The resiliency of image memorability: A predictor of memory separate from attention and priming

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Abstract

Recent work has demonstrated there is a power within images to impact our later memories—an *intrinsic stimulus memorability* that influences memory behavior consistently across observers. This memorability is computed as explicitly reported memory performance on each image, and is significantly correlated from observer to observer. Interestingly, neuroimaging work has found that memorable versus forgettable images show distinct, early patterns within the brain even when participants are not performing an explicit memory task. Thus, a key question is whether memorability effects reflect a more automatic, bottom-up process, or are the result of top-down attentional processes. Further, how do bottom-up and top-down processes interact with stimulus memorability to influence ultimate memory performance? The current study explores these questions through the lens of four classical psychological phenomena shown to influence memory. First, a directed forgetting task shows that cognitive control is unable to override the effects of stimulus memorability. Second, an experiment manipulating depth of processing reveals a performance boost for memorable images regardless of the depth at which they are encoded. Third, results from a visual search experiment show that memorable images do not trigger automatic attentional capture, or pop-out. Finally, results from a repetition priming task demonstrate that memorability and priming are independent phenomena. In sum, memorability is an isolable phenomenon, occurring automatically, and resilient to top-down influence.

1. Introduction

One great mystery of the human experience is why our memories often act against our will – we sometimes remember events that are not particularly important to us, yet may forget the names and faces of new acquaintances that we try desperately to remember. Recent work has pinpointed a novel image attribute that can help explain what we ultimately remember – *memorability*, defined as the likelihood of a novel stimulus being eventually remembered or forgotten (Bainbridge, 2019). Surprisingly, despite our diverse unique experiences, we tend to remember the same scenes (Isola et al. 2011b), faces (Bainbridge et al., 2013; Bainbridge, 2017), and even visualizations (Borkin et al., 2013) as each other (see Fig 1 for examples). This consistency across observers allows memorability to be conceptualized as a measurable, stable property of a *stimulus* (Bainbridge et al., 2013), in contrast to "memory," which is a process and behavior conducted by a single *observer*. Memorability is simply measured as memory performance (usually hit rate, HR) across a group, but in spite of its consistency, it is not predictable by a comprehensive set of other attributes, including aesthetics, emotionality, or the brightness of an image (Isola et al., 2011a; Bainbridge et al., 2013). Intrinsic stimulus memorability determines approximately 50% of the variance in memory performance, with the remaining 50% explained by differences in the observer, their environment, and external noise (Bainbridge et al., 2013). The memorability of a stimulus also remains consistent over different time scales (Isola et al., 2013), image contexts (Bylinskii et al., 2015), as well as different experimental paradigms (Broers et al., 2017; Goetschalckx et al., 2017). Given that the stimulus is so influential on the memory of an observer, a key question is how the brain processes these memorable images. When we view a memorable image, does it automatically elicit privileged processing in the brain that leads to successful memory encoding? Or, do memorable images instead elicit different top-down processes that ultimately lead to successful memory?

Neuroimaging research has thus far identified a neural signature for memorability, suggested to occur during late perception (Bainbridge et al., 2017; Mohsenzadeh et al., 2019). Specifically, memorable images cause higher activation as well as show memorability-based representational patterns in late visual areas (inferotemporal cortex, IT) and the memory-related medial temporal lobe (MTL) and anterior hippocampus (Bainbridge et al., 2017; Bainbridge and Rissman, 2018). In contrast, early visual areas (V1 to V4) show no difference between memorable and forgettable stimuli. These differences in the brain for memorable versus forgettable images emerge just 150 ms after stimulus presentation and after stimuli shown as quickly as 34 ms (Khaligh-Razavi et al., 2016; Broers et al., 2017; Mohsenzadeh et al., 2019), providing evidence that stimulus memorability may impact neural processing as part of a feed-forward sweep after early vision (Di Lollo et al., 2000), around the same time as later visual processing (Liu et al., 2002), but preceding memory encoding (Khaligh-Razavi et al., 2016). However, the mechanisms that underlie memorability are still largely unknown, and no work has yet explored how bottom-up and top-down attentional processes influence (or lead to) memorability effects. Memorability effects in IT have shown stimulus category generality (e.g., face areas are sensitive to memorability of any stimulus category; Bainbridge et al., 2017), possibly hinting towards these effects reflecting an attention-driven signal increase. Further, parietal activations sometimes appear during comparisons of memorable and forgettable stimuli (Bainbridge et al., 2017), indicating a potential involvement of attentional networks.

A key question is thus whether memorability effects may be a proxy for other cognitive processes known to affect memory, such as attention or priming. As memorability scores are defined through performance on an explicit memory task (i.e., intentionally studying and retrieving images), is memorability a largely endogenous memory effect and can it be manipulated with top-down (or feedback-driven) strategies, such as cognitive control or manipulating the depth of processing? Conversely, perhaps the brain shows early sensitivity to memorability because memorable images are automatically encoded, through bottom-up attentional capture or greater priming effects. Examining such questions will give insight into the nature of why our behavior and our brains are sensitive to the memorability of an image.

The current study explores memorability in the context of four classical psychological phenomena known to influence memory: directed forgetting, depth of processing, visual search, and repetition priming. First, given that memorability is defined based on explicit memory performance, can we override these memorability effects through cognitive control, and does changing the processing depth of the task eliminate these effects? Experiment 1 explores whether cognitive control can override memorability effects, and finds it cannot; you cannot make yourself forget a memorable image. Experiment 2 explores the relationship of task encoding depth and memorability, and finds memorability effects are preserved regardless of depth of processing. These experiments lend evidence for memorability as an automatic memory phenomenon. How does memorability then relate to other phenomena known to automatically influence memory, namely attentional capture and priming? Experiment 3 explores visual search for memorable images, to see whether such images evoke bottom-up attentional capture. While there is faster orienting to memorable targets, there is no evidence for an automatic “pop-out” effect. Finally, Experiment 4 compares memorability to repetition priming and finds that memorability effects are independent from priming. The experiments were conducted using online psychophysics experimental platform PsyToolkit (Stoet, 2010; Stoet, 2017), and across all reported experiments, participant performance replicated the original results and effect sizes of in-lab studies of the same paradigms (Bower & Karlin, 1974; Cooper & Langton, 2006), supporting the idea that online experiments are effective means to collect large samples of psychophysical data. Taken together, these results provide powerful evidence that memorability is an isolable phenomenon, occurring automatically (yet separately from automatic attentional capture and priming), and resilient to top-down influence.

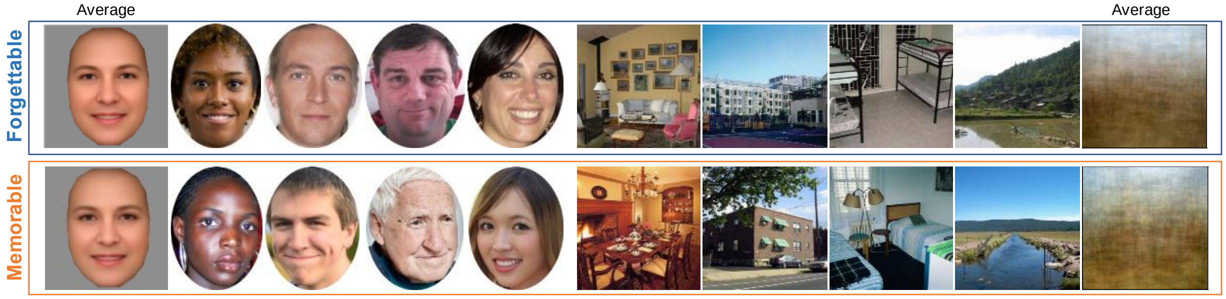


Fig 1. Example forgettable and memorable stimuli. There are no clear intuitive differences between these highly controlled memorable and forgettable face or scene images, yet 30-40% more people remember the images on the bottom than those on the top. On the left is the average face shape and texture across 180 memorable and forgettable faces (created using an Active Appearance Model; Cootes et al., 2001) and on the right is the average scene texture across 180 memorable and forgettable scenes; you can see that average images are also highly similar between memorable and forgettable conditions. The face images used in this figure and all other figures are within the public domain.

2. Experiment 1: Memorability and Explicit Cognitive Control

2.1 Introduction

Memorability is originally defined in the literature as hit rate (HR), or performance in an explicit memory task (Bainbridge, 2019). Thus, the memorability effects we observe consistently across people and the neural effects we find in the brain may be largely due to the nature of the images themselves and how they provoke more top-down attention. Memorable images may contain information that inspires intentional encoding into memory, such as interesting semantic or visual detail. Indeed, previous work has found that people can intentionally remember or forget images given a cue (MacLeod, 1989; Basden et al., 1993). Additionally, faces that are seen as more distinctive are less susceptible to directed forgetting effects than typical faces (Metzger, 2011). Thus, to what degree can manipulating intentional encoding override memorability effects; to what degree can someone try to remember a forgettable image, or forget a memorable image?

A directed forgetting task was conducted with stimuli of differing memorability; participants were asked to remember or forget stimuli that were preselected to be of low, medium, or high memorability (unbeknownst to the participant), and then they were tested on their true memory. Depending on the interaction of cognitive control and memorability, there are two possible hypotheses. First, it is possible that memorability effects are largely explained by top-down cognitive control (i.e., a person decides a memorable image is interesting and encodes it). Similarly, it is possible that cognitive control would have a stronger influence on memory than memorability does, as cognitive control has a strong effect on explicit memory behavior (MacLeod, 1989). If either of these are the case, then we should see that cognitive control is the main determinant of ultimate memory behavior, not the memorability of the original image. An alternate hypothesis is that memorability is an intrinsic image property that is unaffected by cognitive control; while people will tend to forget images they try to forget and remember those they try to remember, memorability will have a stronger and separate effect on what they eventually remember and forget.

2.2 Materials and Methods

2.2.1 Participants

Seventy-two participants were recruited on online crowdsourcing platform Amazon Mechanical Turk (AMT) and tested using PsyToolkit (Stoet, 2010; Stoet, 2017), an online platform for running precisely timed psychophysical experiments. For this and all other experiments, data were collected following the standards of the MIT Institutional Review Board in accordance with the Declaration of Helsinki, and all participants provided consent for the study. Only participants with over a 95% AMT approval rating and an IP address in the United States were recruited for the experiments, so that their exposure to different facial demographics would most closely match those of the stimulus set (designed to approximate the U.S. population). All participants were compensated for their time.

2.2.2 Stimuli

All experiments in the study used stimuli from a set of highly memorable (top 25% of HR; M=0.73, SD=0.07), medium memorable (middle 25% of HR; M=0.51, SD=0.02) and highly forgettable face images (bottom 25% of HR; M=0.32, SD=0.05) used previously to test memorability effects in the brain (Bainbridge et al., 2017). These images are highly controlled between conditions, to be equalized for other properties that could relate to memorability, including spatial frequency, color, age, race, gender, emotion, attractiveness, and false alarm rate (all $p > 0.05$; controlled using the Natural Image Statistical Toolbox: Bainbridge & Oliva, 2015). The images were originally taken from the 10k US Adult Faces Database (Bainbridge et al., 2013), which contains a publicly-available set of 2,222 faces labeled with memorability scores from a continuous recognition test and various attributes from a large-scale online study. All faces are naturalistic face images cropped by an oval to diminish background effects, and resized to 256 pixels in height (with varying width to fit the face). Experiment 1 used 40 stimuli each from the three tiers of memorability, and also included 120 foil images of medium memorability with the same matched properties.

2.2.3 Experimental Methods

The experiment followed the methodology of classical directed forgetting studies (MacLeod, 1989). There were two phases to the experiment: a study phase and a test phase (Fig 2). During the study phase, there were 20 stimuli each in 6 conditions, varying along two factors: 1) memorability (low, medium, high), and 2) instructions to the participant (remember / forget), resulting in 120 target stimuli total. For the test phase, there were an additional 120 faces of medium memorability to act as foil faces, with matched statistics with the target faces. Each participant saw half of the targets and foils (60 images each) to reduce the length of the experiment, so each stimulus was seen by 36 participants. Note that while participants completed a small number of trials, a large number of participants completed the experiment (N=72), resulting in a large number of samples per condition. Using shorter paradigms with large participant samples is best for maximizing data quality, as online participants are most attentive during the first five minutes of a study (Buhrmester et al., 2011), although AMT data has been shown to be of equal quality and higher demographic diversity than in-lab samples (Buhrmester et al., 2011; Berinsky et al., 2012).

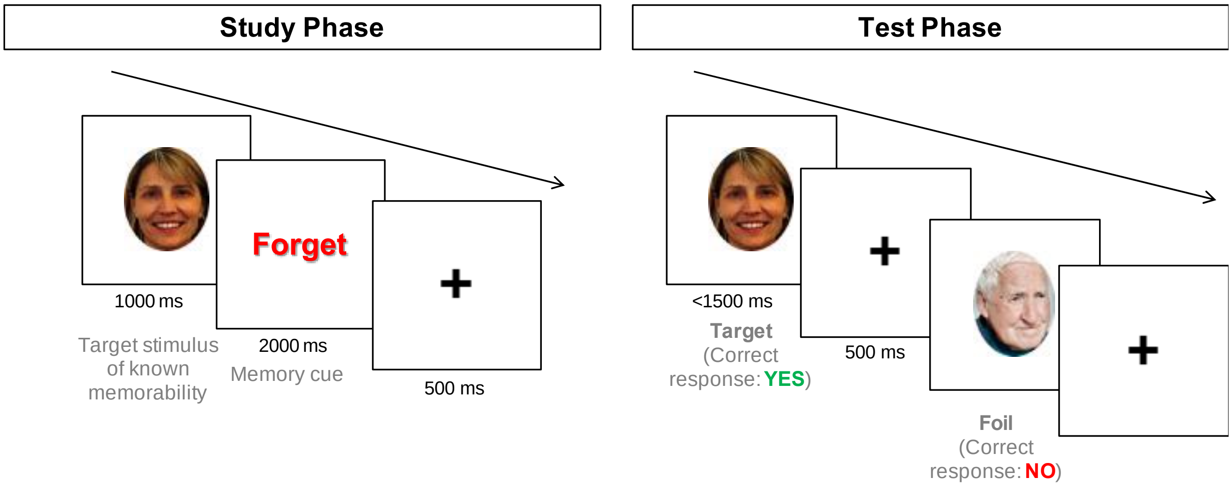


Fig 2. The experimental methods of the study and test phases of the directed forgetting paradigm used in Experiment 1. In the study phase, participants saw a stream of face images (of low, medium, or high memorability) and for each one, were directed to either remember or forget that image, with the incentive of a monetary bonus. In the test phase, participants were told to instead try and remember all of the images they saw in the study phase, regardless of memory cue, and rewarded with a monetary bonus based on performance.

In the study phase, participants were told that they were going to see a stream of face images, and after each image they would get a cue to either “remember” or “forget” the face. Participants were told they would be tested later on their memory and they would receive bonus money based on their memory performance. These ambiguous instructions incentivized them to correctly follow the memory cues, as they were unaware that they would ultimately be tested on their recognition for all images. During the study phase, participants saw 60 face images, each one presented for 1000ms, followed by a 2000ms remember or forget cue, and then a 500ms fixation cross. In total, the study phase took approximately 4 minutes.

For the test phase, participants were then tested for their memory. They were told to try and recall everything that they saw (counter to their original expectations), and respond based on whether they had seen the image before, regardless of whether they were originally asked to remember or forget it. They were given up to 1500ms to respond to each face which was then followed by a 500ms fixation cross, and they were rewarded with bonus money based on correct responses.

2.3 Results and Discussion

A summary of the main results can be seen in Fig 3. A 2-way repeated measures ANOVA on participant memory performance during the test phase for the different conditions found a significant main effect of memorability level, $F(2 , 426)=33.93$, $p=9.02\times10^{-13}$, $\eta_p^2=0.32$. There was also a significant effect of the memory cue, with a lower HR for images participants were told to forget than those they were told to remember ($F(1, 426)=5.76$, $p=0.019$), although a smaller effect size of $\eta_p^2=0.08$. However, there was no significant statistical interaction between the two factors ($F(2, 426)=0.26$, $p=0.760$, Bayesian factor analysis using Bayesian Information Criteria (BIC) supports the null hypothesis (Wagenmakers, 2007; Jarosz & Wiley, 2014): $BF_{01}=7.19$), indicating that directed forgetting does not appear to influence memorability effects and vice versa; i.e., memorable images do not cause greater directed memory effects.

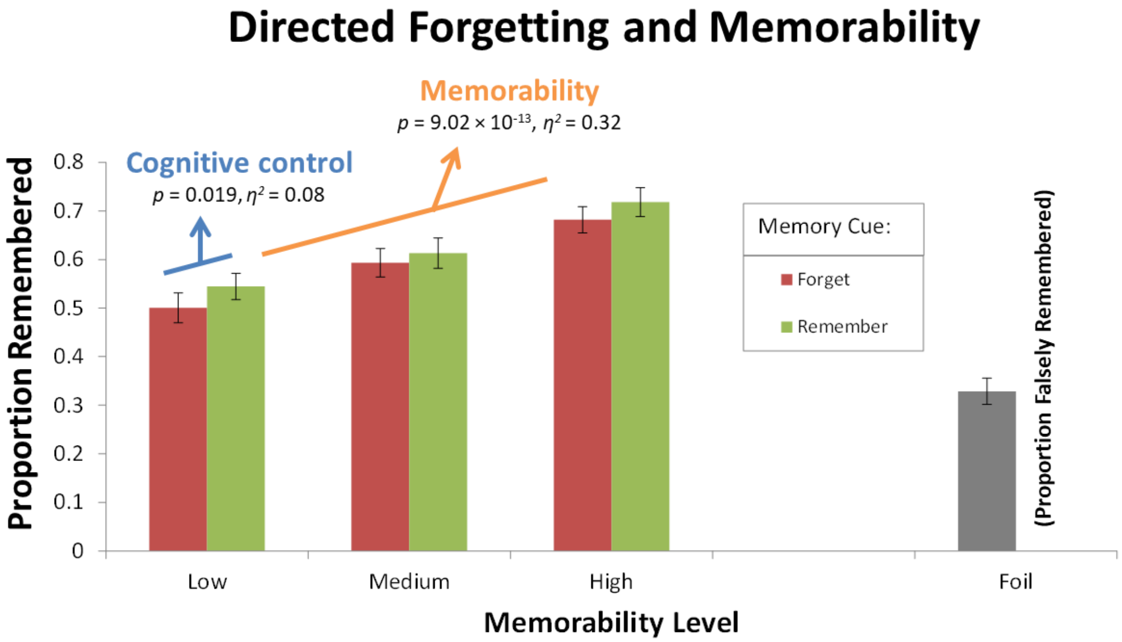


Fig 3. The hit rates of the different conditions, varying along memorability level (low, medium, or high) and memory cue (forget or remember). The false alarm rate for the foil images (all of medium memorability) is also presented as a point of comparison. Error bars indicate standard error of the mean. While there was an effect of the memory cue (people remembered images they were told to remember better than those they were told to forget), image memorability had a significant effect on subsequent memory of larger effect size, with no statistical interaction with directed forgetting.

Looking at specific effects within memorability using paired t-tests, highly memorable images were remembered significantly more than moderately memorable images ($t(71)=4.26$, $p=6.13\times10^{-5}$), and moderately memorable images were remembered significantly more than low memorable ones ($t(71)=4.59$, $p=1.88\times10^{-5}$). In fact, participants significantly better remembered the memorable images they were told to forget than the forgettable ones they were told to remember ($t(71) = 4.95$, $p=4.91\times10^{-6}$).

In sum, these results indicate that participants still significantly remembered memorable images over forgettable images, regardless of the memory cue they were presented with at the study phase and in spite of a monetary bonus incentivizing them to override any effects of the stimulus. At the same time, the study was able to replicate directed forgetting effects, though with a weaker effect size than that of memorability. These directed forgetting effects reflect the influence of cognitive control over memory, but may also capture associative memory processes in which participants are learning associations between image targets and verbal memory cues (i.e., "remember" or "forget"). Regardless, these results show that memorability is a relatively immutable property of an image or entity in the face of directed forgetting, and that memorability effects cannot be explained by a cognitive control account. Interestingly, just as directed forgetting does not affect implicit memory measures like priming (Vuilleumier et al., 2005), directed forgetting does not alter the influence of memorability on memory performance, providing evidence that memorability could have a more implicit effect on memory. Essentially, in spite of one's efforts, you cannot make yourself remember a forgettable image, or make yourself forget a memorable image.

3. Experiment 2: Memorability and Depth of Processing

3.1 Introduction

Another top-down phenomenon that could interact with memorability is depth of encoding, or different levels of processing (Lockhart & Craik, 1990). When stimuli are processed in terms of their semantics or meaning (i.e., deep encoding), they tend to be remembered better than when they are processed in terms of their perceptual features alone (i.e., shallow encoding) (Bower & Karlin, 1974; Sporer, 1991; Innocenti et al., 2010). This is thought to be due to the greater amount of attentional load and effort required to engage deeper processes (Lockhart & Craik, 1990). Memorability effects could thus occur due to deeper encoding or more attentional resources put into remembering memorable images. Perhaps observers perform more elaborative semantic processing with memorable images (e.g., perhaps they are more interesting or have more semantic content), and thus encode the images more deeply.

This issue was addressed using an encoding depth task (Bower & Karlin, 1974), where participants categorized sets of memorable and forgettable face stimuli using tasks of three different encoding depths – identifying the color of a fixation cross (shallowest task), the gender of a face (shallow task), or judging the honesty of the face (deep task). Participants were then given an unexpected memory test. If memorability effects occur due to deeper encoding, then controlling for depth of encoding should eliminate a difference between memorable and forgettable images. Alternatively, if memorability is intrinsic to images and distinct from encoding depth, we expect to find separate effects of stimulus memorability and task encoding depth on subsequent memory.

3.2 Materials and Methods

3.2.1 Participants and Stimuli

Seventy-two AMT participants were recruited. A set of 120 highly controlled face stimuli of low and high memorability were used as stimuli in this experiment (see Section 2.2). Faces were used as several encoding depth studies have established paradigms using faces (Bower & Karlin, 1974; Sporer, 1991). A set of 120 foils of medium memorability was also used in this experiment (see Section 2).

3.2.2 Experimental Methods

The experiment followed the general methodology of previous classical depth of encoding experiments (Bower & Karlin, 1974), see Fig 4. The experiment comprised four parts that were unknown to the participants at the start of the experiment. The first three parts comprised the study phase, using tasks of three different encoding depths where participants had to make different binary decisions on the face images, and the fourth part was an unexpected test phase. For the shallowest processing task, participants were asked to identify the color (black or white) of a fixation cross that appeared on the face image (the “fixation task”). For a deeper task, participants were asked to identify the gender (male or female) of a face image (the “gender task”). This task is often used as the shallow processing task in depth of encoding experiments (Bower & Karlin, 1974), however as gender determination requires holistic face processing, it is likely that it is “deeper” than the fixation cross task which does not require processing features of the faces. Lastly, for the deepest task, participants were asked to judge how honest (honest or dishonest) they thought a face was (the “honesty task”; Bower & Karlin, 1974). All tasks had a black or white fixation cross on each face (with color distributed evenly over memorable and forgettable images), so stimuli were visually identical across tasks. Forty target face stimuli were used in each task, with half being highly memorable images and the other half highly forgettable, resulting in 120 target stimuli total. Each participant saw half of the stimuli (60 images) to reduce the length of the experiment, so each stimulus was seen by 36 participants. Each image was displayed for 1000 ms and was separated by a 500 ms fixation cross, for a total time of 30 s per phase. The order of these three tasks was counterbalanced across participants, images were randomly sorted into each task, and participants were asked to focus only on the task at hand and not think about the other tasks they had completed.

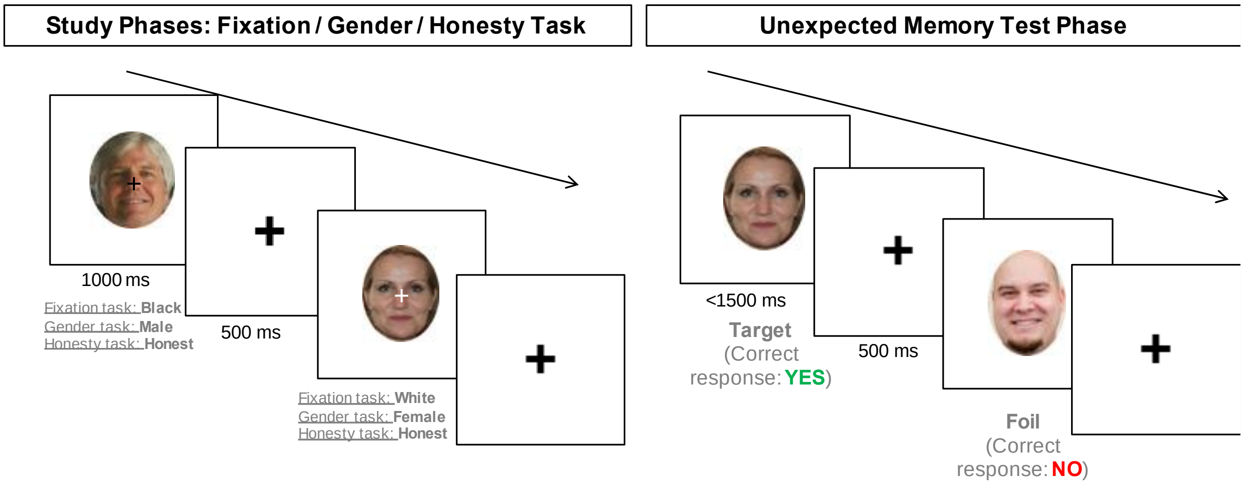
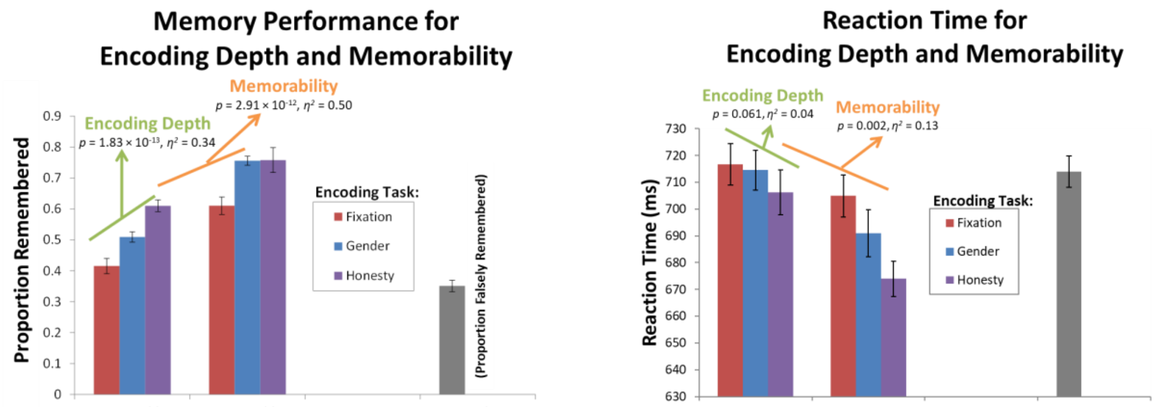


Fig 4. The depth of encoding experimental design of Experiment 2. The experiment consisted of four phases. The first three were identical in paradigm, but had three different tasks, counterbalanced in order across participants: 1) the fixation task, 2) the gender task, and 3) the honesty task. Displayed are example responses that would be indicated based on the task. After the three study phases, participants then completed an unexpected memory test on all the stimuli that were presented in the three previous parts.

The fourth part for all participants consisted of an unexpected memory test phase. Participants were presented with a stream of images and were told to identify which they had seen earlier in the experiment. Sixty of the images were targets, while 60 were foils, and they were presented in a randomized order. Participants were given up to 1500 ms to respond to each face which was then followed by a 500 ms fixation cross. Both reaction time and performance accuracy were recorded. The experiment took approximately 5 minutes in total.

3.3 Results and Discussion

A graphical summary of the results can be seen in Fig 5. In a 2-way repeated measures ANOVA of memorability and encoding depth, there is a significant main effect of memorability on HR ($F(1, 426)=70.73$, $p=2.91\times10^{-12}$, $\eta_p^2=0.50$). There is also a significant main effect of task encoding depth on HR ($F(2, 426)=36.32$, $p=1.83\times10^{-13}$, $\eta^2=0.34$), with smaller effect size, where images that were encoded with a deeper task show a higher HR. There was also a significant statistical interaction between memorability and encoding depth ($F(2,426)=4.77$, $p=0.01$). Post-hoc tests were used to investigate specific differences between the conditions and this interaction effect. Memorable images were remembered significantly more often than forgettable images on all tasks (fixation: $t(71)=6.37$, $p=1.61\times10^{-8}$; gender: $t(71)=8.12$, $p=1.02\times10^{-11}$; honesty: $t(71)=5.23$, $p=1.61\times10^{-6}$). Looking at paired t-tests based on the encoding task, for forgettable images, performance was significantly higher for the gender task than the fixation task ($t(71)=3.98$, $p=1.62\times10^{-4}$), and higher for the honesty task than the gender task ($t(71)=3.84$, $p=2.67\times10^{-4}$). For memorable images, performance was significantly higher for the gender task than the fixation task ($t(71)=5.63$, $p = 3.33\times10^{-7}$), but there was no difference for the honesty task compared to the gender task ($t(71)=0.10$, $p = 0.923$). This is likely due to the fact that performance for these two tasks for memorable images is essentially at ceiling; when told to explicitly remember these images (see Experiment 1 with the same image sets), participants have about the same performance (gender task $M=0.76$, honesty task $M=0.76$, explicit memory $M=0.73$). This effect also likely explains the statistical interaction between memorability and encoding depth.



A) B)

Fig 5. Performance on the unexpected recognition memory test based on different conditions. (A) Hit rate by condition. Memorable images had significantly higher hit rates than forgettable images. Similarly, greater encoding depth also resulted in higher hit rates. The bar for the foil images here reflects false alarm rate, for a point of comparison. Error bars indicate standard error of the mean. (B) Reaction time by condition. Memorable images had significantly faster reaction times than forgettable images. There was also a trending significant effect of task encoding depth, with deeper tasks causing faster recognition, however there was no statistical interaction between memorability and encoding depth. The reaction time to respond to foil images was comparable to that of forgettable images.

Reaction time (RT) results mirror those of memory performance. Based on a 2-way within-subjects repeated-measures ANOVA (memorability × encoding depth) on RTs, participants responded significantly faster to memorable images in the memory test than to forgettable images ($F(1, 426)=10.87$, $p=0.002$, $\eta_p^2 = 0.13$). There was no significant main effect of encoding depth on RT ($F(2, 426)=2.98$, $p=0.061$, $\eta_p^2 = 0.04$), though there was a trend of faster reaction times for images that were studied with deeper encoding. There was no significant statistical interaction between memorability and encoding depth with RT ($F(2, 426)=0.94$, $p=0.393$, $BF_{01}=5.30$). Based on a paired t-test, RTs during the memory test to memorable images were significantly different from those to foil images (*t*(71)=3.30, *p*=0.002), however forgettable image RTs were not different from those of foils (*t*(71)=0.27, *p*=0.790, BF_{01}=10.40). Comparing across tasks, RTs in the memory test were not significantly different between memorable and forgettable images for the fixation task (*t*(71)=1.02, *p*=0.313), however they were for the gender task (*t*(71)=2.06, *p*=0.043) and the honesty task (*t*(71)=3.24, *p*=0.002).

Collectively, these results show strong effects of both memorability and encoding depth on subsequent memory. However, performance was significantly better for memorable than forgettable images on all tasks, and memorability effects had higher effect sizes than encoding depth effects for both performance and RT. This indicates that controlling for encoding depth does not equalize memorability; even if you are encoding a set of images deeply and semantically, you will still remember memorable images better than forgettable images. Or, similarly, even when focusing on an irrelevant perceptual item (i.e., fixation crosses overlaid on the images), you will still remember memorable images better than forgettable images. These results imply that effort, distribution of attentional resources, or elaboration of encoding are unlikely to explain the phenomena we find with memorability.

4. Experiment 3: Memorability and Automatic Attentional Capture

4.1 Introduction

Memorability effects are resilient to top-down effects (cognitive control or deeper, elaborative encoding), so instead these effects may mirror bottom-up effects on memory. Specifically, perhaps memorable images automatically evoke memory encoding because they are visually salient and automatically capture attention. The higher neural signal for memorable images found along the ventral visual stream could be a heightened attentional signal that then leads to successful encoding (Bainbridge et al., 2017). A visual search paradigm can provide a nuanced understanding of the interplay of memorability and attention, lending evidence as to whether memorability is an attention-driven stimulus property. Do memorable targets quickly capture attention, and are thus easily identified? Do memorable distractors capture attention and make it harder to zero-in on a target? Previous work has found that it is easier to find distinct stimuli amongst standard stimuli than vice versa (Treisman & Gormican, 1988; Wolfe, 2001), or to find an unfamiliar target (И) amongst familiar (N) targets (Wang et al., 1994). As memorable stimuli (versus forgettable stimuli) have been found to be correlated with subjective ratings of "distinctiveness" (Bainbridge et al., 2017), it is possible that memorable stimuli may show the same pattern.

To examine these questions, a face image visual search experiment was conducted, with targets and distractors of varying memorability. If memorability captures attention, we should anticipate that memorable targets will be very quick to be identified, but also that memorable distractors will detract attention from the visual search. However, if memorability does not capture attention, then we would not see a meaningful effect of target or distractor type.

4.2 Materials and Methods

4.2.1 Participants and Stimuli

Seventy-four participants were recruited from AMT, and the experiment consisted of the highly memorable and highly forgettable face images used in Experiment 1.

4.2.2 Experimental Methods

The experiment was coded and conducted using PsyToolkit (see Fig 6). The stimuli were grouped into 32 conditions that varied along four factors: 1) whether the target was present or absent, 2) whether the target was memorable or forgettable, 3) whether the distractors were memorable or forgettable, 4) search set sizes of 4, 8, 12, or 16 stimuli. Participants were asked to respond as quickly and accurately as possible whether a target was present or absent with a key press.

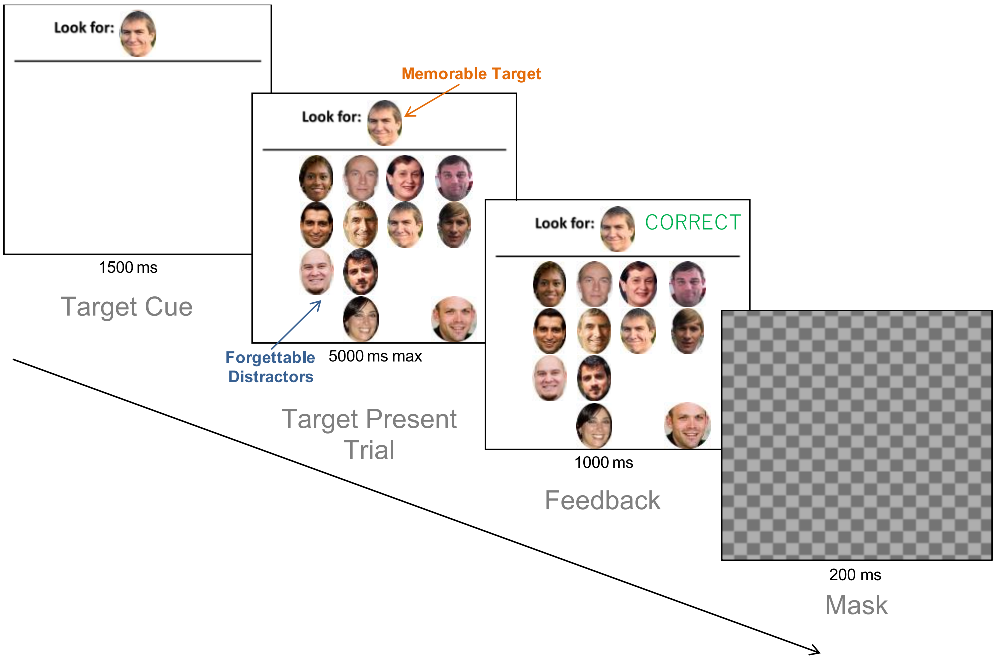


Fig 6. The visual search experimental paradigm for Experiment 3. Participants searched for memorable or forgettable target face images amongst memorable or forgettable distractor image arrays, with different search sizes. In half of the trials the target was present, while in the other half the target was absent. Participants made a response on every trial.

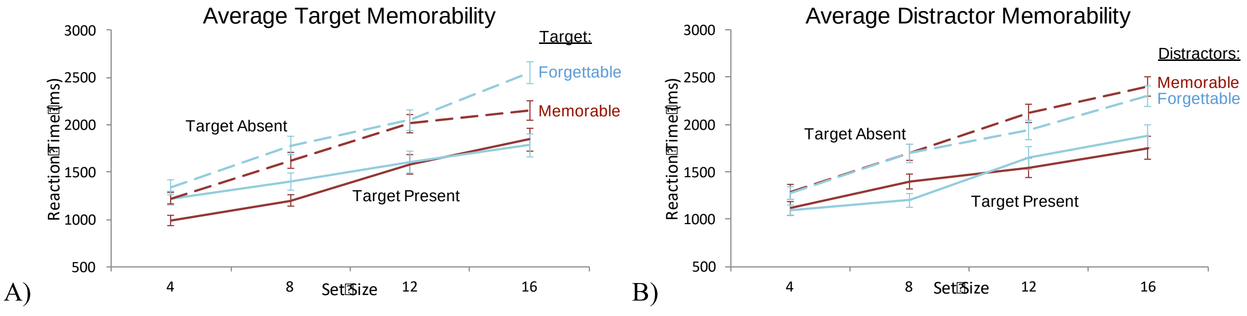
For each trial, the target to search for was presented above the search display for 1500 ms. Then, a search display as a 4×4 grid (similar to the visual search display of previous studies;

Golan et al., 2014) appeared below the target. The number of images in the grid was determined based on the set size of that trial (4, 8, 12, or 16), and were placed in randomized locations (with unused locations blank). On target present trials, the target was placed in a random location in the grid amongst distractors, while on target absent trials, only distractors were used. The target (if present) was either taken from the highly memorable or highly forgettable set, and the distractors were all taken from either set, based on condition. The specific images used were selected randomly.

Participants were given 5000 ms to make their response of target present / absent and RT was measured. They were given feedback for 1000 ms after every response. A noise mask was displayed for 200 ms, and then there was a rest between trials for 2000 ms. The target cue appeared before the search grid and remained on for the whole trial to diminish any memory-related effects on performance (e.g., the observer forgetting what the target looked like). Participants completed 32 trials (one per condition), and the experiment took approximately 3 minutes in total. Only trials where participants responded correctly on the task (target absent / present) were used in the analyses. Analyses were conducted using two methods. First, generalized linear mixed models (GLMM; Lo & Andrews, 2015) were conducted on RT as a dependent variable, to combine both categorical (target presence, target memorability, distractor memorability) and continuous factors (set size). Target presence, set size, target memorability, distractor memorability, and their interactions were modeled as fixed-effects repeated measures, and covariance type was modeled as compound symmetry. A second analysis looked at visual search slope (the slope of a regression line fit to each participant's plots of set size by RT, as in Wolfe, 1998) in repeated-measures ANOVAs with two factors of two levels each (target memorable / forgettable and distractors memorable / forgettable). Visual slope allows us to quantify the degree to which stimulus properties automatically “pop-out” or require a serial search through the array. A slope close to 0 indicates a pop-out effect, in which the target is detected at the same speed regardless of the number of images in the set (e.g., a green square amongst black ones). In contrast, a steep slope indicates a serial search, in which more stimuli in the set leads to an increase in search times (i.e., participants are searching through each item). Examining this slope can provide evidence for whether memorability automatically causes visual pop-out, or is a more complex feature.

4.3 Results and Discussion

Average RT based on target and distractor memorability can be seen in Fig 7. As expected from previous visual search studies (Treisman & Gelade, 1980), target absent trials took significantly longer to identify than target present trials (GLMM: F=127.25, $p < 0.001$). Analyses were conducted separately for target present and target absent trials, as the interaction of memorability and attention could differ between these two different trial types (as there is no memorable or forgettable target in the target absent trials).



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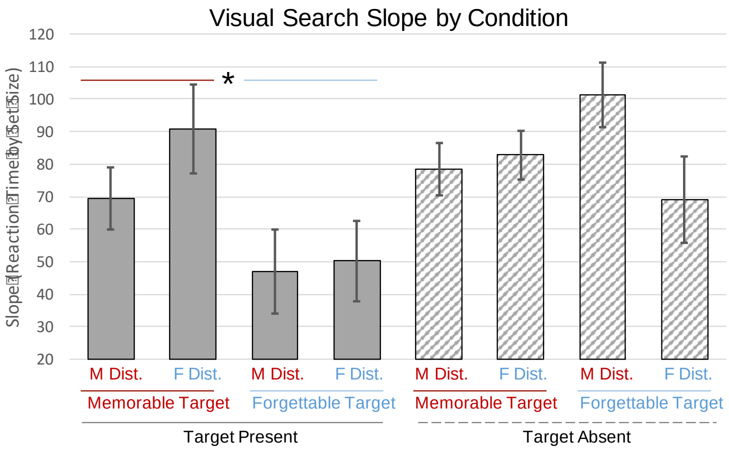

Fig 7. Performance on the visual search task, sorted by target and distractor memorability. (A) The mean reaction times of the conditions averaged by *target memorability*, at each search size. Dashed lines indicate target absent trials, while solid lines indicate target present trials. Dark red lines indicate memorable target trials, while light blue lines indicate forgettable target trials. Error bars indicate standard error of the mean. As expected, target absent trials take longer to identify than target present trials (i.e., dashed lines have higher RTs than solid lines). Larger set sizes also result in longer search times. Importantly, memorable targets are faster to identify than forgettable targets. (B) The mean reaction times of the conditions averaged by *distractor memorability*, at each search size. Dashed lines indicate target absent trials, while solid lines indicate target present trials. Dark red lines indicate memorable distractor trials, while light blue lines indicate forgettable distractor trials. Error bars indicate standard error of the mean. Again, target absent trials as well as larger search set sizes result in longer search times. However, there is no effect of distractor memorability on search times. (C) A chart of the average search slope (reaction time by set size) for each condition, organized by three factors: memorable (M) / forgettable (M) distractor (Dist.), memorable/forgettable target, and target present/absent. Error bars indicate standard error of the mean. Two 2-way ANOVAs were tested on these slope data examining the interaction of target memorability and distractor memorability, separately for target present and target absent trials. For target present trials, memorable targets had significantly higher slopes than forgettable targets for target present trials (* = main effect of target memorability, $p = 0.014$), while there was no difference based on

distractor memorability, nor a statistical interaction between targets and distractors. For target absent trials, no significant differences were found amongst conditions.

For the target present trials, there was a significant main effect of set size (F=126.98, $p <$ 0.001), with larger set sizes resulting in a longer RT, as expected. There was also a significant main effect of target memorability (GLMM: F=13.55, p < 0.001; main effect of target memorability in 2-way ANOVA on slope: $F(1, 68)$=6.36, p=0.014, η_p^2=0.086), with memorable targets identified faster than forgettable targets (dark red versus light blue solid lines in Fig. 7A). However, there was no significant main effect of distractor memorability (GLMM: F=1.90, p=0.169; ANOVA on slope: $F(1, 68)$=0.920, p=0.341, η_p^2=0.013; BF_{01} = 4.17; the dark red versus light blue solid lines in Fig. 7B). There was also no significant statistical interaction of distractor memorability and target memorability (GLMM: F=0.16, p=0.685; ANOVA on slope: $F(1, 68)$=0.522, p=0.473, η_p^2=0.008), nor distractor memorability and set size (F=1.03, p=0.310). There was a significant statistical interaction of target memorability and set size (F= 4.73, p=0.030). Looking at paired t-tests of target memorability at each set size, while there is a significant effect of target memorability at the lower set sizes of 4 ($t(71)$=3.11, p=0.003) and 8 ($t(71)$=2.61, p=0.011), there is no effect at the sizes of 12 ($t(63)$=1.01, p=0.316, BF_{01}=4.49) and 16 ($t(63)$=0.572, p=0.569, BF_{01}=6.24). There was no significant 3-way interaction of distractor memorability, target memorability, and set size (F=0.001, p=0.970).

The target absent trials showed a similar pattern (Fig 7). Based on a three-way GLMM (target memorability × distractor memorability × set size) for target absent trials there was again, as expected, a significant main effect of set size (F=331.89, p < 0.001), where it took participants longer to confirm a target absent trial with more stimuli. There was no significant main effect of target memorability (GLMM: F=0.03, p=0.864; ANOVA on slope: $F(1, 68)$=0.40, p=0.530,

η_p^2=0.006), and no significant main effect of distractor memorability (GLMM: F=0.23, p=0.631; ANOVA on slope: $F(1, 68)$=2.33, p=0.131, η_p^2=0.033). There was no statistical interaction of target memorability and set size (F=2.56, p=0.110), no interaction of distractor memorability and set size (F=1.38, p=0.240), and no interaction of target memorability and distractor memorability (F=1.05, p=0.305; ANOVA on slope: $F(1, 68)$=3.30, p=0.074, η_p^2=0.046). There was also no significant 3-way statistical interaction of target memorability, distractor memorability, and set size (F=0.194, p=0.660). Looking at paired t-tests of target memorability at each set size, there is an effect of target memorability at the set sizes of 4 ($t(67)$=2.91, p=0.005), 8 ($t(67)$=2.34, p=0.022), 16 ($t(68)$=4.35, p=4.75×10^{-5}), but not at 12 ($t(67)$=0.15, p=0.881, BF_{01}=10.37).

This visual search task reveals a significant effect of target memorability on visual search, where memorable targets are identified more quickly than forgettable targets. These results fit in with previous predictions that more distinctive, as well as unfamiliar, images tend to be more quickly identified (Treisman & Gormican, 1988; Wang et al., 1994; Wolfe, 2001), and indicate that memorable items may also capture attention. At the same time, memorability does not "pop out" of the search display like other features might, as evidenced by the steep (rather than flat) search slopes. It thus seems likely that memorability may be an image property that requires deeper processing than more "pop-out" image properties (it similarly does not cause automatic spatial cueing: see *Supplemental Information*).

There are also still open questions on the extent to which memorability influences visual search. An effect of target memorability appears at three set sizes in the target absent trials, although there is no target in the search display to capture attention. There may thus be a memory-related (rather than attention-based) effect of the memorability of the target cue on performance (i.e., it is harder to remember a forgettable target cue, so participants must refer back to it more frequently, which slows them down). Second, the effect of target memorability when the target is present only occurs at the smaller visual search set sizes (4 and 8), indicating that the effect is dependent on specific testing parameters. Lastly, there was no effect on search times of distractor memorability – an array of memorable distractors does not automatically capture attention and slow down search. In sum, these results provide evidence for memorability as a higher-order visual property that may cause attentional capture in specific cases, but does not cause automatic "pop-out" or always capture attention. Thus, it seems unlikely that the neural sensitivity in the ventral visual stream to memorability is solely driven by increased attention for memorable images. However, could these patterns of memorability instead be explained by another automatic memory phenomenon: priming?

5. Experiment 4: Memorability and Priming

5.1 Introduction

As memorability appears to be a nonconscious, automatically processed stimulus property related to memory that is independent of attentional effects, how is it linked to perceptual priming, a similarly automatic and nonconscious form of memory (Tulving & Schacter, 1990)? Like memorability, perceptual priming is unaffected by changes in low-level visual features (Fiser & Biederman, 2001) and top-down attention (Vuilleumier et al., 2005). Memorability might thus reflect the "primability" of a stimulus – to what degree behavioral and neural responses are affected by increasing repetitions of an initially novel stimulus. Memorable images might be those that cause greater priming effects, while forgettable images show less priming.

To test the link between memorability and “primability”, a perceptual priming experiment was conducted, in which participants had to rapidly categorize scene images for indoor / outdoor (Experiment 4-A) or natural / manmade (Experiment 4-B). Images were repeated four times each, but with the repetitions spread across the stimulus presentation stream in a randomized order. Due to perceptual priming, with increasing repetitions a stimulus will become easier (and faster) to categorize. If memorability and primability are linked, then memorable images should show a more pronounced drop in reaction time with each repetition, in comparison to forgettable images. However, if memorability and primability are separate phenomena, then the memorability of the stimulus should not affect repetition priming effects.

5.2 Materials and Methods

5.2.1 Participants and Stimuli

Forty-nine participants recruited from AMT participated in Experiment 4-A, and a separate set of 48 participants participated in Experiment 4-B. For this experiment, scene images were used instead of face images, as they can be quickly categorized for multiple category dichotomies (e.g., indoor / outdoor, natural / manmade), yet do not have the same demographic-based biases as faces (Chiroro & Valentine, 1995; Anastasi & Rhodes, 2005). The scene images came from a highly controlled stimulus set for both low-level visual features (e.g., color, spatial frequency) and higher-level attributes (e.g., number of objects, average object size; see Fig 1 for example images), demonstrated to show different patterns in the brain for high versus low memorable images (Bainbridge et al., 2017). The original scene images came from the SUN Database, with over 131,000 images (Xiao et al., 2010; Isola et al., 2013). Images were selected to fall into two conditions: memorable scenes (top 25% of HR; M=0.98, SD=0.02) and forgettable scenes (bottom 25% of HR; M=0.69, SD=0.09). There was no significant difference between the two sets in false alarm rate (*p*=0.06).

For Experiment 4-A, the scene images varied along two factors with 4 conditions total, with 12 stimuli each, or 48 stimuli total: 1) memorable or forgettable, and 2) indoor or outdoor. Experiment 4-B had the same stimulus condition distributions, except its second factor was natural or manmade, and all images were outdoor scenes.

5.2.2 Experimental Methods

Both experiments were conducted using PsyToolkit and followed the same experimental paradigm (Fig 8). For each trial, a fixation cross was displayed for 300 ms. A scene image was then presented at central fixation, and participants were given 2000 ms to classify the image as indoor or outdoor in Experiment 4-A or natural or manmade in Experiment 4-B with a key press, with reaction time recorded. Each image was repeated four times over the course of the experiment in a randomized order, although participants were not told in advance that they would see image repetitions. Participants were informed if they responded incorrectly, or took too long (over 2000 ms) to respond, to encourage quick and accurate responses. For both experiments, participants completed 192 randomized order trials, which took approximately 3 minutes in total. Only trials with the correct task responses were used in the analyses.

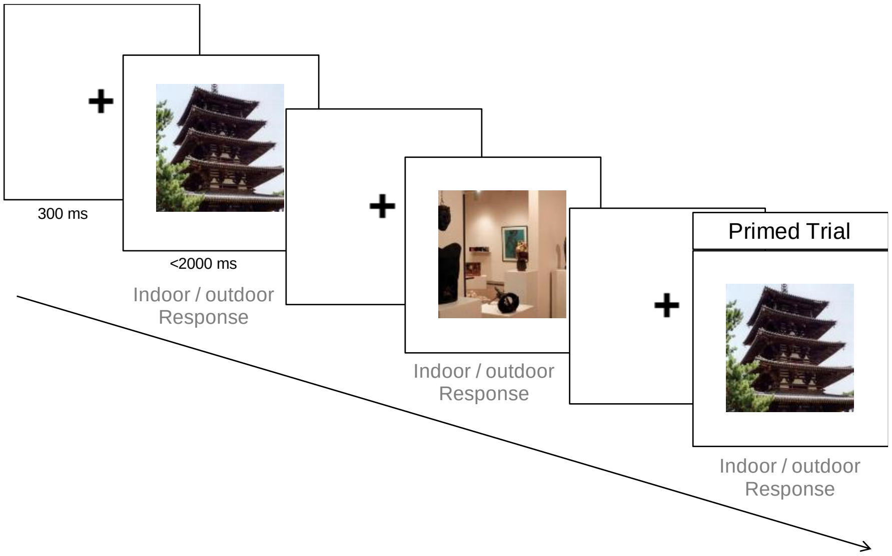

Fig 8. The perceptual repetition priming experimental paradigm for Experiment 4. Half of the images were highly forgettable, while the other half were highly memorable. Participants responded as quickly as possible to a perceptual categorization task (indoor / outdoor for Experiment 4-A, natural / manmade for Experiment 4-B) for a stream of images, where sometimes an image would repeat. On these repetition trials, we can observe the effects of perceptual repetition priming (reaction time decreasing on repeated stimuli), and if this differs between memorable and forgettable stimuli.

5.3 Results and Discussion

5.3.1 Experiment 4-A: Indoor / Outdoor Task

A graphical summary of the results can be seen in Fig 9. A 2-way repeated-measures ANOVA (memorability × repetition number) was conducted on RT. As expected based on previous perceptual priming work (Wiggs & Martin, 1998; Turk-Browne et al., 2006), with increasing repetitions of an image, participants were able to more quickly identify it as indoor/outdoor ($F(3, 184)$ 29.23, $p=2.60\times10^{-12}$). However, memorable and forgettable images had no significant difference in how long it took to classify them as indoor/outdoor ($F(1, 184)=0.002$, $p=0.968$, $BF_{01}=4.89$). There was also no significant statistical interaction between the two factors for RT ($F(3, 184)=1.54$, $p=0.213$, $BF_{01}=2.26$), indicating that forgettable and memorable images did not experience different degrees of priming. A GLMM on RT as a dependent variable and modeling memorability as a categorical factor and repetition number as a continuous factor shows the same patterns; RT speeds up with more repetitions ($F=9.36$, $p=0.002$), but memorability shows no effect ($F=0.17$, $p=0.679$), nor is there a statistical interaction between memorability and repetition number ($F=0.26$, $p=0.611$). Based on paired t-tests, forgettable images and memorable images showed no significant RT differences at any repetition number (all $p > 0.05$). Thus, while scene images do show perceptual priming, there appears to be no differences between memorable and forgettable images.

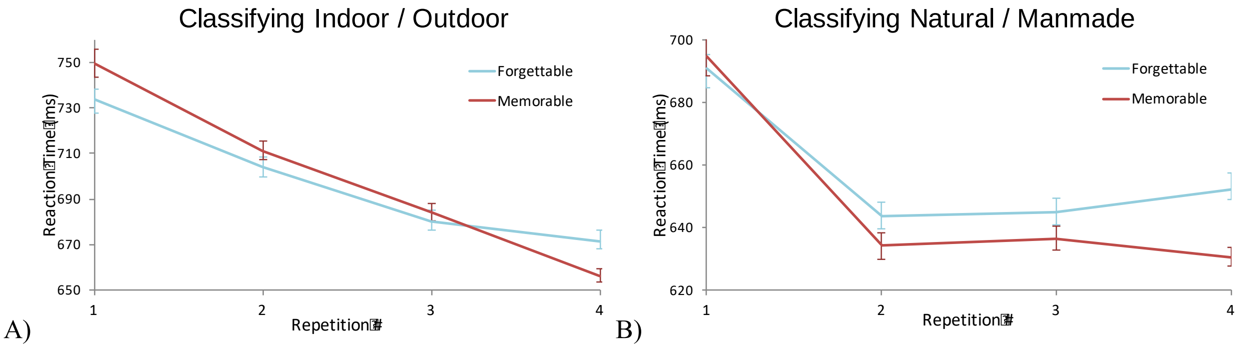

Fig 9. Mean reaction times for forgettable versus memorable scenes in the two perceptual priming experiments. (A) Experiment 4-A (indoor / outdoor). Perceptual repetition priming occurred equally for forgettable and memorable images. (B) Experiment 4-B (natural / manmade). Again, there was no significant effect of memorability, nor an interaction of perceptual repetition priming effect and memorability, showing that memorability is unlikely to be equivalent to “primability”. Error bars indicate standard error of the mean.

5.3.2 Experiment 4-B: Natural / Manmade Task

The study was replicated using a different categorization task (natural/manmade), see Fig 9. Again, there was a significant effect of image repetition on classification speed ($F(3, 184) =13.39$, $p=5.55\times10^{-7}$) but no effect of memorability ($F(1, 184)=4.14$, $p=0.054$), although the Bayesian Factor analysis provides unclear evidence, $BF_{01} = 0.67$. However, importantly there was no statistical interaction between image repetition and memorability ($F(3, 184)=1.27$, $p=0.293$, $BF_{01}=2.58$), indicating that the effect of memorability does not change with priming. A GLMM modeling memorability as a categorical factor and repetition as a continuous factor also finds a significant effect of repetition ($F=5.67$, $p=0.018$), but no effect of memorability ($F=0.09$, $p=0.767$) nor a statistical interaction of memorability and repetition ($F=0.43$, $p=0.514$). Looking at each repetition using paired t-tests, memorable images were significantly faster to classify than forgettable images at the forth repetition ($t(47)=3.31$, $p=0.002$), however there were no significant differences at the first, second, or third presentations of the image (all $p > 0.40$). Again, this study shows no strong evidence for a differential repetition priming effect between forgettable and memorable images.

Both Experiments 4-A and 4-B replicate the finding that while people become faster at categorizing scenes (for either indoor/outdoor or natural/manmade) with increasing repetitions of an image, this speed increase (or “primability” of the stimulus) is not related to memorability. These current results show evidence that memorability does not resemble other common implicit memory phenomena, such as repetition priming, despite being a similarly automatic, unconscious marker of memory.

6. Discussion

This set of four experiments elucidates the role of intrinsic stimulus memorability in memory encoding, and how it relates to other key attentional and memory processes (Tulving, 1985). Namely, this study shows that:

Memorability effects cannot be overridden by cognitive control, as you cannot make yourself forget a memorable image, or remember a forgettable image (Experiment 1).

Memorability effects are independent from the depth at which images are processed – whether judging the color of a fixation cross or the honesty of a face, memorable images are better remembered than forgettable ones (Experiment 2).

Memorability does not cause automatic bottom-up attentional capture, as memorable images do not pop-out in a visual search task, and the effect of target memorability on search times is tenuous (Experiment 3).

Memorability is independent from priming – although these are both automatic, unconscious forms of memory, these are two separate memory phenomena (Experiment 4).

Stimulus memorability is thus separate from other attentional and priming processes known to affect memory. This is somewhat surprising, as memorability is originally measured by aggregated memory performance, yet it does not show the same malleability to cognitive control and task encoding depths that individuals' memory performance does. This measure of memorability thus must be picking up on something intrinsic to the images themselves that then aids in higher memory performance. The full nature of what makes an image memorable is still largely a mystery, as both low-level visual saliency accounts (Isola et al., 2011a) as well as mid-level semantic features such as attractiveness and emotion have not successfully fully captured the variance of memorability (Bainbridge, 2013). Current work is investigating the role of second-order attribute interactions in explaining memorability (such as image-space sparseness, Lukavský & Děchtěrenko, 2017), as well as using convolutional neural networks to learn the features that make an image memorable (Khosla et al., 2015). Current views suggest that stimulus memorability is capturing an aspect of the statistical relationship of a stimulus to the visual world, which can help prioritize distinctive information for memory encoding (Bainbridge, 2019). The fact that memorability effects are immutable in the face of cognitive control, task depth, and top-down attention implies that the effects of the stimulus are powerful, and potentially meaningful for a range of applications. Knowing that certain images are going to be remembered and certain others will be forgotten regardless of the observer, task, and image context has resounding implications for education, entertainment, and the design of treatments for those with memory impairments (Bainbridge et al., 2019). Additionally, this means memorability may be an important attribute to measure and control for when designing experiments of vision and memory, as the effects of the stimuli could override the effects of the task manipulation. Indeed, several image features have been shown to be correlated with memory distortions (i.e., boundary transformations) of an image (Bainbridge and Baker, 2020). It will be particularly interesting to observe how top-down attention and memorability processing interact in the brain, and how they relate to memory encoding and retrieval. Would a directed forgetting task (as in Experiment 1) show two different networks that influence memory outcome – one driven by the memorability of the stimuli, and one driven by cognitive control of memory? Could successful directed forgetting be predicted at the trial-level by the interaction of these two networks? Additionally, how might this interaction be manipulated by modulating a reward incentivizing control of memory?

While these results show that memorability is impervious to top-down memory strategies, they also show a difference between memorability and other automatic memory phenomena. Like other markers of implicit memory phenomena like priming, memorability processing is automatic (Bainbridge et al., 2017) and rapid (Mohsenzadeh et al., 2019), even when participants are performing an entirely perceptual task during the studying of images (as replicated in Experiment 2). However, based on the results of the current study, it appears the automaticity of this processing of memorability is not due to a striking visual salience that causes memorable images to “pop-out” and capture attentional resources. Indeed, all stimuli used in this study were highly controlled for low level visual attributes (color and spatial frequency), and neuroimaging work using this same stimulus set shows no activation or pattern difference between memorable and forgettable images in early visual cortex (Bainbridge et al., 2017). Memorability also does not show a relationship to priming in the current study, although sensitivity to memorability has been identified in the perirhinal cortex (Bainbridge et al., 2017), a region also implicated in repetition suppression due to priming and familiarity-based recognition (Heusser et al., 2013; Wang et al., 2014). In contrast with priming and familiarity which depend upon stimulus repetition, memorability effects manifest at the level of single trials for novel images in the context of a perceptual task (Bainbridge et al., 2017). Interestingly, we did not find memorability was affected by image repetitions in the current study, suggesting memorability may not be directly impacted by familiarity. Thus, a key next question will be to directly compare the neural effects of memorability and familiarity given that they show a behavioral dissociation: do neural memorability patterns remain consistent with repetitions of an image, and how do memorability effects compare to effects of highly familiar images versus novel images? As an initial first step, Bainbridge & Rissman (2019) found dissociable regions sensitive to stimulus memorability (measured by a large-scale crowd-sourced recognition test on the stimuli) versus an individual subject's memory performance (measured by hits versus misses), where stimulus memorability sensitivity occurs in MTL and late visual areas, while individual subject memory performance is reflected in parietal and frontal cortex. Other work has suggested a triple dissociation of recollection, familiarity, and novelty in the MTL (Daselaar et al., 2006), and so perhaps looking at the dissociation of recollection versus familiarity from the angle of the stimuli rather than the observer (i.e., memorable versus familiarized stimuli) may give greater insight into the steps the brain takes between perceiving an item and encoding it.

Overall, these results indicate that sensitivity to stimulus memorability is an automatic process separate from attentional capture and priming. This process is highly resilient to intentional strategies that influence memory performance, including cognitive control and more elaborative processing. While previous neuroimaging results had hinted at the automatic and rapid nature of memorability processing, these results highlight its key differences from other cognitive phenomena known to influence memory performance. Future work will need to pinpoint the calculations the brain is making when it is sensitive to the memorability of a stimulus and understand how this information aids in memory encoding success. Additionally, there is the broader question of what aspects of an image make it memorable, and how that relates to the statistics of our surrounding visual world. In sum, memorability is an independent, intrinsic property to images, occurring as a strong, automatic determinant of what we will ultimately remember, resilient to outside influence.

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