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The lower bounds of massive memory: Investigating memory for object details after incidental encoding

Dejan Draschkow[1], Saliha Reinecke[1], Corbin A Cunningham[2] and Melissa L-H Võ[1]

Abstract

Visual long-term memory capacity appears massive and detailed when probed explicitly. In the real world, however, memories are usually built from chance encounters. Therefore, we investigated the *capacity and detail* of incidental memory in a novel encoding task, instructing participants to detect visually distorted objects among intact objects. In a subsequent surprise recognition memory test, lures of a novel category, another exemplar, the same object in a different state, or exactly the same object were presented. Lure recognition performance was above chance, suggesting that incidental encoding resulted in reliable memory formation. Critically, performance for state lures was worse than for exemplars, which was driven by a greater similarity of state as opposed to exemplar foils to the original objects. Our results indicate that incidentally generated visual long-term memory representations of isolated objects are more limited in detail than recently suggested.

Keywords

Object memory; incidental memory; visual long-term memory; object recognition; fidelity; memory details

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Introduction

Humans have an incredible capacity for visual information. Research on visual long-term memory (VLTM) capacity has demonstrated that humans are able to remember thousands of images, even if they only viewed them for a short period of time (Brady, Konkle, Alvarez, & Oliva, 2008; Standing, 1973; Standing, Conezio, & Haber, 1970; Vogt & Magnussen, 2007). Traditionally, VLTM is examined by explicitly instructing participants to memorise any number of objects (e.g., photographic images). However, diverging evidence as to how well these items are remembered exists in the literature and it seems to be dependent on how the previously memorised images in VLTM are probed. Specifically, gist-based alternative forced-choice tasks (e.g., two-alternative forced-choice memory tests [2AFC]) suggest VLTM capacity supports thousands of images (Standing, 1973) in very high detail (Brady et al., 2008; Konkle, Brady, Alvarez, & Oliva, 2010). Moreover, Hout and Goldinger (2010, 2012) have demonstrated that incidental memory for non-target items can be well above chance when probed with a 2AFC memory test. Still, a recent study revealed limitations to storage capacity for objects when the recall procedure requires more detail—in this case, when VLTM was probed using an old/new recognition (ONR) task compared with 2AFC probing procedures (Cunningham, Yassa, & Egeth, 2015), as 2AFC procedures usually result in better performance compared with ONR (Macmillan & Creelman, 2004). In fact, differences in memory performance due to differential probing procedures are supported by cognitive models that depend on two distinct components of recognition memory: familiarity (general knowledge that an item was previously encountered) and recollection (detailed memory for a previously seen object, for example, the location and time it was

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[1]Department of Psychology, Goethe University, Frankfurt am Main, Germany
[2]Department of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, MD, USA

Corresponding author:
Dejan Draschkow, Scene Grammar Lab, Department of Cognitive Psychology, Goethe University, Theodor-W.-Adorno-Platz 6, Frankfurt am Main 60323, Germany.
Email: draschkow@psych.uni-frankfurt.de

previously seen) (Yonelinas, 2001, 2002). These distinct components in recognition memory could be supported by different neural mechanisms (Diana, Yonelinas, & Ranganath, 2007; Fortin, Wright, & Eichenbaum, 2004), suggesting that 2AFC and ONR might be tapping into differences in the cognitive processes utilised in how these memories are retrieved (Cunningham et al., 2015).

Critically, although there is a debate about overall VLTM capacity, the findings in these studies show converging evidence that detailed memory (*fidelity*) does not decrease, no matter what probing procedure was used. Specifically, when observers were tested with items in the same category (i.e., exemplar comparison) or the exact same item but in a different state (i.e., state comparison), memory performance for these two probing procedures was similar (Brady et al., 2008; Cunningham et al., 2015). This has been interpreted as a challenge for the general belief that memories stored in VLTM are sparse in detail (Brainerd & Reyna, 2005) and contrasts a body of research providing evidence for quite limited storage for memory details (Rensink, O'Regan, & Clark, 1997; Simon & Levin, 1997; Wolfe, 1998).

One reason we might not have seen meaningful distinctions in memory performance between exemplar and state comparisons is because the memorization procedure in these studies does not resemble how we tend to interact with objects in everyday life. For example, in many of these studies, observers are asked to detect repeated images (e.g., Brady et al., 2008; Cunningham et al., 2015), thus actively trying to hold these objects in memory. In natural behaviour, however, observers make on the fly judgements about their environment and object recognition is not followed by an active effort to maintain a representation of the object. It is therefore of critical importance to understand whether very specific object details are still retained without the observers' intent to do so. Specifically, if an encoding task were more incidental in nature and required a focus on physical appearance, differing from previous studies, would we find continuously decreasing memory performance for more difficult comparisons?

In two experiments, we investigated a form of encoding closer to the natural constraints of realistic tasks: incidental memorization during visual discrimination. We provided observers with a task where they had to identify digitally manipulated items among a set of photorealistic objects. By probing memory for incidentally encoded objects, we expect to tap in to a more sensitive measure of visual long-term representations and investigate the decrease of memory performance as similarity between items in memory increases.

Methods

Participants

A total of 20 participants per experiment (Experiment 1: mean age = 23.45 years, range = 18-54 years, 15 females; Experiment 2: mean age = 22.95 years, range = 18-32, 17 females; Similarity rating: mean age = 23.3 years, range = 19-48 years, 16 females) were recruited at the Goethe University Frankfurt. Up to four participants were tested simultaneously at computer workstations with identical configurations. All participants had normal or corrected-to-normal vision, were volunteers receiving course credit, and gave informed consent.

Stimuli and apparatus

Photographic images of objects collected from Brady and colleagues (2008) were used as stimulus material (available at: https://bradylab.ucsd.edu/stimuli.html). In the study phase, 910 intact and 144 distorted images were presented to the participants (see Figure 1d for stimuli examples). The images were distorted using the "ripple" function of Adobe Photoshop CC2014 at 30%. Stimuli were presented using OpenSesame (Mathôt, Schreij, & Theeuwes, 2012) on a 19-in monitor (resolution = 1680 × 1050, refresh rate = 60 Hz, viewing distance = approx. 65 cm, subtending approx. 6.34° × 6.34° of visual angle).

Procedure Experiment 1

To investigate the fidelity of incidentally generated long-term memory representations, while keeping the procedure comparable with previous studies, we employed a go/no-go distortion detection paradigm in Experiment 1 (Figure 1a). During the study phase, participants were instructed to detect distorted among non-manipulated object images. The images were positioned in the middle of the screen on white background. All 1054 objects were presented in random order for 3 s. This duration was chosen to be comparable with previous studies (Brady et al., 2008; Cunningham et al., 2015). When participants detected a distorted object, they were asked to press the left mouse button. In this case, the presentation of the objects was limited to the time it took participants to make the response. These trials were removed from the analysis as only non-distorted objects which had been presented for 3 s were of relevance. Participants were given feedback for 500 ms only on the trials in which they responded ("CORRECT" or "INCORRECT"). A fixation dot was presented centred for 800 ms before the next object appeared. Participants completed five practice trials to familiarise themselves with the stimuli and procedure.

The study phase was followed by an ONR memory test, which did not differ between experiments (Figure 1c). To test participants' memory performance, observers were shown a single image in the centre of the screen and instructed to press the "Y" button if they had seen the object in the study phase or the "N" button if they had not (e.g., "Have you seen EXACTLY this object before?"). In this ONR test, 150 objects from the study phase (old) and

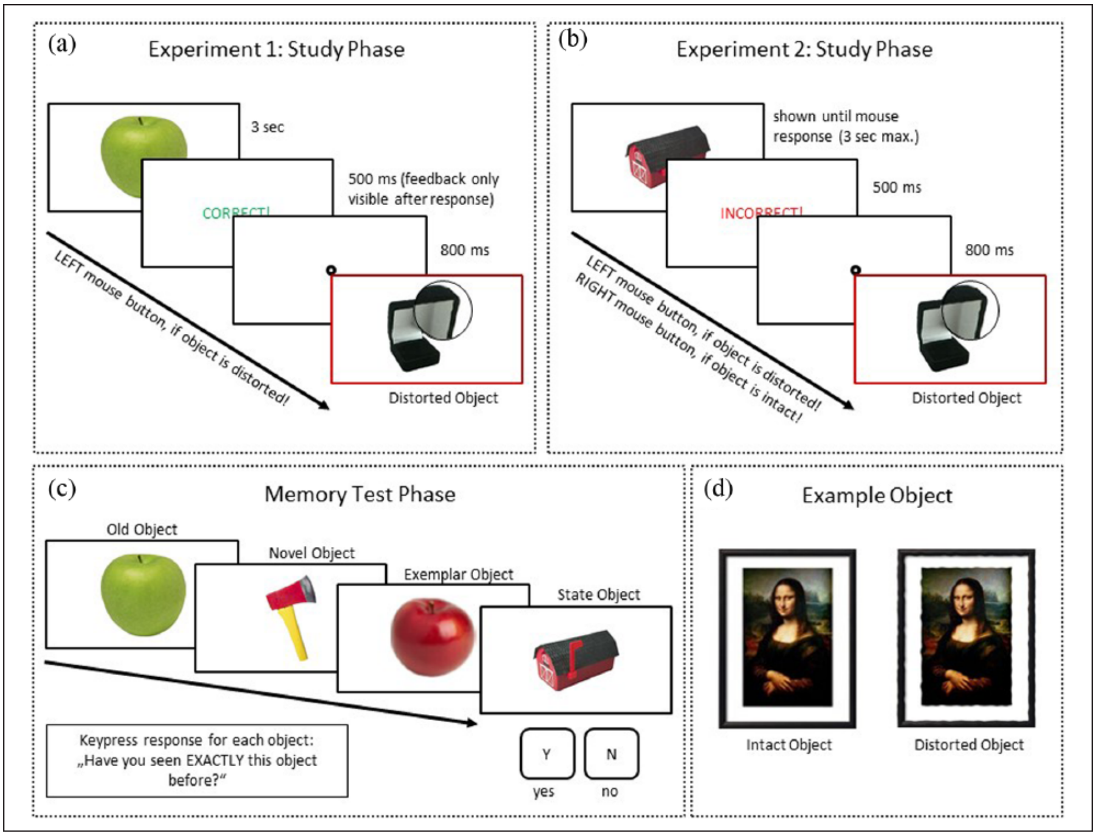

Figure 1. The procedure of the study phase, respectively, for (a) Experiment 1 and (b) Experiment 2. In Experiment 1, a go/no-go procedure was employed, with participants responding only if they saw a distorted object (the magnification serves only illustration purposes and was not part of the experiment). In Experiment 2, participants completed the same procedure as a forced-choice task. (c) The memory test phase was the same in both experiments. (d) Distorted object in comparison with the same intact object. Only one version was used in the experiments.

150 new objects were used, for a total of 300 trials. The new objects were divided between 50 novel, 50 exemplar, and 50 state lures. Novel trials contained an object that was never seen before. Exemplar trials contained a new object that shared similar exemplar category with a previously seen object in the study phase (e.g., both objects are apples). Memory for specific details from the images was assessed using state lures, which contained an item that was the exact same object as one seen in the study phase, but appeared in a different position or state (e.g., postbox with flag upright). No distorted objects were included in the memory test and no matching pairs of any of the distorted objects were presented.

Procedure Experiment 2

Experiment 2 was designed to investigate whether encoding time beyond the time necessary to make the visual judgement affects the fidelity of incidentally generated long-term memories. Participants were instructed to press the left mouse button if they decided an object was distorted (as in Experiment 1) and to press the right mouse button if they decided an object was normal (Figure 1b). Each object was visible until response and feedback was provided for incorrect responses. In all other respects, the procedure was identical to Experiment 1.

Similarity rating

To investigate how similar the state and exemplar lures were to the originally presented objects, we asked 20 independent participants to rate the similarity of state and exemplar lures against the original objects. For comparison of similarity, only the state and exemplar object pairs (50 pairs for each category, 200 images in total) were used. All images were unaltered. In each trial, a pair of images was presented next to each other on a white background. Participants had to rate every pair on a 5-point-Likert-type-scale (1 = "*low similarity*," 5 = "*high similarity*") with six practice trials and 100 experimental trials (50 for state and 50 for exemplar pairs). All object pairs were shown to participants in random order and were presented until keyboard response. Participants were told that there was no right or wrong answer and that they should use the whole range of the rating scale. A central fixation dot was shown for 800 ms before each trial started.

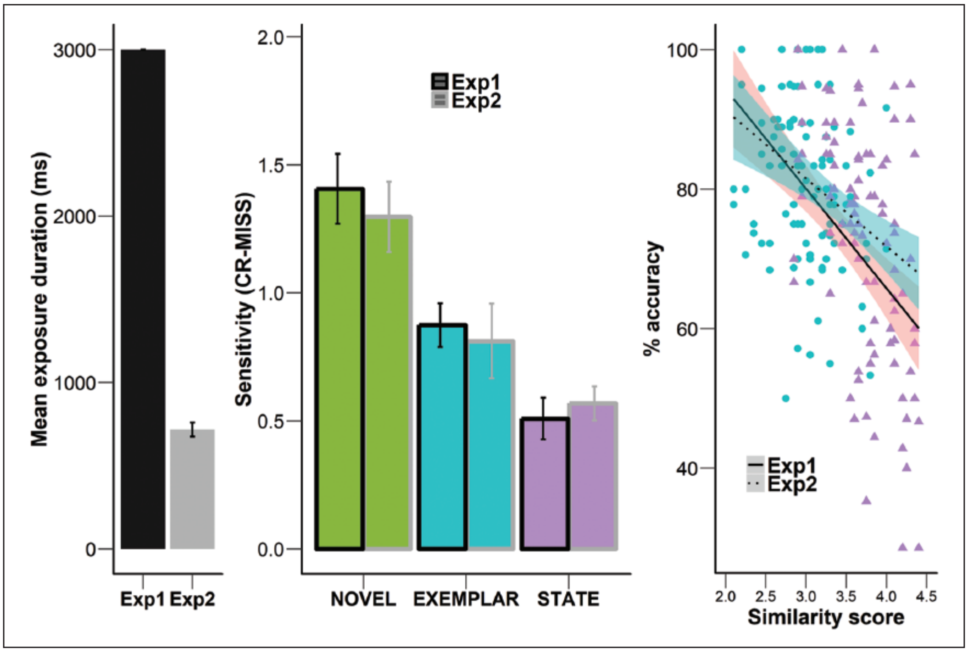

Figure 2. The left graph shows the mean exposure duration (*y*-axis) to objects during encoding for both experiments. On the middle graph, sensitivity is plotted as a function of the three lure conditions for Experiment 1 (black boundaries) and Experiment 2 (grey boundaries). Error bars represent standard error of the mean. The right graph shows memory accuracy for both experiments as a function of the similarity score of objects. Regression lines for each experiment are fitted with shaded areas representing the 95% confidence intervals. Triangles depict state objects, whereas circles depict exemplars.

Analysis

For analysing the effects in our data, repeated-measures analyses of variance (ANOVAs) were run using the *ez* package (Lawrence, 2015) in the R statistical programming environment (R Development Core Team, 2012). Results are reported with generalised eta-squared (η^2) measure of effect size, *p* values corrected for violations of sphericity according to Greenhouse–Geisser, the original degrees of freedom, and Mauchly's *W* value. Differences between means of conditions were analysed using planned pairwise *t*-tests with the *lsr* package (Navarro, 2015). Cohens' *dz* or *d* measures of effect size are reported, respectively, for correlated measurements or independent groups. Simple linear regression was performed with the lm() function in R.

Results

Participants had viewed each object included in the analysis for 3 s during the study phase in Experiment 1 and for a mean of 718 ms in Experiment 2 (Figure 2, left). In Experiment 1, detecting distorted objects was quite challenging, as 46% of the distorted objects were missed during the study phase. The false alarm rate for normal images was 12%. Only the pairs of correctly identified images were included in the analysis of the memory test phase (8.5% excluded trials). In Experiment 2, 60% of the distorted objects were missed during the study phase. The false alarm rate for normal images was 7%. Pairs of wrongly identified images were excluded from the analysis of the memory test phase (4.8%).

To account for response biases in responding "old" versus "new" and better compare memory performance between the two experiments, sensitivity measures for the three lure conditions were calculated. Equivalently to d prime, the difference between the *z*-transformed probabilities of correct rejections and misses was calculated for each condition (Figure 2, middle). This measure was used due to the set-up of the study—correct rejections captured the ability to discriminate the tested lure from the originally presented one. Misses on the other hand indicate a bias to respond to items as "new."

In the 2 × 3 ANOVA with the factors experiment (1 vs 2) and lure condition (novel vs exemplar vs state), there was a main effect of the lure condition on sensitivity, $F(2, 76) = 56.9$, $p < .001$, $\eta^2 = 0.32$, Mauchly's $W = 0.84$, but no effect of the experiment, $F(1, 38) < 1$, and no significant interaction between condition and experiment, $F(2, 76) < 1$. Sensitivity for novel objects was significantly higher than for categorically similar, but new objects (i.e., exemplar comparison condition) in both experiments, Experiment 1: $t(19) = 4.5$, $p < .001$, $dz = 1.0$; Experiment 2: $t(19) = 3.7$, $p = .001$, $dz = 0.8$. Critically, the difference between the sensitivity for exemplar and state objects was significant as well, Experiment 1: $t(19) = 7.2$, $p < .001$, $dz = 1.6$; Experiment

2: $t(19)=2.2$, $p=.04$, $dz=0.49$, showing a decrease in fidelity after incidental encoding. Novel, $t(37.9)=0.565$, $p=.575$, $d=0.179$, exemplar, $t(30.6)=0.37$, $p=.714$, $d=0.117$, and state lure detection performance, $t(36.5)=0.564$, $p=.576$, $d=0.178$, did not differ between Experiments 1 and 2. Sensitivity was above chance in all conditions in both experiments, all comparisons $t(19)>5$, $d>1.2$.

Confirming intuition, state pairs ($M=3.72$, standard error $[SE]=0.11$) were judged as being more similar than exemplar pairs ($M=2.99$, $SE=0.12$), $t(19)=-6.143$, $p<.001$, $dz=1.374$. A simple linear regression was calculated to predict accuracy based on how similar the lure was to the original object (Figure 2, right). A significant regression equation was found, $F(3, 196)=18.24$, $p<.001$, $R^2=0.206$, with lure similarity significantly predicting accuracy, $\beta=-0.189$, $SE=0.05$, $t=-3.51$, $p<.001$. There was no effect of experiment (Experiment 1 vs Experiment 2), $\beta=-0.\ 122$, $SE=0.12$, $t=-1.06$, $p=.291$, and no interaction between similarity and experiment (Experiment 1 vs Experiment 2), $\beta–=0.05$, $SE=0.35$, $t=1.35$, $p=.180$. These results suggest that as similarity between the memory for an old object and the tested new lure object increases (i.e., become more similar), participant performance to correctly reject those similar lures decreased. To test whether similarity was responsible for the difference in sensitivity between state and exemplar pairs, we calculated a second linear regression to predict accuracy based on the condition of the lure (state vs exemplar), but critically included the similarity score as a covariate. A significant regression equation was found, $F(4, 195)=14.18$, $p<.001$, $R^2=0.209$, with lure similarity score significantly predicting sensitivity, $\beta=-0.129$, $SE=0.02$, $t=-5.64$, $p<.001$. Critically, there was no more difference in sensitivity between the state and exemplar lures, $t<1$, indicating that the initial effect of this categorical distinction was driven by similarity and not the categorical type of comparison (i.e., exemplar or state).

Discussion

Across two experiments, we investigated the fidelity of incidentally generated visual long-term memories (VLTM). In Experiment 1, over a thousand objects were presented for 3 s each and participants were instructed to detect distorted objects among a stream of intact objects. In a following surprise memory test, an object lure from a novel category (novel), of the same basic-level category (exemplar), the same object in a different state or pose (state), or exactly the same object (old) was presented, and participants indicated whether they had seen the object before. Taking into account response biases, sensitivity measures in both Experiment 1 and 2 were low. This result extends the evidence for limitations to storage capacity for explicitly memorised objects when the recall procedure requires more detail (Cunningham et al., 2015) to incidentally generated memory content. Memory for specific details from the images (i.e., state details) suffers when incidentally encoded during a visual discrimination task in comparison with memory for exemplars. This diverges from previous VLTM studies in which there was no discernible difference between these conditions (e.g., Brady et al., 2008; Cunningham et al., 2015). Our results are backed by additional similarity ratings between objects and their lures and suggest that an encoding procedure more closely related to natural behaviour makes fidelity of the memory system vulnerable to increasing lure similarity (Figure 2, right graph), indicating that not the categorical type of comparison (i.e., exemplar or state) leads to a decrement in memory performance, but an increase in similarity between objects and lures. This falls in line with arguments for limited storage for memory details (Brainerd & Reyna, 2005; Rensink et al., 1997; Simons et al., 1997; Wolfe, 1998).

The limitations of memory performance for incidentally encountered isolated items in our study contrasts with the previous findings of high fidelity memory performance after explicit memorization. That, however, does not speak for a general superiority of explicit memorization tasks when compared with incidental memorization. On the one hand, although sensitivity measures were low, this study demonstrates above chance memory performance even for objects that were seen for less than a second among over a thousand other objects, suggesting that some object details are indeed reliably encoded and utilised. On the other hand, when participants search for objects (i.e., more natural task) embedded in meaningful scenes (i.e., more natural stimuli), there actually seems to be the reverse trend—incidentally generated memories are more reliable than ones established after explicit memorization (Draschkow, Wolfe, & Võ, 2014; Josephs, Draschkow, Wolfe, & Võ, 2016). Furthermore, in this study, the presented objects can be seen as distractors to the task of identifying distortions, whereas in previous studies each object was task relevant (e.g., Brady et al., 2008; Cunningham et al., 2015). Target memory appears to operate differently than distractor memory (Thomas & Williams, 2014; Williams, 2010a, 2010b). In visual search, objects that are task-relevant are remembered better than ones which are irrelevant (Castelhano & Henderson, 2005; Draschkow & Võ, 2016; Tatler & Tatler, 2013; Williams, Henderson, & Zacks, 2005). However, even irrelevant items are reliably encoded (Castelhano & Henderson, 2005; Draschkow & Võ, 2016; Hout & Goldinger, 2012). Thus, differences in the role that the object plays in the task could also contribute to the pattern of results in this study. Combined, these studies suggest a close interaction between task and context that needs to be further investigated and accounted for by VLTM models.

Importantly, our main goal for this study was to examine whether there are some instances where visual long-term memories, when probed, will result in a decrease in performance for comparisons that require more detailed memory (i.e., going from an exemplar comparison to a state comparison). Although it is intuitive that similarity plays a role in VLTM and has already been shown (Kim & Yassa, 2013), it is important to point out that these memory effects are built on varying similarity between comparisons and have less to do with the arbitrary categories that have been applied to the comparisons (i.e., exemplar vs state). Previous work in this domain had not yet found this to be the case (Brady et al., 2008; Cunningham et al., 2015). It seems that when a task is more incidental, or rather focuses on identifying physical characteristics about the image, this allows us to tap into a more sensitive assessment of visual long-term representations.

In an effort to be more comparable with previous studies, in Experiment 1, objects were presented for 3 s, although participants probably needed significantly less time to gather all of the necessary visual information to decide whether the object was distorted or not. Therefore, in Experiment 2, participants only viewed the objects for as long as it took them to make the visual discrimination—intact versus distorted—resulting in much less exposure duration. Despite a decrease of presentation duration to less of a third, there was no significant drop in memory performances, suggesting that the main process of incidental encoding was finished when the visual decision was made. Similarly, explicit memorization procedures showed that decreasing encoding time from 3 to 1 s does not affect VLTM fidelity (Brady, Konkle, Gill, Oliva, & Alvarez, 2013). Further research is needed to disentangle the impact of exposure duration on VLTM fidelity for both incidental and explicit types of encoding.

In sum, our results suggest that when long-term memories are acquired in more realistic task settings (during performance of a memory unrelated task), it appears that as lure similarity increases, we find a decrease in memory performance. We argue that for isolated items, VLTM capacity during incidental encoding is reliable but demonstrates limitations in its detail.

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