Memorability: How what we see influences what we remember

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Abstract: Everyone has a unique set of individual experiences that make up their memories. However, we all also continuously encounter some items that are incredibly easy to remember and others that are too easy to forget. Indeed, recent work has found that the intrinsic *memorability* of an image can be quantified and used to predict memory behavior broadly across people, despite our diverse experiences. In this chapter, I describe memorability as an intrinsic stimulus property from the perspectives of psychology, neuroscience, and real-world applications. First, I compare past and new perspectives on memorability as a means to quantify an image. I discuss how it relates to other stimulus attributes, and other cognitive phenomena such as attention and cognitive control, and show that memorability effects are largely distinct.

Next, I describe the current understanding based on recent neuroimaging research of how, where, and when the brain distinguishes memorable versus forgettable images. Finally, I explore real-world applications of memorability in clinical and computational modeling domains, and present potential avenues for future exploration.

Keywords: memorability, distinctiveness, perception, memory, neuroimaging, attention, neural networks

1. Introduction

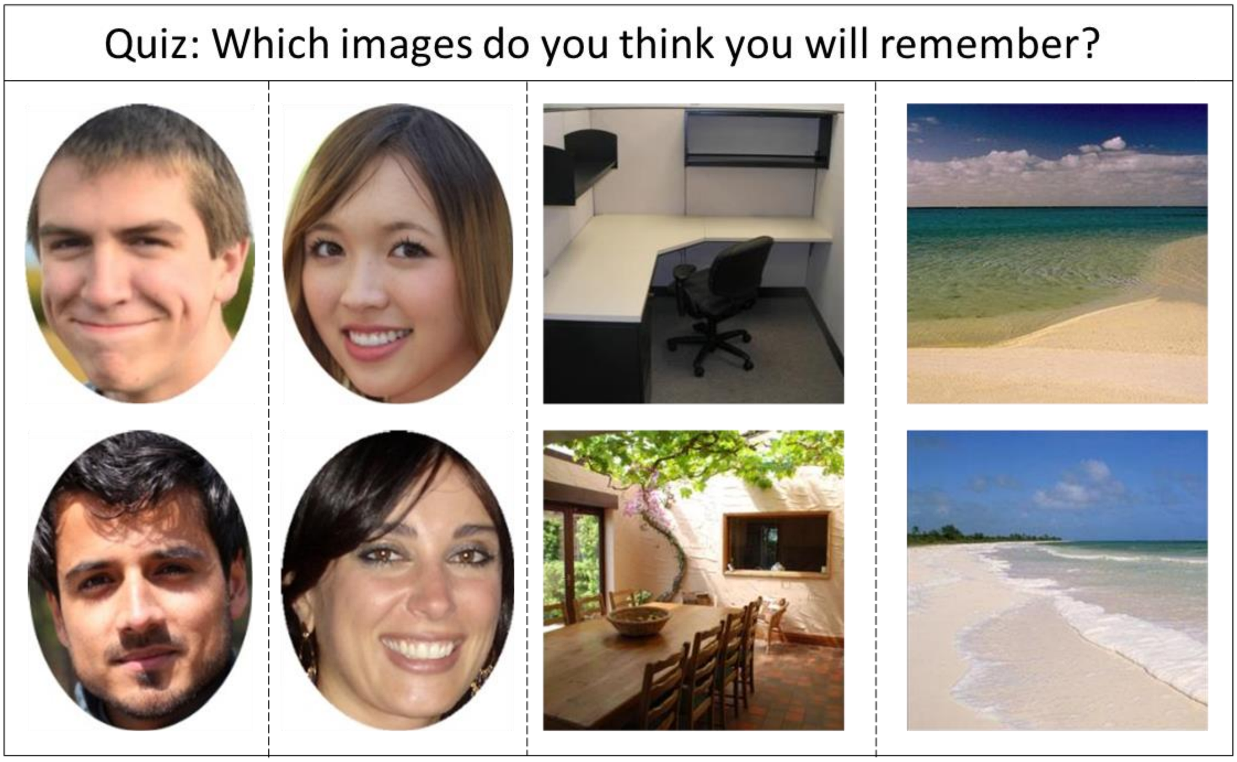

Figure 1 – Which image do you think you will be more likely to remember in each vertical pairing—the top or the bottom image? See the bottom of the first paragraph for the answer.

Take a look at the faces and scenes above (Figure 1). For each vertical pair of images, which do you think you will remember better—the top or the bottom image? (The answer is at the end of this paragraph.) People are readily able to form intuitions of what they believe they will remember (e.g., the well-lit, tree-filled dining room seems obviously more striking and beautiful than the dull office scene), but surprisingly, people have relatively little insight into what they will actually remember or forget. In fact, people cannot guess what they will remember much better than chance (Isola et al., 2014). What is even more surprising is that despite this lack of metacognitive insight into memory, recent research has found that there are consistencies in the images that we do remember or forget. In other words, people tend to remember and forget the same items as each other, in spite of different individual experiences with, for example, faces and scenes. We can then conceptualize *memorability* as an intrinsic, measurable property of a stimulus, measuring the likelihood for any given person to remember that image later. So, while you may not be able to tell which images you will recognize from Figure 1, we as researchers can tell with a degree of certainty which of the above you will remember, based on their measured memorability alone: 30% more people will remember the top row of images over the bottom row.

In this chapter, I will unfold the concept of memorability and discuss the current state-of-the-art research on the topic, particularly for *visual* memorability. First, I will discuss the foundational research showing how and why memorability can be thought of as an intrinsic attribute of a stimulus in spite of our wide ranging individual experiences. Second, I will describe research exploring what other image attributes relate to memorability (i.e., could it be a proxy for something else, like aesthetics?) as well as how other cognitive phenomena (e.g., attention, priming) relate to memorability. Third, I will discuss what may be happening in the brain when we view memorable images, and how such neural processing relates to better understood processes of vision and memory. Finally, I will present exciting possible applications of memorability research, from computer vision to clinical applications, that can help us understand and better create a more memorable sensory world.

2. Memorability as an Intrinsic Stimulus Attribute

A. Memorability as a means to measure face distinctiveness

Memorability can be quantified as essentially any performance metric from a memory test. While much recent work has used recognition hit rate (HR) as a measure of memorability (Isola et al., 2011; Bainbridge et al., 2013), several works also use metrics that incorporate false alarm rate (FA), such as d-prime (Bainbridge, 2017) or corrected recognition (Bainbridge & Rissman, 2018). For several decades within the memory literature, the word “memorability” has been used as a way to loosely mean “images with high memory performance” based on these performance metrics. In 1966, when the Dow Chemical Company was looking for a means to quickly warn people of the risk of infectious hazards, they conducted a large-scale national study with 300 participants to find an ideal symbol that would lack intrinsic meaning yet be memorable (Baldwin & Runkle, 1967). They settled on the biohazard symbol still used today (☣), which was the best remembered, yet assigned the least meaning in their experiment. This meant people viewing the symbol would be able to quickly identify it (and thus a toxic hazard), without confusing it with something else.

Scientifically, memorability as an attribute with which to understand images became increasingly important from the late 1970s up to the early 1990s, as researchers were exploring the factors that influence face memory. Memorability was studied as it related to perceptual attributes like *distinctiveness* and *typicality*, in light of models of face memory representations as forming a multidimensional face space (Valentine, 1991). Specifically, these models suggest that our mental representation of a face exists as a point positioned amongst multiple sets of axes representing various attributes of a face, centered around either a prototype or an average (Valentine et al., 2016). The axes are most often proposed to be physical traits such as age, race, face shape, and hair features (Valentine, 1991; Busey, 2001); however, others propose more socially-driven features like dominance and valence (Oosterhof & Todorov, 2008). An individual face would be represented as a vector made up of values along each of these axes: e.g., high dominance, low valence, etc. Observers are fastest to recognize items without many surrounding items in their representational space, and distinctive faces are those that are far from the center, with sparse competition, and thus they are remembered best. Various studies found that higher distinctiveness of a face—measured either by subjective ratings (Light et al., 1979; Winograd, 1981; Bartlett et al., 1984; Vokey & Read, 1992), geometric distances from an average face (Bruce et al., 1994), or computational models (Busey et al., 2001; Hancock et al., 1995)—resulted in that face being more memorable, while faces closer to the center of the representation (i.e., typical faces) seemed more familiar (as measured by false alarm rate, FA). Indeed, exaggerating the distinctiveness of a face (dubbed the *caricature effect*) causes improved recognition of that face (Rhodes et al., 1987; Mauro & Kubovy, 1992). This distinctiveness-based hypothesis of face memory representations also provides an explanation for the observed phenomenon of the *own-race bias*, where one better recognizes members of their own race than another's (Valentine & Endo, 1992). People with homogenous racial experiences theoretically learn a visual face representation based on that singular race, and aren't able to generalize to other races. However, this effect goes away as people experience more contact with other races (Chiroro & Valentine, 1995).

Memorability was thus largely studied as an *outcome* of perceptual distinctiveness, with some work equating the two (e.g., Bruce et al., 1994: "for the moment, we use the two terms [memorability and distinctiveness] interchangeably"), and most work not considering memorability as a separately measurable image attribute. While visually distinctive faces tended to elicit better memories, distinctiveness could not fully account for the spread of memory performance (Shepherd et al., 1991; Bruce et al., 1994). Other than distinctiveness, it was not clear what might make an image more memorable, or whether memorability itself beyond distinctiveness was an interesting or meaningful face attribute to explore.

B. Memorability as an isolated image attribute

The early 2010s saw the explosion of powerful internet speeds and capacity and, with it, large-scale databases of thousands of images. Reborn from this vast amount of data came a new question related to memorability: what could we glean from these images in how they influenced human memory? Previous research had shown an impressive capacity to visual recognition memory, with observers able to successfully recognize (over 90% performance) over 2,500 studied new images (Standing, 1973; Brady et al., 2008). However, in spite of this high performance, some items fared better than others. Was this just due to random error, or were there consistencies in people's performance at the item level? To explore this question, Isola and colleagues (2011a) tested a set of 2,222 scene images from the Scene Understanding Database (SUN; Xiao et al., 1010) in a simple online memory test: participants on online crowd-sourcing platform Amazon Mechanical Turk (AMT) viewed a stream of images, pressed a button for any repeated images, and then were compensated at the end of the experiment for their participation. Each image was seen by approximately 80 participants, and their combined hit rate for an image was used as a measure of the memorability of the image. Memory performance was moderately high (M=67.5%, SD=13.6%), with a mean false alarm rate of 10.7% (SD=7.6%).

However, the linchpin of this work was in Isola and colleagues' consistency analysis. They split their participants into two randomly chosen halves and separately calculated the memory performance for each image based on each half. They then took these two sets of image-based memory performance scores and correlated them with each other to measure the consistency in performance between the halves. These split halves were repeated over 25 iterations and averaged, so that any findings were not accidentally due to the randomly chosen halves. What they found was a high correlation between these split halves (Spearman's rank correlation ρ=0.75); what one half of the participants remembered was generally what the other half also remembered. In other words, hit rates (or memorability scores) are highly consistent across people—even though this experiment was tested with a highly heterogeneous online sample. This also means that memorability can be conceptualized as a continuous, intrinsic stimulus property that can be measured or even manipulated.

However, it was possible that such effects were largely thanks to a diverse image set, with both highly variable visual attributes (e.g., visual clutter in the image) as well as semantic features (e.g., scene category). How would such a study fare in the realm of faces, which are much more visually and semantically homogenous? We conducted a similar online memory experiment, collecting memorability scores for 2,222 face images (Bainbridge et al., 2013). These faces came from the 10k US Adult Faces Database (Bainbridge et al., 2013), which contains over 10,000 faces that are unfamiliar, non-celebrities with demographics matching those of the United States Census (e.g., age, gender, race). We found generally lower levels of memory performance compared to scenes (HR: M=51.6%, SD=12.6%; FA: M=14.4%, SD=8.7%), however again there was significant consistency across split-halves of participants (ρ=0.68). Further, memorability was shown to account for as much as 50.5% of the variance in memory performance, meaning that these intrinsic stimulus qualities are a large factor in what we will ultimately remember.

Beyond face and scene images, memorability is also robust within several other types of items. Abstract visualizations (graphs, figures, and infographics) show high consistencies in memorability (ρ=0.83; Borkin et al., 2013), as do simple words (ρ=0.58; Mahowald et al., 2018). Objects within scene images also show intrinsic memorabilities, which in turn influence the memorability of that scene itself (Dubey et al., 2015). Intrinsic memorability is also not merely limited to static images. In spite of how difficult unfamiliar face identity recognition is (Bruce, 1982; Hill et al., 1997; Henderson et al., 2001; Jenkins et al., 2011), memorability ranking is intrinsic to a face identity, across transformations of a face, such as expression or viewpoint changes (Bainbridge, 2017). Memorability is also intrinsic to video stimuli; Cohendet and colleagues (2018) found significantly high consistencies (ρ=0.57) in memory performance for 10-second clips from movies participants had seen before in their lives, up to years prior. These results suggest that memorability may be an intrinsic attribute of a wide range of stimulus types, even those with very different visual and semantic structure (e.g., words, graphs), and for dynamic, changing stimuli such as videos or faces.

While this body of work has shown high consistency in people's memory performance for a wide variety of stimulus types, the natural next question is: why? What causes an image to be memorable or forgettable? How does our new perspective on memorability relate to the previous understanding of it as a means to measure visual distinctiveness? And, to what degree can stimulus-driven memorability effects on a person's memory performance be explained, or mitigated, by other cognitive processes, such as attention? In the next section, I discuss the current understanding of what makes an image memorable.

3. Memorability in Relation to Other Stimulus Attributes and Cognitive Phenomena

A. Memorability and other image attributes

Intuitively, it feels like memorability should be easy to relate to other well-characterized image properties, such as visual distinctiveness, aesthetics, or visual saliency. However, thus far, while the field has identified several characteristics that correlate with memorability, it has not yet identified any combination that fully defines it.

Multiple studies have found that simple image features such as hue, saturation, or spatial frequency (i.e., amount of details versus gist-like visual features) do not correlate strongly with memorability (Isola et al., 2014; Dubey et al., 2015; Bainbridge et al., 2017). In comparing the influence of low-level visual versus semantic content on memorability, Lin et al. (2018) found that scrambled images removed of a majority of semantic content (but with preserved low-level visual content such as color and edges) still retained consistencies in memorability, but only at very short time periods (seconds rather than minutes). This means that a large degree of memorability effects may be due to higher order perceptual properties, or deeper semantic or conceptual aspects of the image.

Several aspects of image content important to capturing attention or triggering emotion have surprisingly little correlation with memorability. The number of objects or image coverage by objects in a scene is not related to the overall scene's memorability (Isola et al., 2011), and scene properties such as aesthetics, how interesting a scene is, and how memorable people think it will be (subjective memorability) are also not correlated with memorability (Isola et al., 2014). However, scene images with faces or text tend to be highly memorable, and a combination of semantically-based object and scene attributes (e.g., object/scene category, emotion, actions, dynamics) is predictive of memorability. Again, memorability appears to relate best to semantic properties of an image rather than more visually-related properties of an image.

The story is less clear for the case of novel faces, where perceptual or semantic features are less variable (i.e., faces have the same basic-level category and their components don't vary by category). A comprehensive set of face and memory attributes from the literature (Vokey & Read, 1992; Oosterhof & Todorov, 2008), including typicality/atypicality (i.e., distinctiveness), attractiveness, emotion, and subjective ratings of memorability, were compared to actual memorability scores (Bainbridge et al., 2013). Several of these attributes were correlated with memorability, as expected: atypical, subjectively memorable, unfamiliar, and uncommon faces tended to be more memorable. Memorable faces also tended to be rated as more emotional, irresponsible, unattractive, and unintelligent (although they were generally more kind and trustworthy). However, the sum of this comprehensive attribute set was only able to account for 46.6% of the variance of memorability (Figure 2), indicating that face memorability cannot be fully explained as a compound of other well-known semantic face attributes. Also, perceived distinctiveness of faces, even captured by several terms (atypical, unfamiliar, uncommon) does not fully explain face memorability. Looking at facial distinctiveness in a more quantified manner, Euclidean distances between facial points (e.g., tip of nose, corner of right eye) on an individual face and the corresponding points on an average face do not show correlations with memorability; in other words, actual visual distance from an average face does not predict memorability. Finally, while attractiveness and memorability remain unchanged across different image transformations (viewpoint and expression changes) of the same face identity, no other attribute does (including atypicality or subjective memorability; Bainbridge, 2017). These results serve as a surprising contrast to previous work that had often equated visual distinctiveness with memorability (e.g., Bartlett et al., 1984; Vokey & Read, 1992; Bruce et al., 1994). This leaves the large, open question of what causes an image to be memorable—if it's not visual distinctiveness, then what? Perhaps these prior findings on the relationship of semantic content to memorability may serve as a clue; perhaps an item can be memorable because of distinctiveness (or, statistical dissimilarity from the patterns of learned experience) in a wide variety of ways: perceptual distinctiveness, semantic distinctiveness, emotional distinctiveness, etc. However, elucidating the determinants of memorability will require future experimentation.

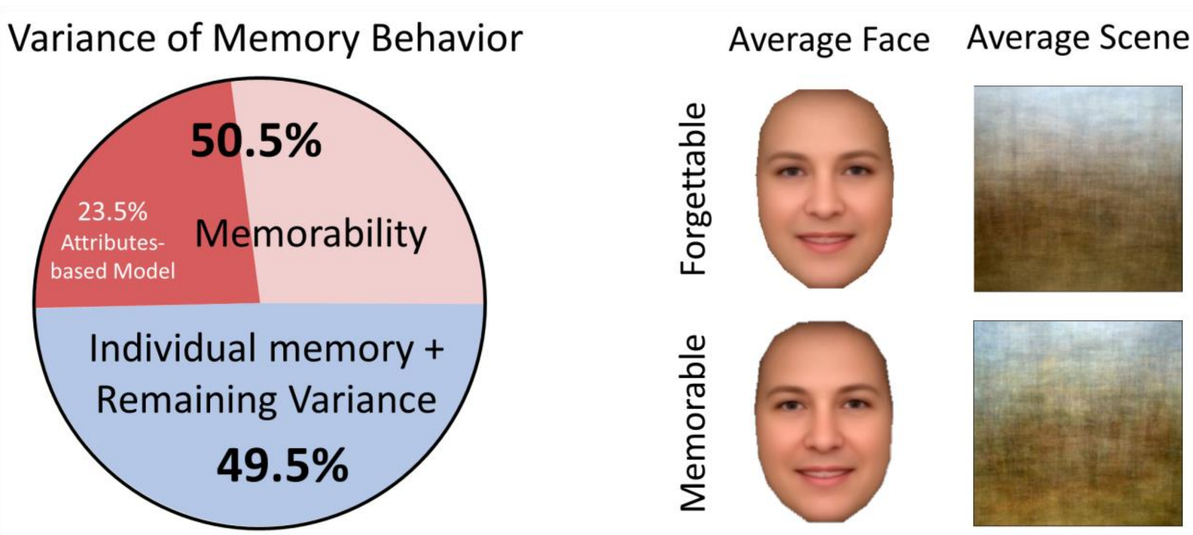

Figure 2 – (Left) The breakdown of the variance of face memory behavior. Fully 50.5% of the variance in memory behavior can be accounted for by the intrinsic memorability of the stimuli themselves, while the remaining variance is a combination of factors related to individual experience, environmental factors, context, noise, and other remaining variance. Within memorability, less than half of its variance can be explained by the contributions of a comprehensive set of other face-related traits, such as attractiveness, distinctiveness, or what people think will be memorable. (Right) The average memorable and forgettable faces and scenes from the stimulus set used in Bainbridge et al. (2017). Although these averages are made up of images from opposite ends of the memorability spectrum, they look largely similar, indicating that memorability cannot be fully described by simple visual features.

B. Memorability and other cognitive phenomena

While the previously discussed studies on memorability have largely used a continuous recognition task, the consistency of memorability has also been tested using other memory paradigms. This is essential in order to know that the effect is robust to the images themselves, rather than the task they're being tested in. Memorability remains consistent when tested in a memory test with separate study and test phases, even when the test phase is a day or a week later (Goetschalckx et al., 2017). This means that memorability effects resonate over a long range of time. Memory performance is dependent to a degree on the images presented in the same context (e.g., a forgettable kitchen may still be memorable if all other images in the experiment are gardens); however, even across different image contexts, images can show an intrinsic level of memorability (Bylinskii et al., 2015). Memorability has been tested mainly using recognition-based paradigms, where a participant indicates if they've seen an item before or not. Interestingly, recent evidence suggests that what is memorable in this sense may not be related to more successful free recall, i.e., reconstructing an image in the absence of any cue (Bainbridge et al., 2019). In fact, there may be different types of images that are intrinsically *recognizable* versus *recallable*. However, no work has yet explored what makes an image easily recallable, and so for this chapter, I use *memorability* to mean *recognizable*.

Beyond memorability, several cognitive phenomena are known to influence memory, including attention (MacLeod, 1989; Chun & Turk-Browne, 2007) and the semantic depth at which we encode memories (Lockhairt & Craik, 1990). In a series of online psychophysical experiments, I investigated how the processes of bottom-up attention, top-down attention (i.e., cognitive control / directed forgetting), depth of processing, and priming related to memorability, and whether they were synonymous with the phenomenon (Bainbridge, 2018). Two paradigms were tested to look at bottom-up attention: 1) a spatial cueing task (as in Posner, 1980), to see if memorable versus forgettable faces on either side of a fixation cross improved performance on an unrelated categorization task, and 2) a visual search task, to see if memorable images (as a search target or as distractors in a search display) influenced performance in finding a target item. Memorable images neither influenced spatial attention, nor automatically captured attention in a visual search task. Memorable targets only showed a mild speed boost in visual search; however, these effects were present even in the target absent trials (where the target wasn't in the search display, and participants had to indicate as such). This means that while a memorable target was easier to hold in memory, its presence in a search display did not automatically capture attention. As for top-down attention, two key results point to the resilience of memorability effects. First, while participants could intentionally affect their memories to some degree (when cued to forget or remember an image, they could influence their memories, as in MacLeod, 1989), the effects of memorability were stronger; participants could not make themselves forget a memorable image or remember a forgettable image, even when incentivized by a reward. Second, encoding tasks with different levels of semantic depth (shallowest: judge fixation cross color; shallow: judge face gender; deep: judge face honesty) also influenced memory performance as predicted by Lockhairt and Craig (1980), but the effects of memorability were again stronger; no matter how deeply participants encoded images, memorable images still ultimately won in later recognition. Finally, memorability effects were dissociable from priming effects; memorable images did not necessarily cause more priming (i.e., repetitions of a memorable image were not processed more quickly than those of a forgettable image), and thus there are separable implicit effects on memory behavior.

In sum, these results show that memorability is a phenomenon robust to attention, cognitive control, and priming. This has important implications for potential applications of memorability. For example, for an image to be memorable, it does not necessarily have to be visually striking or salient like other image types that cause automatic attentional capture. Second, memorability effects are impressively strong; even with completely unrelated, boring tasks (classifying fixation cross color overlaid on the image), or when you intentionally try to override stimulus memorability, it still has a large sway on what you will ultimately remember. These psychophysical results also leave open the question of what may be happening in the brain when viewing memorable images. The above evidence suggests that memorability processing is automatic and implicit, yet it is not through an automatic capture of attention, nor is it related to the implicit memory effect of priming. In the next section, I describe our current understanding of memorability processing in the brain in an attempt to better understand its relation to the underlying neural substrates for vision and memory.

4. The Neurological Bases of Memorability

A. Spatial representations in the brain

The concept of "memorability" lies somewhere between vision and memory. Memorability is a measurable attribute of an image, just like color, aesthetics, or emotion. Yet, by definition, memorability is defined by the behavioral outcome of memory. Thus, how might the processing of memorable images in the brain compare to what we know about visual processing or memory processing?

In a rapid event-related functional magnetic resonance imaging (fMRI) experiment, Bainbridge et al. (2017) scanned participants in a perceptual task, where they categorized gender for a series of 360 face images and indoor / outdoor for a series of 360 scene images.

Unbeknownst to the participants, the images were composed of half highly memorable images and half highly forgettable images, controlled for several low-level visual features (e.g., color, edges) and mid-level attributes (e.g., emotion, aesthetics, number and size of objects). After the scan, participants were given a surprise recognition test for these images, to see how classical markers of successful memory encoding might compare to processing of memorable images. Contrasting processing for memorable images (of both faces and scenes) versus forgettable ones, we found a significant swath of activation spreading from higher-order visual areas to memory-related regions (Figure 3). These visual areas encompassed regions known to be selective for stimulus properties and stimulus categories, such as the fusiform face area (FFA; Kanwisher et al., 1997) which is selective for faces, the lateral occipital complex (LOC; Grill-Spector et al., 1999) which is selective for objects and shape, and the parahippocampal place area (PPA; Epstein & Kanwisher, 1998) which is selective for scenes. However, the early visual cortex (EVC), known to be selective for low-level visual properties like edge information, showed no difference between memorable and forgettable images, again demonstrating that these memorability effects are not due to low-level visual differences in the images. In terms of memory-related regions, the perirhinal cortex (PRC) and parahippocampal cortex (PHC), regions in the medial temporal lobe (MTL) both implicated in memory processing, and with connections to the hippocampus (Brown & Aggleton, 2001), showed significant sensitivity to memorability, as did the anterior hippocampus.

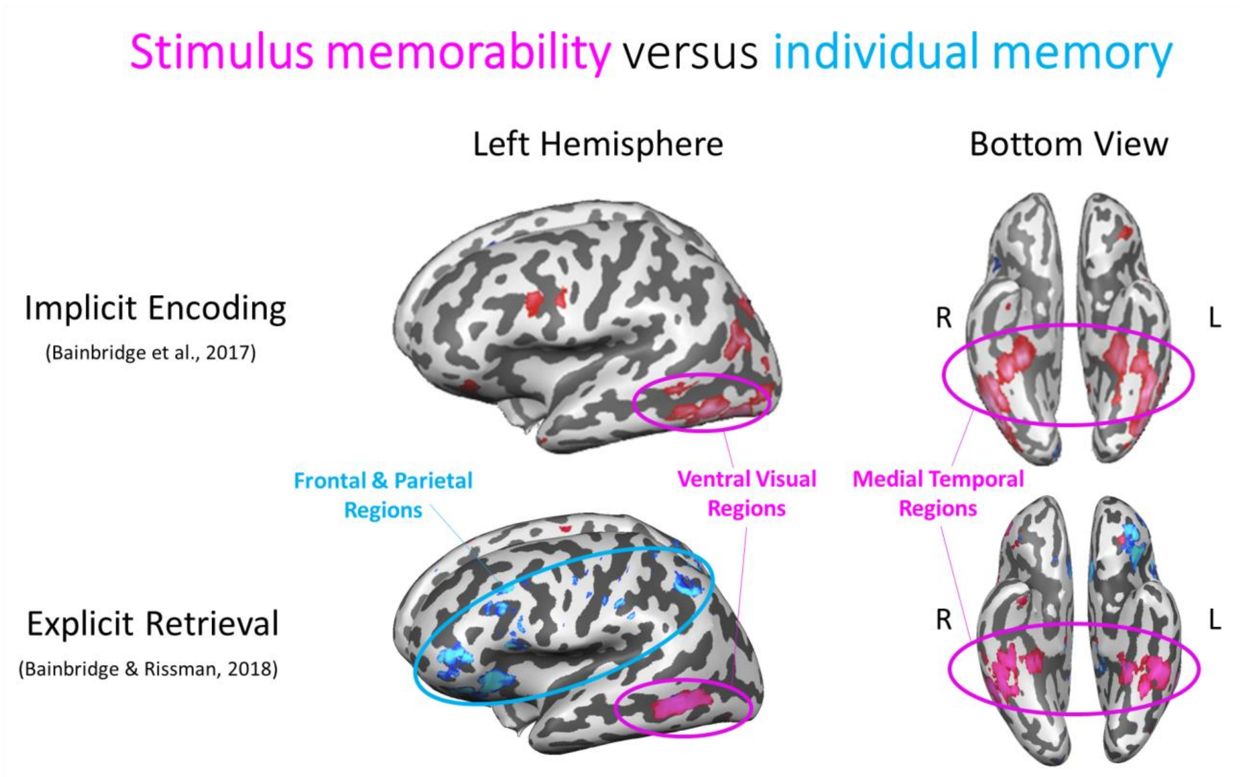

Figure 3 – Regions sensitive to stimulus memorability (black) versus an individual's memory performance (gray). Ventral visual regions and medial temporal lobe regions are particularly sensitive to the memorability of a stimulus, even across different tasks such as an implicit encoding task with faces and scenes (Bainbridge et al., 2017) and an explicit retrieval task with faces (Bainbridge & Rissman, 2018). In contrast, frontal and parietal regions seem particularly sensitive to a classic subsequent memory effect, reflecting what an individual participant remembers or forgets.

Importantly, the neural effects found for memorability are highly distinct from those found for subsequent memory. Many previous studies have used a "subsequent memory" paradigm to record signal for memory encoding (Brewer et al., 1998; Wagner et al., 1998). In these studies, stimuli are sorted post-experiment based on what individual participants remembered or forgot, and then their activation (or patterns) during encoding are directly contrasted. This contrast of later remembered versus forgotten images serves as a means to approximate a signal of successful memory encoding. This signal is specified by each individuals' memory, while in contrast, stimulus memorability is a value that is consistent across individuals. Memorable images are images that are also likely to be successfully encoded, but one can tease apart the two phenomena (*stimulus memorability* versus *individual memory*) by observing cases where the two diverge. Importantly, patterns of memorability remain the same regardless of whether the image is later remembered or not, and similarly subsequent memory activation is the same regardless of stimulus memorability (Bainbridge et al., 2017). Generally, while memorability-based sensitivity appears in more ventral visual and memory-related regions, individual memory-based sensitivity occurs in more parietal and frontal regions, as often reported in the literature (Kim, 2011).

Thus far, these results only show activation differences between memorable and forgettable images (i.e., viewing memorable images results in higher average signal than viewing forgettable images). However, a question of deeper interest is how the brain may organize these memorable or forgettable images. We also tested whether any regions in the brain showed a representational structure corresponding to an organization based on memorability. This was done using a representational similarity analysis (RSA; Kriegeskorte et al., 2008), an analysis where one creates a matrix comparing neural similarity of all pairs of stimuli in the brain, and then can compare such a similarity matrix with a hypothesized model (Figure 4). For example, based on the multidimensional face space discussed above (Valentine, 2001), one might hypothesize that forgettable images would be clustered around the center of the space and be highly similar, while memorable images would be on the outskirts of this representational space and be dissimilar from all other stimuli. Testing this hypothesized model throughout the brain, surprisingly we found the opposite—memorable images tended to be highly similar, while forgettable images tended to be highly dissimilar (Bainbridge et al., 2017). This representational geometry bore out in the same ventral visual and memory-related regions for memorability, while a similar geometry for individual memory again appeared in frontal and parietal regions (Figure 3).

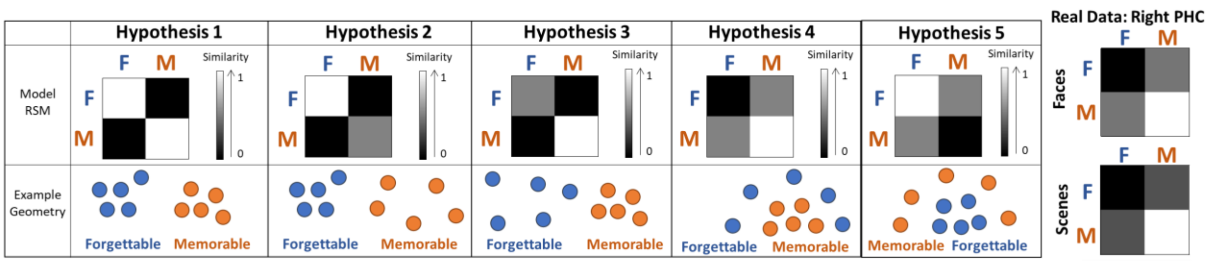

Figure 4 – Hypothesized model representational spaces in relation to memorability. Here are five hypotheses of how stimuli may be represented in the brain based on their memorability. Each hypothesis shows a cartoon illustration of what the representational geometry may look like (i.e., which stimuli are more neurally similar or dissimilar), and has its corresponding representational similarity matrix (RSM). The RSM is a matrix correlating the neural response of each stimulus with every other stimulus. Hypothesized results from same-condition stimuli are averaged to create a simplified representation with four squares. So, for example in Hypothesis 1, forgettable stimuli are highly similar to other forgettable stimuli (white), memorable stimuli are similar to other memorable stimuli (white), but memorable and forgettable stimuli are very different from each other (black). On the right are averaged RSMs created from real data from Bainbridge et al., 2017 in the right parahippocampal cortex (PHC). For both faces and scenes, the data best match Hypothesis 4.

This geometry was confirmed in a separate study by Bainbridge & Rissman (2018) in which we re-analyzed data from an explicit face memory retrieval fMRI study from eight years prior (Rissman et al., 2010). In the new re-analysis, we collected memorability scores for each of the faces in an online memory study, and examined whether we could uncover new memorability-based effects from the original fMRI data. As these stimuli were not originally split into highly forgettable versus memorable stimuli, memorability could also be examined as a continuous metric in the brain. We again found a dissociation of stimulus memorability and individual memory in these same regions, with the same representational geometry, despite a different task (i.e.: separate study and test phases, explicit memory paradigm, scan during retrieval rather than encoding) not originally designed to investigate memorability (Figure 3). Memorability score could also be predicted by activity patterns in these same regions, based on a support vector regression model.

These results show that the brain may specifically represent the memorability of an image, with a representational organization consistent across stimulus types, tasks (encoding and retrieval), and regardless of whether the participant is actively engaged in a memory task or not. The sensitivity shows a representational organization where memorable images are more similar to each other, while forgettable images are more dissimilar. While this geometry runs counter to expectations from a multidimensional attribute space model (Valentine, 2001), it aligns with prior work on subsequent memory finding *pattern completion*, where images that are later remembered tend to have more similar patterns (Chadwick et al., 2010; Xue et al., 2010; LaRocque et al., 2013). However, it is still an open question how intermediary processes may unify these two different models. These results also show that sensitivity to memorability is automatic and exists most strongly in high-order visual regions and memory-related regions, and less so in early visual regions or executive control and attention network regions.

B. Temporal processing

Memorability is processed automatically, but how early is this automatic processing—is it rapid and feedforward, or slower and recurrent? In a rapid serial visual presentation (RSVP) study, Broers and colleagues (2017) had participants view streams of 6 images at a time at very fast presentation rates (as low as 13ms per image and ranging up to 360ms per image), and then, after a delay, report whether they had seen a target image (of either low or high memorability) in that stream or not. Memorable images were recognized significantly better than forgettable images at all image presentation speeds. This means that separations between memorable and forgettable images arise with incredibly brief exposure (13ms), and so in that time, the brain is able to garner enough information to differentiate memorable and forgettable images. A 13ms presentation time may be too short for the brain to conduct recurrent processing with the image (Di Lollo, et al., 2000), and so memorability differences may emerge in the first feed-forward signal. Using the same implicit memorability task as Bainbridge and colleagues (2017) in a magnetoencephalography (MEG) experiment, Khaligh-Razavi and colleagues (2016) found automatic sensitivity to memorability at 200-400ms, in contrast with memory encoding signals they found at 600-800ms. Previous work has identified the 600-800ms time frame as elaborative memory recall (Paller et al., 1988; Friedman & Johnson Jr., 2000), while sensitivity to novelty may occur around 300ms (Friedman, 1990), and links between later perceptual processes and memory may occur around 400ms (Kutas & Federmeier, 2000). Thus, memorability sensitivity may reflect an early interaction between higher-order perceptual processing and stored statistical representations in memory. When the task becomes a more difficult RSVP task (with 11-image sequences, 34ms per image), memorable and forgettable images differentiate in neural signal as early as 149ms (Mohsendazeh et al., 2018). This early differentiation occurs even when only task-irrelevant (non-target) images are analyzed, and even though memorable and forgettable images were controlled to have no low-level visual differences. This signal persisted over long time scales associated with higher level visual processing (up to 300ms). Further, the processing of stimulus memorability occurred after early visual signals (e.g., item decoding occurred around 100ms in Mohsendazeh et al., 2018), but before those items were fully encoded into memory (Khaligh-Razavi et al., 2016). In sum, these temporally-based results show that memorability is rapidly and automatically processed once a stimulus is viewed, and that it occurs at the same processing time scale as higher order image properties such as stimulus category (Liu et al., 2002), after early visual signals but before signals related to elaborative memory encoding.

These neuroimaging results suggest new insights about how we process incoming information and automatically determine whether it should be remembered or forgotten. The automaticity of these memorability-related signals implies that we may already have a mental scaffolding of the statistics of our visual world, against which we compare a stimulus and automatically determine whether it should be remembered. Such a mechanism could be useful in quickly sorting the utility of information, tagging certain items as essential to remember and others as less important, in a world where we are constantly bombarded with novel sensory input that we cannot completely capture in our memories. Such a mechanism may also relate to previous findings of novelty detection, where certain regions of the brain (particularly in the MTL, such as the PRC) are sensitive to new items (Desimone, 1996; Brown & Aggleton, 2001; Daselaar et al., 2006), and show a marked decrease in activity when information is repeated, in a phenomenon called *repetition suppression* (Schacter & Buckner, 1998). Given that all stimuli in the above neuroimaging studies were trial-unique (i.e., presented only once in the experiment) and thus novel, perhaps this novelty detection may be picking up on something larger about the statistical distinctiveness of an input given our learned experiences, or memorability. Ultimately, future work will be needed to understand the neural relationship of memorability effects to other phenomena such as novelty detection (Desimone, 1996), depth of information processing (Dew

& Cabeza, 2013), pattern separation and pattern completion (Leugeb et al., 2007), and recent work finding a sensitivity in the PRC to item significance (Inhoff & Ranganath, 2015). Additionally, while current studies have used either spatially-resolved fMRI or temporally-resolved MEG, a next essential step will be exploring questions about memorability using neuropsychological techniques that can combine timing and space information, so we can see exactly which regions are processing memorability and when. Is the early sensitivity to memorability occurring in visual regions along the ventral visual stream, or in a memory-related area such as the PRC? Visual regions show memorability-based differences even for non-selective stimulus categories (e.g., the face-selective FFA shows higher activation for memorable versus forgettable scenes; Bainbridge et al., 2017). While the work of Broers et al. (2017) and Mohsendazeh et al. (2018) indicate that memorability is processed rapidly in a feed-forward sweep, what later feedback signals might it trigger when processing a stimulus (e.g., does more elaborative visual coding occur for more memorable images regardless of stimulus category)? And, how do other cortical networks related to cognitive control and attention interact with this sensitivity to memorability, to ultimately result in successful memory encoding?

While we still have not achieved a complete understanding of why and how the brain shows processing differences between memorable and forgettable stimuli, our current understanding of memorability already has broad-reaching implications for daily life. In the final section, I present exciting applications of memorability, as well as the important questions that will lay the groundwork for future memorability research.

5. Applications and Future Directions

A. Memorability in the real-world

Figure 5 – Photographs containing memorability-morphed faces generated by the algorithm in Khosla et al. (2013). The algorithm predicts that the face to the left will be forgotten by more people than the face to the right. The right image might serve as a good profile picture for social media because it will be better remembered, while the image to the left could work for someone wanting to be a forgettable spy.

Knowing what images are likely to be later remembered or forgotten regardless of observer characteristics can be a powerful utility; in a way, one can use this knowledge to manipulate memory. This has applications for a broad range of fields such as education, advertising and media, eyewitness testimony, and medicine (Oliva et al., 2013). For example, one could intentionally select memorable materials for textbooks or advertisements so they would deliver a lasting message. Casting agents for movies or TV shows could search for memorable leads and forgettable extras. Intelligence agencies could intentionally recruit people with forgettable faces as spies. People could enhance the memorability of their own photographs or use subtle makeup to enhance the memorability of their own face, to boost subscriptions on social media services, success in dating apps, or recruitment from job searching sites (Figure 5).

While these applications sound like clips out of a science fiction world, some of these applications are already becoming possible. Measuring and predicting image memorability is growing as a popular topic in the fields of computer vision and machine learning. As a first step, Khosla and colleagues (2013) were able to make a computer vision model that iteratively manipulated the active appearance model (Cootes et al., 2001) of a face to make it more similar to other memorable faces, while preserving important attributes such as identity, attractiveness, and age. They found that these faces automatically manipulated to be more memorable were indeed significantly better remembered in an online memory experiment than those made to be forgettable. In more recent work, researchers have been using convolutional neural networks (CNNs) to automatically quantify the memorability of general images. Khosla et al. (2015) created the LaMem dataset of 60,000 images annotated for memorability and trained a corresponding CNN named MemNet for predicting memorability. Its predictions ultimately showed significant correlations with human-based memorability scores (ρ=0.64). In an attempt to unify separate neuroscientific and computer vision efforts to understand memorability, Han and colleagues (2014) created a model combining fMRI-derived features based on connectivity amongst several higher-level attentional and semantic networks with computer vision features to predict memorability. In the past few years, several other groups have begun racing to perfect a computational model that can automatically predict memorability (e.g., Celikkale et al., 2015; Squalli-Houssaini et al., 2018; Basavaraju et al., 2018). Beyond the useful applications of being able to automatically quantify the memorability of an image, this work using computational models could also lend insight into the human cognitive representations of memorability. For example, work by Lukavský and Děchtěrenko (2017) has found that when distances between the characterization of an item's deep image features quantified by a CNN and those of its neighbors are larger, these images tend to be better remembered, providing support for memorability relating to stimulus distinctiveness for higher-order image features.

Another important implication of memorability as a stimulus attribute is that its effects are ubiquitous. For better or worse, all visual and memory psychology and neuroscience experiments have used stimuli that have varied in memorability. It could be possible that previously found memory effects are partially driven by the stimuli themselves; for example, perhaps some subsequent memory effects are not about the stage of memory encoding itself, but about the stimuli that cause successful encoding to happen. Indeed, strong memorability effects in the brain have been successfully uncovered from prior studies investigating different questions about memory (Bainbridge & Rissman, 2018). Unbalanced image sets could also lead to biases in memory findings—for example, if all stimuli are highly memorable or highly forgettable, the final results could ultimately look very different, given the different stereotyped patterns of activity for memorable and forgettable images (Bainbridge et al., 2017). Thus, moving forward, researchers will need to keep memorability in mind as an important image feature to account for, or intentionally control. Luckily, knowing memorability in advance could allow for better fine-tuning of an experiment's memory outcomes or task difficulty, as well as better fine-tuning of real-world applications of memory. For example, in the realm of criminal justice, knowledge about biases that memorable images have on memory could improve eyewitness identification and criminal lineup selection; people within a criminal lineup could be matched for memorability to eliminate biases towards memorable faces, and people who are likely to cause false memories could be intentionally avoided as lures.

Finally, memorability has meaningful clinical applications, for those with impairments in perception and memory. In individuals with perceptual impairments, such as prosopagnosia (an impairment at perceiving and recognizing faces; Duchaine & Nakayama, 2006), are memorability effects eliminated, or do highly memorable face images still outperform forgettable ones? If the latter is the case, strategies could be used to enhance the memorability of a face or surrounding features to make it more detectable to those with such impairments. In terms of memory impairments such as Alzheimer's Disease (AD), a similar question is whether those with such impairments still show consistencies in the images they remember and forget. Recent work (Bainbridge et al., 2017b) found that even though those with increasing memory impairments did show diminished overall memory performance, the memorability rankings of images was preserved across impairments. This means that patients tended to remember and forget the same images as healthy controls, and importantly, this means clinicians can intelligently select images for therapeutic tools knowing what a patient is likely to remember or forget in advance. Extra memory rehearsal could be focused on particularly forgettable images, or images in an environment could be updated to be more memorable so they are retained for longer by patients. Notably, there was also a particularly meaningful subset of images that were consistently remembered by healthy individuals yet forgotten by those with precursors to AD. When looking at memory performance for this specific subset of images in a separate subject pool, there was a 10% boost in patient group categorization over other image subsets of the same size. This optimized image subset only required 18.3 images per participant, yet yielded equal patient categorization performance to the full image set, with 4.3x the images. These results have exciting implications for the design of diagnostic tests—optimizing images to be maximally meaningful can allow for faster and more successful identification of early markers for AD. With several AD treatments and therapies entering later stages in clinical trials (Alzheimer's Association, 2018), the early identification of AD is becoming increasingly important. Such a short, optimized test could be easily used by any adult before undergoing more extensive screening.

B. The future landscape of memorability

The recent renewed interest in memorability and stimulus item-effects that influence memory is still relatively new, and there are many large, open questions on how memorability relates to current understandings of perception and memory.

When memorability was previously studied as a means to measure distinctiveness, it was often paired with its counterpart of *familiarity*. While memorability is conceptualized as differentiating a new item during encoding (i.e., this face is so different, it needs to be remembered), familiarity is conceptualized as comparing a new item to similar items seen before (i.e., this face looks like one of my friends, I will remember this). Familiarity and memorability show different behavioral effects (Vokey & Read, 1992), and often differentiable neural regions of sensitivity (Daselaar et al., 2006). In the past, memorability was generally quantified as true memory, or hit rate (HR), while familiarity was quantified as false alarm rate (FAR) (Bartlett et al., 1984) —something feels familiar, so you believe you've seen it before. Just as various work has found consistency in memorability, there is also evidence that familiarity is consistent across observers (Bainbridge et al., 2013). In fact, there is significant reliability in all ways of splitting hit rate and false alarm rate (Bainbridge et al., 2012): 1) high HR / high FAR, "familiar" images that cause both true and false memories; 2) high HR / low FAR, "memorable" images that only cause true memories; 3) low HR / high FAR, a mysterious set of images that causes many false alarms but few true memories; and 4) low HR / low FAR, “forgettable” images that cause low behavioral responses. It will be incredibly interesting to see what attributes influence membership in these different categories, and how these differences may play out in the brain, given previously identified differences amongst novelty, familiarity, and recollection processing (Daselaar et al., 2006).

Another essential topic will be in the development of models to explain memorability effects. While CNNs are currently making progress in predicting the memorability of images, it is still unclear what information these CNNs are picking up on, and whether they would successfully generalize to more difficult image sets (e.g., faces), where there aren’t obvious features that boost the memorability of an image (e.g., the presence of people or text). Thus far, while visual distinctiveness as well as subjective ratings of distinctiveness have not been able to successfully explain memorability effects, memorability may still come about from distinctiveness defined differently—e.g., as semantic distinctiveness, or statistical distinctiveness across a range of processing levels. More work will need to tease apart the meaningful axes and see to what degree perceptual versus conceptual information (Konkle et al., 2010) plays a role in determining memorability. Additionally, future work can study the degree to which memorability can extend to other stimulus types and modalities, such as sounds, physical movements, or even odors, in order to understand how memorability may work across different types of memory (e.g., motor memory, olfactory memory). A final piece of the puzzle will be gaining the ability to construct precise predictions of memory behavior by measuring and combining the stimulus factors (e.g., memorability, item state), participant factors (e.g., attentional state, past memories), and environmental factors (e.g., image context, temporal context) that determine memory performance. Luckily, as memorability exists as a measurable attribute within any set of stimuli, it could be extracted and analyzed from hundreds of pre-existing memory or perception experiments (Bainbridge & Rissman, 2018).

6. Conclusion

As we navigate through our daily lives, we constantly encounter a stream of new sensory information, that we either filter out or save into our memories. While many factors influence our memories, such as our state of mind, our previous experiences, and other cognitive tasks currently underway, this sensory information that we are encountering also has a power to influence our memories. Through an intrinsic memorability to these items, a new image may be easily remembered by any of us, or easily forgotten. While memorability has been a measure used previously as a lens into perceptual distinctiveness, recent work has breathed new life into the topic, to characterize memorability as a highly consistent property across observers. We know some qualities of an image that will make it memorable (e.g., presence of people and text) and several attributes that have surprisingly little relationship (e.g., aesthetics, subjective memorability), yet we are still far from a full understanding of what makes an item memorable or forgettable. The memorability of an item is impressively resilient, unchanging in the face of different tasks, longer delays, different contexts, attentional differences, cognitive control, and priming. Interestingly, the brain shows sensitivity to stimulus memorability, showing differences in its patterns between memorable and forgettable images rapidly, automatically, and with a representation in which memorable images are similar to each other. Memorability also has meaningful applications for computer vision (measuring and manipulating the memorability of images) as well as clinical realms (predicting what patient populations will remember or forget). There is still much to be uncovered about this phenomenon of memorability, as future work is needed to understand the development and limitations of this phenomenon. In sum, these effects of memorability show us the importance of looking not just at how we remember, but *what* we remember, in order to understand the complex interplay of vision and memory, and how we prioritize information in our complex, sensory worlds.

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