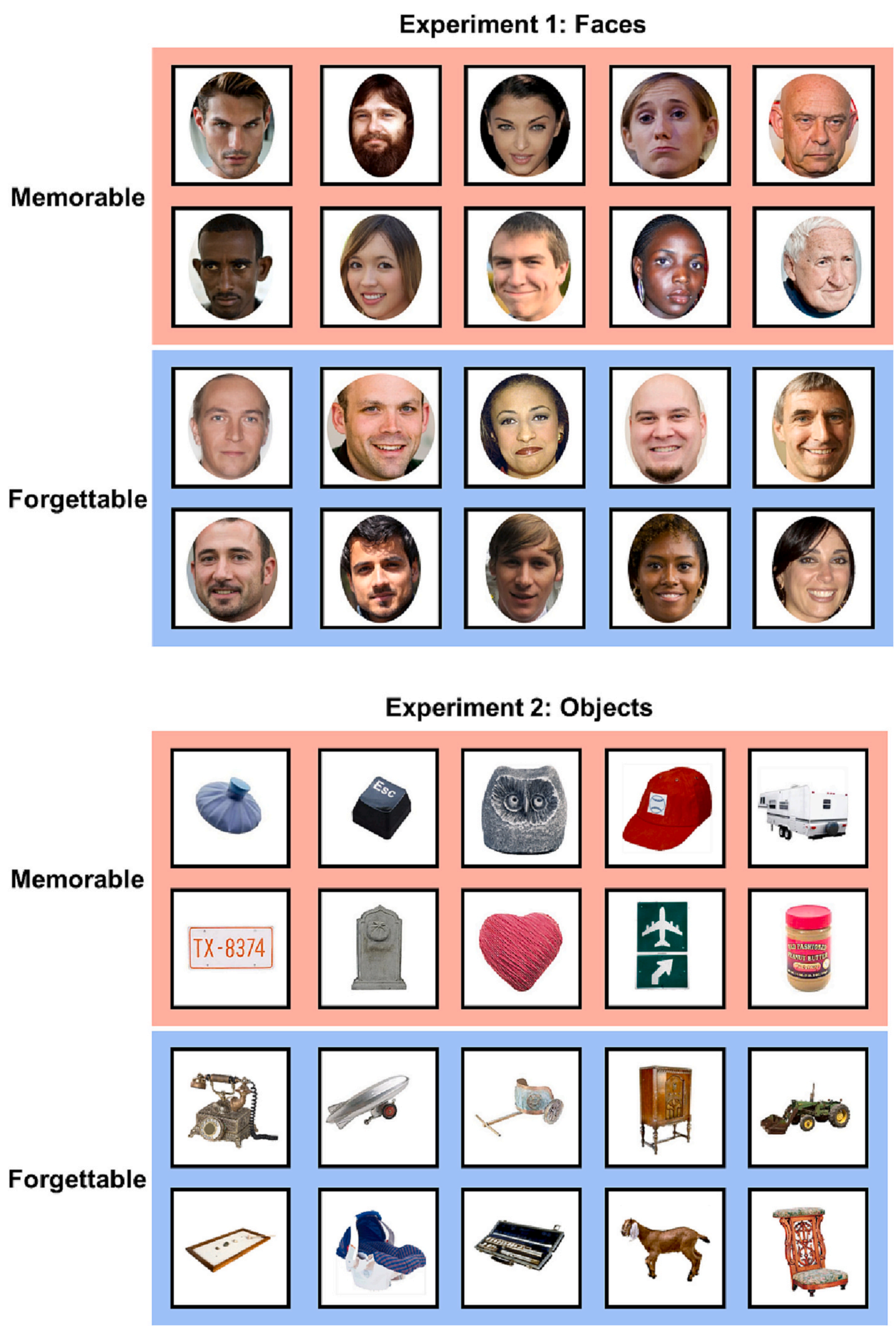

Fig. 1. Sample stimuli.

"new" when shown an old item, and correct rejection rate is the probability of saying "new" when shown a new item.

For each stimulus memorability group, we manually created 39 sets of 12 images such that each set has a similar mean memorability score. All stimulus sets are publicly posted at the Open Science Framework website (https://osf.io/jgqh7/). This set up ensured that each stimulus was encoded in each condition (a description of all 6 conditions is given in the Procedure section) by four participants, which we will describe in the Stimulus Rotation section.

For Experiment 2, we first selected the top 234 memorable object images and the top 234 forgettable object images from Saito et al. (2021) (see Fig. 1). The memorability for each image was operationalized as the difference in mean recognition response (1 = "Definitely Old", 2 = "Probably Old", 3 = "Maybe Old", 4 = "Maybe New", 5 = "Probably New", 6 = "Definitely New") between when the image was presented as an old picture and when it was presented as a new picture. For each stimulus memorability group, we then manually created 39 sets of 6 images so that each set has a similar mean memorability. All stimulus sets are publicly posted at the Open Science Framework website (https://osf.io/jgqh7/). This design ensured that each stimulus was encoded in each condition by four participants, which we will describe in the Stimulus Rotation section below.

An example of the memorable and forgettable face and object stimuli used in Experiment 1 and Experiment 2, respectively.

5.3. Apparatus

The experiments were programmed and run using Inquisit 6 (Inquisit 6, 2020). Since the experiments were conducted online, the computers and monitors participants used were variable. Thus, the size of the stimuli was adjusted according to the monitor size of the participants' computers. More precisely, each stimulus was presented within an imaginary square whose side was 12% the size of the shorter side of their computer monitors.

5.4. Procedure

In Experiments 1 and 2, participants performed the VWM task (see Fig. 2) followed by the VLTM recognition task (see Fig. 3). Each task was preceded by one block of practice trials to familiarize the participants with each task (VWM task: 8 trials; VLTM task: 4 trials).

VWM Task. Importantly, participants were informed that their memory for the stimuli presented during the VWM task would be tested in a subsequent task. Thus, the VWM task also served as an intentional VLTM encoding task (Forsberg et al., 2020; Fukuda & Vogel, 2019).

Each trial started with a 500 ms presentation of a fixation cross at the center of the screen, and an instruction to maintain fixation. Subsequently, a memory array consisting of either three or six stimuli arranged on an imaginary circle was presented for 2000 ms, and participants were instructed to remember as many of them as possible over a 1000 ms-long retention interval. After the retention interval, one test stimulus was presented at the center of the screen along with a 6-point Likert scale below the stimulus, and participants clicked on one of the six options (1 = Definitely Old, 2 = Probably Old, 3 = Maybe Old, 4 = Maybe New, 5 = Probably New, 6 = Definitely New) to indicate their confidence in whether they had seen the test stimulus in the preceding memory array (Old) or not (New). The test stimulus was an old stimulus 50% of the time in each condition. In addition, the test stimulus had a 50% chance of being memorable or forgettable (25% of trials were memorable/New, 25% were memorable/Old, 25% were forgettable/New, and 25% were forgettable/Old). After making a response, the word "Ready?" was presented at the center of the screen along with a button below, and participants clicked on the button when they were ready to start the next trial.

In Experiment 1, participants performed 48 trials each of the Pure 3 Memorable condition (where the memory array consisted of three memorable faces), the Pure 3 Forgettable condition (where the memory array consisted of three forgettable faces), the Pure 6 Memorable condition (where the memory array consisted of six memorable faces), the Pure 6 Forgettable condition (where the memory array consisted of six forgettable faces), the Mixed 6 Memorable condition (where the memory array consisted of thee memorable and three forgettable faces and their working memory for memorable faces was tested), and the Mixed 6 Forgettable condition (where the memory array consisted of thee memorable and three forgettable faces and their working memory for forgettable faces was tested) in a pseudo-randomized order for a total of 288 trials per participant. Importantly, each old stimulus was presented in two trials in the same encoding condition (e.g., if a face was used as an "old" face from a pure-6 array, it would be used again as an "old" face from a pure-6 array on a later trial).

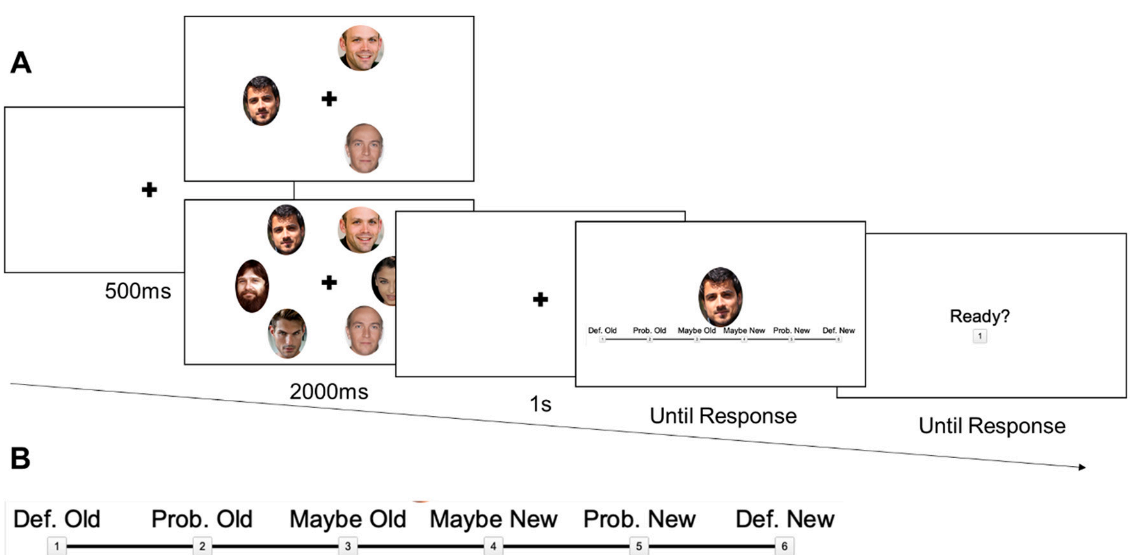

Fig. 2. VWM task.
A) An example of the VWM task procedure using the face stimuli from Experiment 1. Participants saw three or six stimuli in the middle of the screen and were then shown a test face and were asked to indicate if they had seen that face before (old) or not (new) and how confident they were. B) An enlarged schematic of the rating scale participants used to indicate their memory confidence. This same rating scale was also used in the VLTM task.

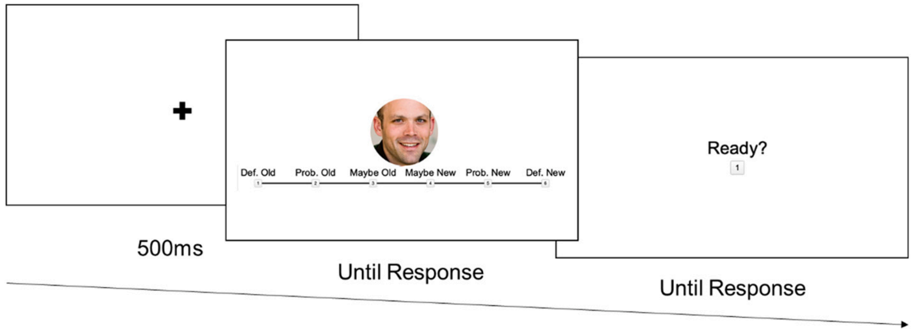

Fig. 3. VLTM Task.

Experiment 2 was identical to Experiment 1 except that the stimuli were pictures of real-world objects and participants performed 24 trials each for the same set of conditions (for a total of 144 trials/participant) because the stimulus set was half the size of the set used in Experiment 1.

VLTM Task. Each trial started with a 500 ms fixation cross at the center of the screen, which was followed by a test stimulus at the center of the screen, along with a 6-point Likert scale below the stimulus, both of which remained on the screen until the participant made a response. The participants' task was to judge whether they had seen the test face (Experiment 1) or object (Experiment 2) during the VWM task (Old) or not (New) by clicking one of the following options: 1 = Definitely Old, 2 = Probably Old, 3 = Maybe Old, 4 = Maybe New, 5 = Probably New, 6 = Definitely New. After a response, the word "Ready?" was presented at the center of the screen along with a button below, and participants clicked on the button when they were ready to start the next trial. Participants saw 144 old and 144 new faces for a total of 288 trials in Experiment 1, and 72 old and 72 new objects for a total of 144 trials (half memorable and half forgettable for both old and new objects) in Experiment 2 in a pseudo-random order.

An example of the VLTM task procedure using the face stimuli from Experiment 1. Participants were shown a stimulus in the middle of the screen and were asked to indicate if they had seen that stimulus at any point during the VWM task (old) or not (new) and were asked to indicate how confident they were.

5.5. Stimulus rotation

To ensure that each stimulus contributed equally to the estimation of memory performance in each condition, we systematically rotated the stimulus set assignment across participants by assigning one of 39 total seed numbers to each participant. For example, for seed 1 participants (n = 4), all the memory arrays for the pure set size 3 conditions (i.e., Pure 3 Memorable and Pure 3 Forgettable) were composed of one item drawn from sets 1–2, another item drawn from sets 3–4, and the last item drawn from sets 5–6. If the trial was an "Old" trial, the item drawn from sets 1–2 was presented as the test item. The item drawn from sets 3–4 was saved for the VLTM recognition task. The item drawn from sets 5–6 was never tested. On the other hand, if the trial was a "New" trial, one item from sets 7–9 was presented as the test item in the VWM task.

Similarly, the Pure 6 array (i.e., Pure 6 Memorable and Pure 6 Forgettable) was composed of one item each from sets 10–11 and sets 12–13, and four items from sets 14–21. If the trial was an "Old" trial, the item drawn from sets 10–11 was presented as the test item. The item drawn from sets 12–13 was saved for the VLTM recognition test. The four items drawn from sets 14–21 were never tested. If the trial was a "New" trial, one item from set 22–24 was used in the VWM task.

For the mixed array trials (i.e., Mixed 6 Memorable and Mixed 6 Forgettable), the memory array was composed of one item each from sets 25–26, sets 27–28, and sets 29–30 from the memorable and forgettable groups. If the trial was an "Old" trial, the test item was the item from sets 25–26 from the corresponding group. The items from sets 27–28 for memorable and forgettable groups were saved for the VLTM recognition test. The items from sets 29–30 were never tested. If the trial was a "New" trial, the test item was drawn from sets 31–33 from the corresponding group in the VWM task.

The remaining items in sets 34–39 for memorable and forgettable groups were presented as new items in the VLTM recognition test.

For each seed value increment, the set was shifted by 1, and by collecting four participants per seed value, each picture was encoded and tested in each condition by four participants.

5.6. Analyses

To confirm that VWM performance predicted VLTM performance, we conducted a series of correlational analyses between VWM and VLTM performance. To quantify memory performance using the same metric for both VWM and VLTM recognition tasks, we used the area under the receiver operating characteristic curves (AUC). The receiver operating characteristic curve is drawn by plotting the cumulative hit rate (the proportion of "old" responses when the stimulus is old) on the y-axis against the cumulative false alarm rate (the proportion of "old" responses when the stimulus is new) on the x-axis from the highest confidence old response (Definitely Old) to the lowest confidence old response (or the highest confidence new response (Definitely New)). The AUC will equal 1 when participants recognized all the encoded information with highest confidence (Definitely Old) and rejected all the new information with highest confidence (Definitely New). On the other hand, when participants cannot discriminate old from new information at all, the AUC will be equal to 0.5. To investigate the efficiency and competitiveness hypotheses, we conducted a series of repeated measures ANOVAs examining the differential impacts of Array Type and Memorability on AUC for both VWM and VLTM.

To compute the proportion with which the amount of information in VWM is retained in VLTM, we defined the memory "stickiness" as (AUC for VLTM task – 0.5) / (AUC for VWM recognition task – 0.5). To investigate the stickiness hypothesis in the context of storage efficiency, we conducted a series of repeated measures ANOVAs examining the differential impacts of Array Type and Memorability on memory stickiness.

6. Results

6.1. VWM performance predicts VLTM performance

First, we tested the hypothesis that VWM serves as a gateway to VLTM encoding by determining the bandwidth of VLTM encoding (Atkinson & Shiffrin, 1968; Cotton & Ricker, 2021; Forsberg et al., 2020; Fukuda & Vogel, 2019). If so, individuals' VWM performance should predict VLTM performance. When we correlated the average VWM performance and the average VLTM recognition performance across all stimuli, we confirmed this prediction for both faces and objects ($r(154) = 0.28$, $p < .001$ for Experiment 1; $r(154) = 0.54$ $p < .001$ for

Experiment 2; see Fig. 4). When we separately examined the relationship for memorable stimuli and forgettable stimuli, the correlations were higher for memorable stimuli ($r(154) = 0.32$, $p < .001$ for Experiment 1; $r(154) = 0.55$, < 0.001 for Experiment 2) than for forgettable stimuli ($r(154) = 0.04$, $p = .58$ for Experiment 1; $r(154) = 0.36$, $p < .001$ for Experiment 2) (*Fisher's Z* $= 2.475$, $p < .01$ for Experiment 1; *Fisher's Z* $= 2.07$, $p < .05$ for Experiment 2). This was expected due to lower VLTM performance for forgettable stimuli. In fact, VWM performance reliably predicted VLTM performance for all stimulus types ($r(154) > 0.31$, $p < .01$) except for forgettable face stimuli whose VLTM performance was at floor (the average AUC for forgettable stimuli was 0.51 for Experiment 1). This result is not necessarily surprising given the difference in the stimulus sets. More precisely, Experiment 1 used stimuli belonging to one category of objects (i.e., faces), whereas Experiment 2 used a more heterogenous stimulus set spanning across multiple categories of objects. Consistent with our findings, past studies demonstrated that memory performance was worse when one has to discriminate a memory representation against a foil from the same category than from a different category (e.g., Awh, Barton, & Vogel, 2007; Fukuda, Vogel, Mayr, & Awh, 2010). Taken together, these results provide confirmatory evidence that VWM determines the bandwidth of VLTM encoding.

6.2. Testing the efficiency hypothesis: memorable stimuli are more efficiently represented in VWM than forgettable stimuli

We first examined whether the memorability benefit emerged due to more efficient VWM maintenance for memorable stimuli than forgettable stimuli (i.e., efficiency hypothesis). If so, VWM performance should be higher for memorable stimuli than for forgettable stimuli. Consistent with this prediction, a 2 (Array Type: Pure 3 and Pure 6) × 2 (Memorability: Memorable and Forgettable) repeated measures ANOVA revealed a significant main effect of Memorability ($F(1, 155) = 143.97$, $p < .001$, $\eta_p^2 = 0.482$ for Experiment 1; $F(1, 155) = 77.942$, $p < .001$, $\eta_p^2 = 0.335$ for Experiment 2) such that memorable stimuli were associated with higher VWM AUC than forgettable stimuli (see Fig. 5). Not surprisingly, there was also a significant main effect of Array Type ($F(1, 155) = 870.57$, $p < .001$, $\eta_p^2 = 0.849$ for Experiment 1; $F(1, 155) = 366.49$, $p < 0001$, $\eta_p^2 = 0.70$ for Experiment 2), confirming the well-established capacity limit of VWM. The interaction between Memorability and Array Type was significant for Experiment 1 ($F(1, 155) = 9.76$, $p = .002$, $\eta_p^2 = 0.06$). Specifically, AUC was more impacted for forgettable stimuli when moving from Pure 3 to Pure 6 than for memorable stimuli. This interaction fell short of statistical significance in Experiment 2 ($F(1, 155) = 3.77$, $p = .054$, $\eta_p^2 = 0.024$).

Next, we confirmed whether the efficiency benefit observed in VWM translated to VLTM. If so, we should observe main effects of both set size and stimulus memorability. As predicted, a 2 (Array Type: Pure 3 and Pure 6) × 2 (Memorability: Memorable and Forgettable) repeated measures ANOVA revealed a significant main effect of Memorability ($F(1, 155) = 203.84$, $p < .001$ $\eta_p^2 = 0.57$ for Experiment 1; $F(1, 155) = 219.76$, $p < .001$, $\eta_p^2 = 0.59$ for Experiment 2) such that memorable stimuli were associated with higher VLTM AUC than forgettable stimuli. There also was a significant main effect of Array Type ($F(1, 155) = 124.70$, $p < .001$, $\eta_p^2 = 0.45$ for Experiment 1; $F(1, 155) = 246.66$, $p < .001$, $\eta_p^2 = 0.61$ for Experiment 2), again replicating the VWM results. The interaction between Memorability and Array Type was significant for Experiment 1 ($F(1, 155) = 38.10$, $p < .001$, $\eta_p^2 = 0.20$). This interaction is likely driven by a floor effect, as memory is nearly at chance for the forgettable face stimuli. The Memorability and Array Type interaction was not significant for Experiment 2 ($F(1, 155) = 2.88$, $p = .092$, $\eta_p^2 = 0.02$), thus mirroring the pattern of results seen in the VWM task. Taken together, we found support for our efficiency hypothesis as

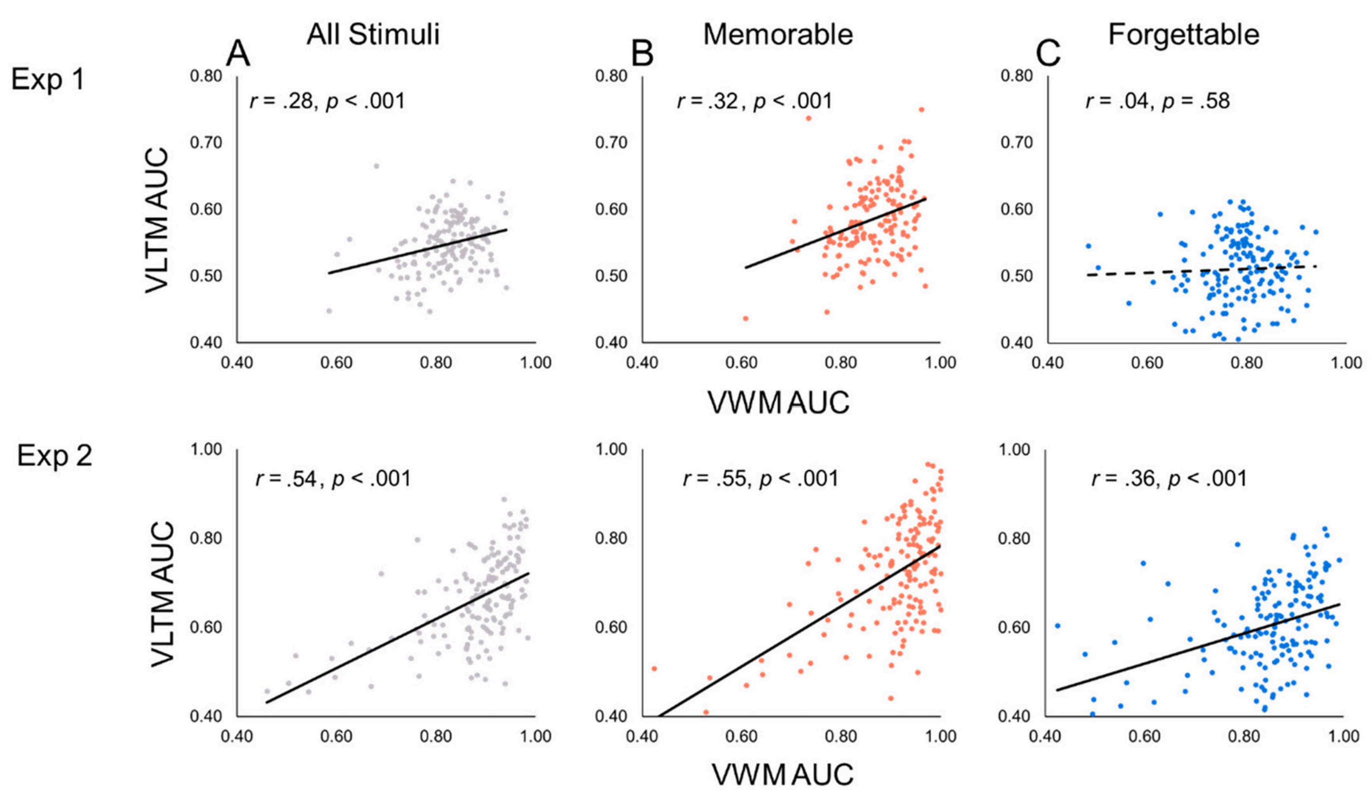

Fig. 4. Predicting VLTM Performance from VWM Performance.
A) The correlation between VWM AUC and VLTM AUC for all stimuli in Experiments 1 (top) and 2 (bottom). B) The correlation between VWM AUC and VLTM AUC for just the memorable stimuli for Experiment 1 (top) and 2 (bottom). C) The correlation between VWM AUC and VLTM AUC for just the forgettable stimuli for Experiment 1 (top) and 2 (bottom).
Solid lines represent significant regressions, dashed lines non-significant regressions.

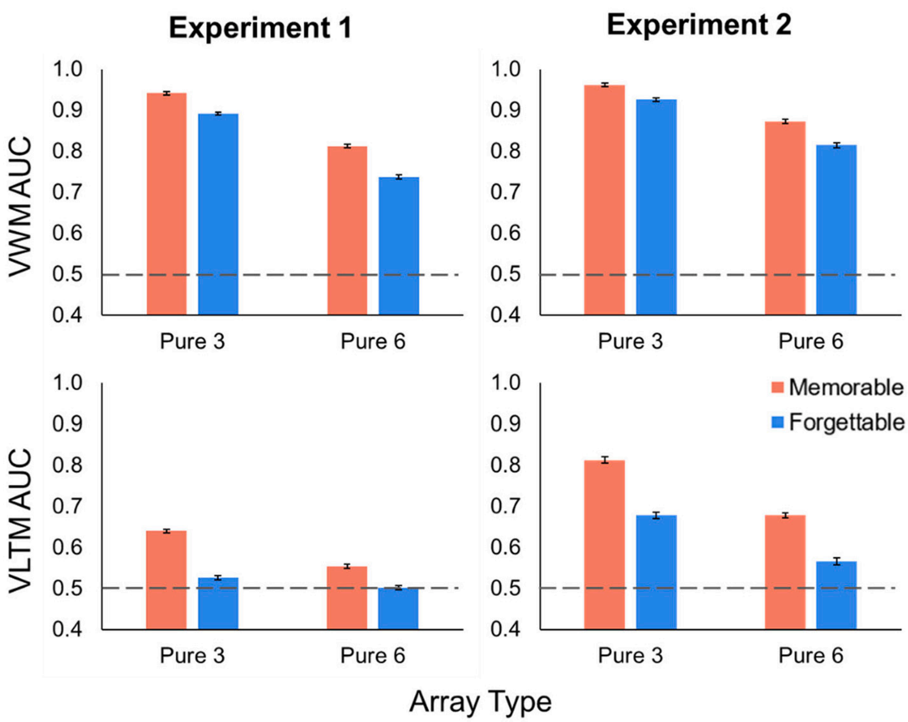

Fig. 5. Testing the efficiency hypothesis.

memorable stimuli were more efficiently represented in the capacity-limited VWM than forgettable stimuli, which then contributed to a memorability benefit in VLTM.

AUC was higher for stimuli encoded from the Pure 3 array compared to the Pure 6 array for the VWM and VLTM tasks for both Experiment 1 and Experiment 2. Importantly, VWM AUC was higher for memorable stimuli compared to forgettable stimuli for Experiment 1 and Experiment 2, providing support for the efficiency hypothesis. VLTM AUC was also higher for memorable compared to forgettable stimuli in both experiments, showing that the efficiency benefit observed in VWM translated to VLTM. The dotted line represents guess rate. Error bars represent Morey's Standard Error of the Mean (SEM) (Morey, 2008).

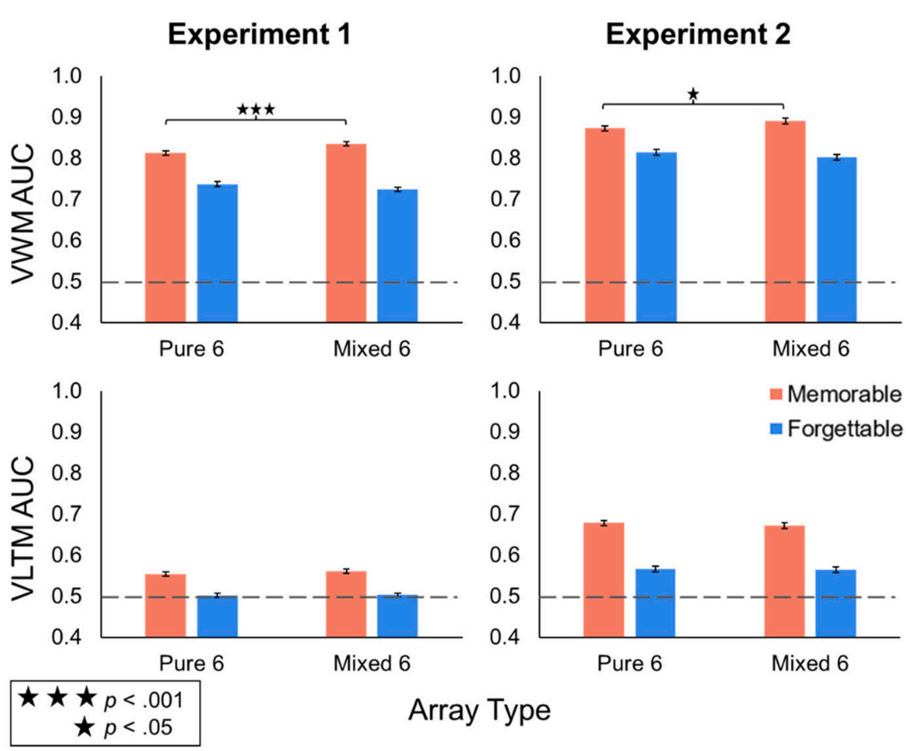

Fig. 6. Testing the competitiveness hypothesis.

6.3. Testing the competitiveness hypothesis: memorable stimuli attract more VWM resources than forgettable stimuli

Next, we tested the competitiveness hypothesis that the memorability benefit arises because memorable stimuli are more competitive in attracting working memory resources than forgettable stimuli. If so, VWM AUC for memorable stimuli should be higher when encoded together with forgettable stimuli than with memorable stimuli. Similarly, forgettable stimuli should be better maintained in VWM when encoded alongside forgettable stimuli compared with memorable stimuli. A 2 (Array type: Pure 6 and Mixed 6) × 2 (Memorability: Memorable and Forgettable) repeated measures ANOVA revealed a significant main effect of Memorability ($F(1, 155) = 313.18$, $p < .001$, $\eta_p^2 = 0.67$ for Experiment 1; $F(1, 155) = 102.50$, $p < .001$, $\eta_p^2 = 0.40$ for Experiment 2), but the main effect of Array type was not significant ($F(1, 155) = 1.06$, $p = .31$, $\eta_p^2 = 0.007$ for Experiment 1; $F(1, 155) = 0.21$, $p = .65$, $\eta_p^2 = 0.001$ for Experiment 2; see Fig. 6). Consistent with our prediction, we observed a significant interaction between Memorability and Array type ($F(1, 155) = 11.775$, $p < .001$, $\eta_p^2 = 0.07$ for Experiment 1; $F(1, 155) = 5.44$, $p = .021$, $\eta_p^2 = 0.03$ for Experiment 2). Planned comparisons revealed that memorable stimuli were significantly better remembered when presented with forgettable stimuli than with memorable stimuli (Mixed 6 Memorable vs. Pure 6 Memorable: $t(155) = 3.66$, $p < .001$, *Cohen's* $d = 0.27$ for Experiment 1, and $t(155) = 2.25$, $p = .026$, *Cohen's* $d = 0.18$ for Experiment 2). However, forgettable stimuli were only numerically better remembered when presented with forgettable stimuli than with memorable stimuli (Pure 6 Forgettable vs. Mixed 6 Forgettable: $t(155) = 1.49$, $p = .14$, *Cohen's* $d = 0.12$ for Experiment 1, and $t(155) = 1.35$, $p = .18$, *Cohen's* $d = 0.11$ for Experiment 2). Though the pattern of forgettable stimuli being better remembered when paired with other forgettable stimuli compared to memorable stimuli is consistent, it did not reach statistical significance. This is likely because the effect of competitiveness is small, and this effect is likely even smaller for the forgettable stimuli given that fewer of them are remembered compared to memorable stimuli. These results demonstrate that memorable stimuli were more competitive in attracting VWM resources than forgettable stimuli.

To see whether the competitive advantage of memorable stimuli in VWM resulted in a reliable benefit for VLTM performance, we repeated the same ANOVA with VLTM AUC. Here, although there was a main effect of Memorability ($F(1, 155) = 78.91$, $p < .001$, $\eta_p^2 = 0.34$ for Experiment 1; $F(1, 155) = 174.48$, $p < .001$, $\eta_p^2 = 0.53$ for Experiment 2), the interaction between Memorability and Array type was not significant ($F(1, 155) = 0.51$, $p = .48$, $\eta_p^2 = 0.003$ for Experiment 1; $F(1, 155) = 0.14$, $p = .71$, $\eta_p^2 = 0.0009$ for Experiment 2). The main effect of Array type was also not significant ($F(1, 155) = 1.02$, $p = .31$, $\eta_p^2 = 0.007$ for Experiment 1; $F(1, 155) = 0.32$, $p = .57$, $\eta_p^2 = 0.002$ for Experiment 2). These results show that the competitiveness advantage of memorable stimuli within VWM was not substantial enough to induce a measurable impact on VLTM performance.

AUC was higher for memorable stimuli than forgettable stimuli for the VWM and VLTM tasks for both Experiment 1 and Experiment 2. Importantly, there was a significant interaction between memorability and array type in VWM. Specifically, VWM AUC for memorable stimuli was higher when the memorable stimuli were encoded with forgettable stimuli compared to when all the stimuli were memorable for both faces (Experiment 1) and real-world objects (Experiment 2), providing support for the competitiveness hypothesis. However, the competitiveness benefit did not transfer to VLTM (no main effect of array type nor an interaction between array type and memorability). The dotted line represents guess rate. Error bars represent Morey's SEM (Morey, 2008).

6.4. Testing the stickiness hypothesis: memorable stimuli are stickier than forgettable stimuli

The results so far demonstrated that the memorability benefit emerged in VWM due to the difference in maintenance efficiency between memorable and forgettable stimuli in VWM, and the competitive advantage of memorable stimuli attracting more processing resources. Next, we examined whether stimulus memorability continued to develop outside of VWM. One possibility is that memorable stimuli are "stickier" than forgettable stimuli in that they are less likely to be forgotten (possibly due to decay or interference) after they leave VWM (i.e., stickiness hypothesis). Consistent with this possibility, a 2 (Array Type: Pure 3 and Pure 6) × 2 (Memorability: Memorable and Forgettable) repeated measures ANOVA on stickiness (i.e., the proportion of memory representations retained in VLTM out of memory representations encoded in VWM; see Analyses section for a definition of how we computed "stickiness") revealed a significant main effect of Memorability ($F(1, 155) = 69.94$, $p < .001$, $\eta_p^2 = 0.31$ for Experiment 1; $F(1, 155) = 136.87$, $p < .001$, $\eta_p^2 = 0.47$ for Experiment 2) such that memorable stimuli were less likely to be forgotten than forgettable stimuli (see Fig. 7). Not surprisingly, there also was a significant main effect of Array Type ($F(1, 155) = 6.71$, $p = .011$, $\eta_p^2 = 0.04$ for Experiment 1; $F(1, 155) = 77.94$, $p < .001$, $\eta_p^2 = 0.34$ for Experiment 2) showing that information encoded in the Array Type 3 condition had a higher chance of being retained in VLTM than those encoded in the Array Type 6 condition. The interaction between Memorability and Array Type was only significant in Experiment 1 ($F(1, 155) = 22.78$, $p < .001$, $\eta_p^2 = 0.13$; $F(1, 155) = 0.83$, $p = .36$, $\eta_p^2 = 0.005$ for Experiment 2), but this was likely driven by the near-floor VLTM performance for forgettable stimuli (see Fig. 5). These results provide support for the stickiness hypothesis.

When we examined the effect of competitive advantage for VWM resources on memory stickiness, a 2 (Array type: Pure 6 and Mixed 6) × 2 (Memorability: Memorable and Forgettable) repeated measures ANOVA revealed a significant main effect of Memorability ($F(1, 155) = 15.59$, $p < .001$, $\eta_p^2 = 0.09$ for Experiment 1; $F(1, 155) = 63.56$, $p < .001$, $\eta_p^2 = 0.29$ for Experiment 2). The main effect of Array type ($F(1, 155) = 0.003$, $p = .95$, $\eta_p^2 = 0.00002$ for Experiment 1; $F(1, 155) = 0.133$, $p = .72$, $\eta_p^2 = 0.0009$ for Experiment 2) as well as its interaction with Memorability were not significant in either experiment ($F(1, 155) = 0.01$, $p = .92$, $\eta_p^2 = 0.00006$ for Experiment 1; $F(1, 155) = 2.24$, $p = .14$, $\eta_p^2 = 0.01$ for Experiment 2). These results suggest that the competitive advantage of memorable stimuli in VWM did not influence their stickiness.

Memorable stimuli were less likely to be forgotten than forgettable stimuli across all array types and for both faces (Experiment 1) and real-world objects (Experiment 2), providing support for the stickiness hypothesis. Stimuli encoded in a Pure 3 array were less likely to be forgotten than stimuli encoded in a Pure 6 array for both Experiment 1 and 2. However, there was no difference in forgetting for stimuli encoded in a Pure 6 array compared to a Mixed 6 array for both Experiment 1 and Experiment 2, and there was also no interaction between array type (i.e., Pure 6 vs. Mixed 6) and memorability. This suggests that a stimulus' competitiveness in VWM did not influence its stickiness in VLTM. Error bars represent Morey's SEM (Morey, 2008).

7. Discussion

Across two experiments, we investigated how a memorability benefit emerges as visual information is encoded into VLTM through VWM. First, we found that observers' performance on the VWM task was predictive of their later VLTM performance, providing additional evidence that VLTM encoding is gated by the capacity-limited VWM (Forsberg et al., 2020; Fukuda & Vogel, 2019). Next, we evaluated two non-mutually exclusive hypotheses that propose that the memorability benefit emerges within VWM, namely the efficiency and competitiveness hypotheses. The efficiency hypothesis posits that memorable stimuli are maintained in VWM with less VWM resources than forgettable stimuli. The competitiveness hypothesis posits that memorable stimuli are more competitive in attracting VWM resources than forgettable stimuli. Overall, we found evidence for both hypotheses.

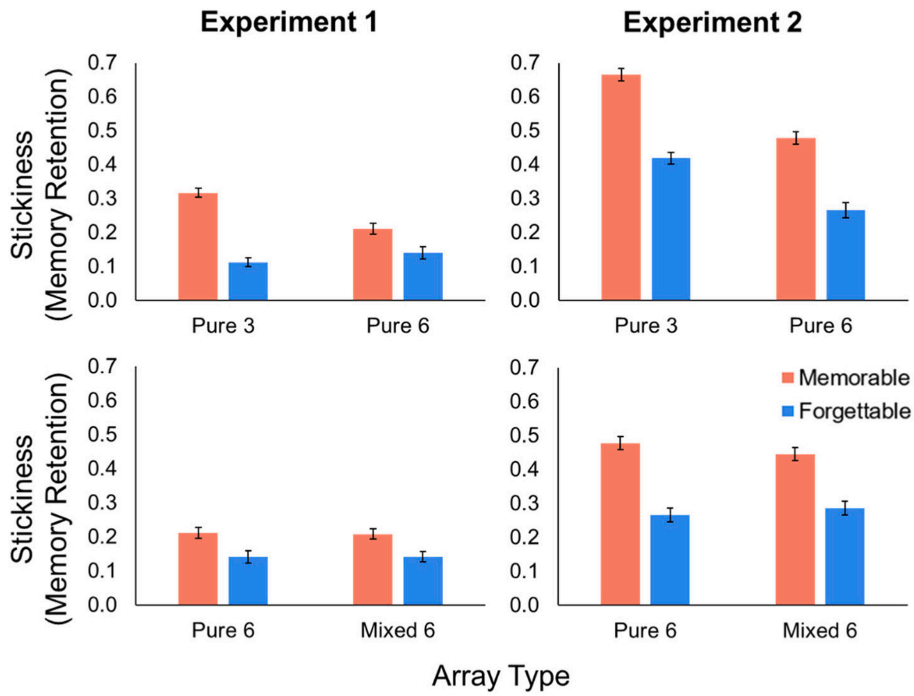

Fig. 7. Testing the stickiness hypothesis.

Memorable stimuli were better remembered within VWM than forgettable stimuli. Furthermore, memorable stimuli were better remembered when presented along with forgettable stimuli than with all memorable stimuli. These results suggest that the memorability benefit does indeed emerge within VWM because memorable stimuli 1) require fewer VWM resources to be maintained in VWM compared to forgettable stimuli; and 2) are also more competitive than forgettable stimuli in attracting limited VWM resources.

If VWM "locks in" the memorability benefit, then we should have seen a near-identical pattern of results for the VLTM task. The efficiency advantage of memorable stimuli did translate to VLTM, as VLTM performance was better for memorable compared to forgettable stimuli. However, the competitive advantage of memorable stimuli in VWM did not translate to LTM. This suggests that the memorability is imbued mainly due to maintenance efficiency in VWM. Within VWM, the efficiency benefit was much larger than the competitive benefit. One possible reason for the competitive benefit not translating to VLTM is that it was a very small effect to begin with. In addition, we also found that memorable stimuli enjoy an additional benefit in comparison to forgettable stimuli after controlling for the difference in VWM performance. That is, memorable stimuli were "stickier" than forgettable stimuli and were less likely to be forgotten post-VWM. This suggests that the memorability benefit develops over multiple stages of memory.

We found some differences in performance between Experiment 1 and Experiment 2. Namely, performance was overall worse for Experiment 1 (which used face stimuli) than Experiment 2 (which used unique object stimuli). This result is in line with previous research that shows that memory performance is worse when one has to discriminate a memory representation against a foil from the same category (Awh et al., 2007; Fukuda et al., 2010).

We chose AUC as our index of memory performance to provide a consistent metric of memory performance for both VWM and VLTM tasks. VWM performance has traditionally been characterized using Cowan's K (Cowan, 2001). To ensure that our results were not only specific to AUC, we computed Cowan's K and found an identical pattern of results (see Supplementary Information). Namely, the increased VWM capacity estimates were due to heightened storage efficiency and competitiveness of memorable stimuli compared to forgettable stimuli. Additionally, since both AUC and Cowan's K combine hit and false alarm rates to characterize memory performance, it is possible that just one of these metrics was responsible for our observed pattern of results. More precisely, it is possible that memorable stimuli are simply more distinctive from one another than forgettable stimuli, thus providing an advantage at the retrieval stage. If so, even though individuals may maintain the same number of stimuli in VWM and VLTM regardless of the memorability, they might be better at discriminating novel stimuli when the stimuli are memorable compared to forgettable. If so, we should only see the effect of memorability on false alarm rates but not on hit rates. When we examined the hit rates and false alarm rates separately, we found that memorability significantly modulated both hit rate and false alarm rate (see Supplementary Information). These results reveal that the memorability benefit cannot be solely ascribed to retrieval advantages such as heightened discriminability of memorable stimuli. Instead, individuals do remember more memorable stimuli than forgettable stimuli.

8. Cognitive mechanisms underlying the efficiency, competitiveness, and stickiness of memorable stimuli

Our results demonstrated that the memorability benefits develop within and outside of VWM. Within VWM, we observed two dissociable benefits, namely, the benefits of efficiency and competitiveness. What are the cognitive mechanisms responsible for these benefits?

8.1. *Efficiency benefit*

For the efficiency benefit for memorable stimuli, one might hypothesize that it reflects existing long-term memory representations that selectively benefit the memorable stimuli. Past studies have demonstrated that existing long-term memory representations can assist working memory performance by alleviating the need for active maintenance of the stimuli within VWM (Carlisle, Arita, Pardo, & Woodman, 2011; Reinhart, McClenahan, & Woodman, 2016). For instance, when one needs to maintain the same visual information in mind across multiple repetitions, the amplitude of the canonical EEG correlate of VWM load (i.e., the contralateral delay activity, or CDA) reduces across the repetitions while the amplitude of the EEG correlate for VLTM contribution (i.e., Anterior P1) amplifies (Carlisle et al., 2011; Reinhart et al., 2016). Additionally, visual information individuals already have corresponding long-term memory representations for are more readily and precisely represented in VWM than VLTM (Bae, Olkkonen, Allred, & Flombaum, 2015; Hedayati, O'Donnell, & Wyble, 2022; Xie & Zhang, 2017, 2018). These findings suggest that existing VLTM representations can help increase the quality and efficiency with which information can be maintained in mind over a short delay. Although we agree with this hypothesis, it cannot explain our findings entirely because both memorable and forgettable stimuli were presented for an equal number of trials during our experiments. While it is possible that our participants had differing past exposures to a consistent subset of the objects used in Experiment 2 (e.g., Nintendo game console vs. a radio from WWII), the overwhelming majority of the memorable faces would have been novel to the participants, and it cannot be expected that participants would have had consistent exposure to these random faces prior to participating in our study (see Fig. X for sample stimuli). Thus, future studies should examine what cognitive mechanisms can allow efficient representations of novel but memorable stimuli.

8.2. Competitive benefit

As for the competitiveness benefit, we speculate that one possible explanation may be differences in attentional allocation at the time of encoding, as attention has been shown to regulate the distribution of VWM resources (Dube, Emrich, & Al-Aidroos, 2017; Yoo, Klyszejko, Curtis, & Ma, 2018). A study by Dube et al. (2017) found that when attentional allocation was manipulated by a probabilistic cue that informed the likelihood of a subsequent memory test, VWM performance varied according to the probabilistic cue such that stimuli that were more likely to be tested were better remembered than those that were less likely to be tested. This allows us to hypothesize that when memorable and forgettable stimuli are presented together, the memorable stimuli are more likely to attract attention, which results in the competitive advantage observed in VWM. However, there is still an open question as to what may attract attention towards memorable stimuli. A recent study suggests that it is unlikely to be differences in perceptual saliency because memorable stimuli do not capture attention in a stimulus-driven manner (Bainbridge, 2020). This suggests that if attentional allocation differs between memorable and forgettable stimuli, it likely happens post-perceptually. Future studies can examine this possibility by manipulating the test likelihood of a stimulus to reduce and amplify the competitive advantage of memorable stimuli over forgettable stimuli.

Of note, the competitiveness benefit observed in VWM did not translate into VLTM although the efficiency benefit did. Although the difference in the magnitude of each benefit in VWM (i.e., efficiency benefit > competitiveness benefit) precludes us from making a strong claim about the qualitative difference between the two benefits, a recent study suggests that these benefits might reflect qualitatively different mechanisms. More precisely, Wakeland-Hart, Cao, deBettencourt, Bainbridge, and Rosenberg (2021) have demonstrated that attentional fluctuation and memorability impact VLTM encoding independently. That is, while memorable stimuli may be able to attract more attention than forgettable stimuli, this attentional allocation does not fully explain their memorability. Future studies should seek more direct evidence by experimentally manipulating the amount of attention allocated to memorable and forgettable stimuli.

8.3. Stickiness

Lastly, our results revealed that memorable stimuli were "stickier" than forgettable stimuli after they passed through VWM. The remaining question is whether this stickiness benefit stems from the same mechanisms that produced the memorability benefit within VWM. Some recent studies seem to suggest the underlying mechanisms are dissociable. For example, Forsberg, Guitard, Adams, Pattanakul, and Cowan (2022) showed that, despite a significant difference in VWM capacity, the rate with which the information encoded into VWM remains in VLTM (the stickiness) is comparable between young adults and school-aged children. Additionally, Rivera-Lares, Logie, Baddeley, and Della Sala (2022) showed that the rate of encoding can be independent of the rate of forgetting. These results are in line with a hypothesis that the benefits that memorable stimuli enjoy within VWM might stem from mechanisms that are dissociable from the stickiness benefit. Future study should examine this possibility directly.

It is also unclear in what way memorable stimuli may be "stickier" than forgettable stimuli. It is possible that memorable stimuli may be more resistant to interference, more robust against decay (i.e., better consolidated than forgettable stimuli), or a combination of both. More studies are needed to specify how differences in the stickiness of memorable and forgettable stimuli develop over time.

9. Is memorability purely perceptual?

Although our results showed that memorability benefits emerge at different processing stages within and after VWM maintenance, it may be possible that all the benefits stem from shared sources such as a perceptual advantage for memorable stimuli. While past studies have provided evidence for perceptual origins of memorability (e.g., Bainbridge et al., 2017; Mohsenzadeh, Mullin, Oliva, & Pantazis, 2019; Rust & Mehrpour, 2020), a large body of work shows that when perceptual differences are equated between memorable and forgettable stimuli (e.g., colour, spatial frequency, facial attractiveness, facial agreeableness), differences in memory performance continue to persist between them (e.g., Bainbridge, 2020; Bainbridge et al., 2017; Isola, Xiao, Parikh, Torralba, & Oliva, 2013). Given that we used the same face stimuli in Experiment 1 as Bainbridge et al. (2017 ;, 2020), it is unlikely that an entirely perceptual explanation can account for the memory differences observed in the current study. As for the object stimuli in Experiment 2, they were randomly sampled from 2400 unique real-world objects curated in a previous study (Brady et al., 2008). Thus, it is theoretically possible that there may be some subtle perceptual differences between memorable and forgettable objects. However, given the previous work demonstrating the insufficiency of a purely perceptual account for object memorability (e.g., Isola et al., 2013), it is unlikely that the memorability benefits we observed are entirely accounted for by randomly occurring perceptual differences between memorable and forgettable stimuli (see https://osf.io/jgqh7/ for all the memorable and forgettable images used). Nonetheless, future studies should examine whether or not the memorability benefits observed at different memory processes originate from common factors.

10. Conclusion

To summarize, we found that the memorability benefit emerges in VWM and continues to develop after. Within VWM, memorable stimuli enjoy a dual benefit. First, they are maintained more efficiently within VWM, as participants had increased memory performance for memorable stimuli compared to forgettable stimuli. Second, memorable stimuli have a competitive advantage over forgettable stimuli, as memory performance for memorable stimuli is improved when they are encoded along with forgettable stimuli. We found that the efficiency advantage seen in VWM translates to VLTM performance, but the competitiveness advantage enjoyed by memorable stimuli in VWM did not translate to VLTM. We also found that memorable stimuli were stickier than forgettable stimuli and were less likely to be forgotten after leaving VWM. This pattern of results was replicated using multiple different metrics of memory performance. Lastly, we successfully replicated the same patterns of results across different stimulus sets (i.e., faces in Experiment 1 and objects in Experiments 2). Given the differences between face and object processing (e.g., Rousselet, Husk, Bennett, & Sekuler, 2008; Sergent, Ohta, & Macdonald, 1992), our findings speak to a universality relating to the cognitive mechanisms underlying the stimulus memorability benefit.

Author note

This research was supported by the Natural Sciences and Engineering Research Council (RGPIN-2017-06866) and the Connaught New Researcher Award.

The data, stimuli, and experimental codes are posted publicly at the Open Science Framework (https://osf.io/jgqh7/). The authors have no conflicts of interest to declare that are relevant to the content of this article.

CRediT authorship contribution statement

Greer Gillies: Conceptualization, Investigation, Formal analysis, Visualization, Writing – original draft. **Hyun Park:** Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing. **Jason Woo:** Investigation, Data curation, Visualization. **Dirk B. Walther:** Supervision, Writing – review & editing. **Jonathan S. Cant:** Supervision, Writing – review & editing. **Keisuke Fukuda:** Conceptualization, Methodology, Formal analysis, Resources, Visualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

The data, stimuli, and experimental codes are posted publicly at the Open Science Framework (https://osf.io/jgqh7/)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2023.105489.

References

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence, & J. T. Spence (Eds.)*, Vol. 2. The psychology of learning and motivation: Advances in research and theory* (pp. 89–195). Academic Press. https://doi.org/10.1016/S0079-7421(08)60422-3.

Awh, E., Barton, B., & Vogel, E. K. (2007). Visual working memory represents a fixed number of items regardless of complexity. *Psychological Science, 18*(7), 622–628. https://doi.org/10.1111/j.1467-9280.2007.01949.x

Bae, G. Y., Olkkonen, M., Allred, S. R., & Flombaum, J. I. (2015). Why some colors appear more memorable than others: A model combining categories and particulars in color working memory. *Journal of Experimental Psychology. General, 144*(4), 744–763. https://doi.org/10.1037/xge0000076

Bainbridge, W. A. (2020). The resiliency of image memorability: A predictor of memory separate from attention and priming. *Neuropsychologia, 141*, Article 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. https://doi.org/10.1037/a0033872

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, 105*(38), 14325–14329. https://doi.org/10.1073/pnas.0803390105

Carlisle, N. B., Arita, J. T., Pardo, D., & Woodman, G. F. (2011). Attentional templates in visual working memory. *The Journal of Neuroscience, 31*(25), 9315–9322. https://doi.org/10.1523/JNEUROSCI.1097-11.2011

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

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

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

Dube, B., Emrich, S. M., & Al-Aidroos, N. (2017). More than a filter: Feature-based attention regulates the distribution of visual working memory resources. *Journal of Experimental Psychology: Human Perception and Performance, 43*(10), 1843. https://doi.org/10.1037/xhp0000428

Forsberg, A., Guitard, D., Adams, E. J., Pattanakul, D., & Cowan, N. (2022). Children's long-term retention is directly constrained by their working memory capacity limitations. *Developmental Science, 25*(2), Article e13164. https://doi.org/10.1111/desc.13164

Forsberg, A., Guitard, D., & Cowan, N. (2020). Working memory limits severely constrain long-term retention. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-020-01847-z

Fukuda, K., Vogel, E., Mayr, U., & Awh, E. (2010). Quantity, not quality: The relationship between fluid intelligence and working memory capacity. *Psychonomic Bulletin & Review, 17*(5), 673–679. https://doi.org/10.3758/17.5.673

Fukuda, K., & Vogel, E. K. (2019). Visual short-term memory capacity predicts the "bandwidth" of VLTM encoding. *Memory & 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. *Psychological Science, 26*(7), 1026–1037. https://doi.org/10.1177/0956797615578122

Hedayati, S., O'Donnell, R. E., & Wyble, B. (2022). A model of working memory for latent representations. *Nature Human Behaviour*. https://doi.org/10.1038/s41562-021-01264-9

Inquisit 6. (2020). Computer software. Retrieved from https://www.millisecond.com.

Isola, P., Xiao, J., Parikh, D., Torralba, A., & Oliva, A. (2013). 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

Isola, P., Xiao, J., Torralba, A., & Oliva, A. (2011, June). What makes an image memorable?. In *CVPR 2011* (pp. 145–152). https://doi.org/10.1109/TPAMI.2013.200

Mohsenzadeh, Y., Mullin, C., Oliva, A., & Pantazis, D. (2019). The perceptual neural trace of memorable unseen scenes. *Scientific Reports, 9*(1), 1–10. https://doi.org/10.1038/s41598-019-42429-x

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorial in Quantitative Methods for Psychology, 4*, 61–64.

Ovalle-Fresa, R., Uslu, A. S., & Rothen, N. (2021). Levels of processing affect perceptual features in visual associative memory. *Psychological Science, 32*(2), 267–279. https://doi.org/10.1177/0956797620965519

Prolific. (2021). Oxford, UK. Available at: https://www.prolific.co.

Reinhart, R. M., McClenahan, L. J., & Woodman, G. F. (2016). Attention's accelerator. *Psychological Science, 27*(6), 790–798. https://doi.org/10.20982/tqmp.04.2.p061

Rivera-Lares, K., Logie, R., Baddeley, A., & Della Sala, S. (2022). Rate of forgetting is independent of initial degree of learning. *Memory & Cognition, 1-13*. https://doi.org/10.3758/s13421-021-01271-1

Rousselet, G. A., Husk, J. S., Bennett, P. J., & Sekuler, A. B. (2008). Time course and robustness of ERP object and face differences. *Journal of Vision, 8*(12), 3. https://doi.org/10.1167/8.12.3

Rust, N. C., & Mehrpour, V. (2020). Understanding image memorability. *Trends in Cognitive Sciences, 24*(7), 557–568. https://doi.org/10.1016/j.tics.2020.04.001

Saito, J. M., Kolisnyk, M., & Fukuda, K. (2021, December 22). *Judgments of learning reveal conscious access to stimulus memorability*. https://doi.org/10.31234/osf.io/54nc6

Sergent, J., Ohta, S., & Macdonald, B. (1992). Functional neuroanatomy of face and object processing: A positron emission tomography study. *Brain, 115*(1), 15–36. https://doi.org/10.1093/brain/115.1.15

Standing, L. (1973). Learning 10,000 pictures. *The Quarterly Journal of Experimental Psychology, 25*(2), 207–222. https://doi.org/10.1080/14640747308400340

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 & Cognition, 47*(2), 351–364. https://doi.org/10.3758/s13421-018-0871-z

Tozios, C. J. I., & Fukuda, K. (2020). Indirect, but not direct, down-regulation of visual long-term memory encoding through strategic biasing of attentional allocation. *J Exp Psychol Gen, 149*(7), 1294–1310. https://doi.org/10.1037/xge0000712

Wakeland-Hart, C., Cao, S., deBettencourt, M., Bainbridge, W., & Rosenberg, M. D. (2021). *Predicting visual memory across images and within individuals*. https://doi.org/10.31234/osf.io/zbu3k

Xie, W., & Zhang, W. (2017). Familiarity increases the number of remembered Pokémon in visual short-term memory. *Memory & Cognition, 45*(4), 677–689. https://doi.org/10.3758/s13421-016-0679-7

Xie, W., & Zhang, W. (2018). Familiarity speeds up visual short-term memory consolidation: Electrophysiological evidence from contralateral delay activities. *Journal of Cognitive Neuroscience, 30*(1), 1–13. https://doi.org/10.1162/jocn_a_01188

Yoo, A. H., Klyszejko, Z., Curtis, C. E., & Ma, W. J. (2018). Strategic allocation of working memory resource. *Scientific Reports, 8*(1), 1–8.