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published in
Journal of Experimental Psychology: Learning Memory and Cognition
2020

DOI (link to publisher)
10.1037/xlm0000847

document version
Publisher's PDF, also known as Version of record

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citation for published version (APA)
Li, X., Xiong, Z., Theeuwes, J., & Wang, B. (2020). Visual memory benefits from prolonged encoding time regardless of stimulus type. *Journal of Experimental Psychology: Learning Memory and Cognition*, *46*(10), 1998-2005. https://doi.org/10.1037/xlm0000847

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American Psychological Association

Journal of Experimental Psychology:
Learning, Memory, and Cognition

© 2020 American Psychological Association
ISSN: 0278-7393

2020, Vol. 46, No. 10, 1998–2005
http://dx.doi.org/10.1037/xlm0000847

Visual Memory Benefits From Prolonged Encoding Time Regardless of Stimulus Type

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It is generally assumed that the storage capacity of visual working memory (VWM) is limited, holding about 3–4 items. Recent work with real-world objects, however, has challenged this view by providing evidence that the VWM capacity for real-world objects is not fixed but instead increases with prolonged encoding time (Brady, Störmer, & Alvarez, 2016). Critically, in this study, no increase with prolonged encoding time was observed for storing simple colors. Brady et al. (2016) argued that the larger capacity for real-world objects relative to colors is due to the additional conceptual information of real-world objects. With basically the same methods of Brady et al., in Experiments 1–3, we were unable to replicate their basic findings. Instead, we found that visual memory for simple colors also benefited from prolonged encoding time. Experiment 4 showed that the scale of the encoding time benefit was the same for familiar and unfamiliar objects, suggesting that the added conceptual information does not contribute to this benefit. We conclude that visual memory benefits from prolonged encoding time regardless of stimulus type.

Keywords: visual working memory, long-term memory, encoding time benefits, real-world objects

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Human visual memory systems, especially visual working memory (VWM) and visual long-term memory (VLTM), are fundamental to human cognition. Their capacities are of great importance as they are strongly related to overall cognitive ability. The standard view is that the storage capacity of VLTM is large and is assumed to hold more than thousands of objects with numerous details (Brady, Konkle, Alvarez, & Oliva, 2008; Konkle, Brady, Alvarez, & Oliva, 2010), while the storage capacity of VWM is limited (e.g., Cowan, 2001) and is assumed to hold about three to four items after hundreds of milliseconds of presentation time (Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Luck & Vogel, 1997). Recent work with real-world objects, however, has challenged the latter view by providing evidence that the VWM capacity for real-world objects is not fixed but instead increases with prolonged encoding time (Brady, Störmer, & Alvarez, 2016).

Brady et al. (2016) showed that people were capable of memorizing real-world objects when encoding time was prolonged, while no such benefit was found for encoding simple stimuli like colors. They argued that compared to simple stimuli, real-world objects have additional conceptual information, which might be related to this encoding time benefit in VWM. However, it is also possible that this benefit is solely due to the involvement of VLTM system, which has a very large capacity and is assumed to play an important role for encoding real-world objects (Brady, Konkle, Oliva, & Alvarez, 2009).

To examine the involvement of VLTM, Brady et al. (2009) employed electrophysiological recordings and measured the contralateral delay activity (CDA). Because the CDA amplitude increases with the number of stored objects and correlates with individual memory capacity (Vogel & Machizawa, 2004), it is generally believed that the CDA provides a neural signature of active storage in VWM. Critically, it was shown that the CDA disappears when the stored information had been entered into VLTM (Carlisle, Arita, Pardo, & Woodman, 2011). Brady et al.

This article was published Online First May 21, 2020.

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Xinyu Li and Zijun Xiong equally contributed on to the current research. Xinyu Li, Zijun Xiong, and Benchi Wang designed the experiment. Zijun Xiong collected and analyzed the data. All authors wrote the article together and approved the final version of the manuscript for submission. This research was supported by the Natural Science Foundation of Zhejiang Province (LY18C090007) to Xinyu Li, a China Scholarship Council (CSC) scholarship (201508330313) and the Guangdong Regional Joint Foundation (2019A1515110581) to Benchi Wang.

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showed an increased CDA amplitude for real-world objects when observers had to memorize five instead of three real-world objects, while no such an effect was found when storing five instead of three simple colors. These findings indicate that more than three real-world objects could be stored in VWM, while the VWM capacity of simple colors was limited to three.

Even though Brady et al. (2016) argued that real-world objects are stored in an active VWM system, they did not rule out the possibility that these objects are also stored in VLTM. That is, participants might employ two different memory systems at the same time to store more items in visual memory. For example, Brady et al. (2016) make the claim that "the current data do not rule out the idea that real-world objects also lead to better episodic long-term memory representations than simple stimuli do (in addition to being better represented in active working memory systems)" (p. 7462). In addition, it should be noted that Quirk and Vogel (2017)[1] failed to replicate the critical CDA results of Brady et al. (with more participants and more trials to increase statistical power). They showed no reliable differences between three and five real-world objects (with the same stimuli set employed in Brady et al., 2016). Also, they failed to replicate the critical behavioral findings but instead showed that with prolonged encoding time, memory performance was improved for both simple colors and real-world objects. These failures in replicating the basic effects make the argument regarding more capacity for real-world objects in VWM less convincing.

Brady et al. (2016) argued that the benefits from prolonged encoding time are due to the fact that compared to simple colors, real-world objects contain additional conceptual information. Yet, compared to simple colors, real-world objects do not only have additional conceptual information, but they are also perceived as being more complex. That is, their perceptual complexity might play a role, especially in discrimination tasks. For simple colors, participants make a judgment based on only one dimension, while for real-world objects, they could complete the comparison based on multiple dimensions (e.g., shape, color, texture, material). Although previous studies have shown that perceptual complexity per se only leads to impoverished memory performance (Alvarez & Cavanagh, 2004; Awh, Barton, & Vogel, 2007), this may not be the case when encoding time is extended. That is, with more perceptual complexity, observers might exploit multiple dimensions as clues to encode and retrieve real-world objects, resulting in encoding time benefit.

The goal of the present study was to investigate whether the encoding time benefit in visual memory depends on the stimulus type employed. As alluded above, compared to simple colors, real-world objects have additional conceptual information and additional perceptual complexity that both may contribute to improving memory performance. Therefore, it is important to examine whether perceptual complexity and/or conceptual information of the to-be-memorized stimuli contributed to these benefits. First, we set out to replicate basic findings of Brady et al. (2016) with basically the same paradigm, in which participants were required to memorize either real-world objects or simple colors that were presented with different encoding times (0.2 s, 1 s, or 2 s). In Experiments 2 and 3, we further addressed the potential impact factor of the encoding time benefit on visual memory and replicated the critical color condition of Experiment 1. In Experiment 4, we presented familiar or unfamiliar real-world objects that had the same perceptual complexity allowing us to investigate the role of conceptual information in the encoding time benefit while controlling for perceptual complexity.

Experiment 1

In the present experiment, we replicated the main experiment of Brady et al. (2016) to examine whether the benefit from prolonged encoding time only exists for real-world objects or whether it also exists for simple stimuli (colors).

Method

Participants. Eighteen female participants (mean age: 19.7 years) with normal or corrected-to-normal vision were recruited from Zhejiang Normal University for monetary compensation. Sample size was predetermined based on Brady et al. (2016). With a relatively small sample size (12), the critical p value for the significant slope of real-world objects was already smaller than .001. Thus, we chose larger sample sizes in the present and subsequent experiments and in the meantime ensured that the conditions could be counterbalanced between subjects. The procedure complied with a generic protocol approved by the Scientific and Ethical Review Committee of the Department of Psychology of Zhejiang Normal University.

Apparatus and stimuli. During the testing, participants were required to keep their chin on a chinrest positioned at a viewing distance of ~65 cm from a 21-in. color monitor in a dimly lit laboratory. Stimulus presentation and response collection were controlled by custom scripts written in Python.

Colored squares and real-world objects were chosen as experimental materials, which were presented against a white background (~122 cd/m^2). The colors of the squares (subtended by 1° × 1°) were randomly selected from nine equal-brightness colors, evenly distributed along a circle in the CIE L*a*b (CIELAB) color space (centered at L = 70, a = 5, b = 0, with a radius of 40). Each image for real-world objects (subtended by 2° × 2°) was downloaded from the online image database (https://bradylab.ucsd.edu/stimuli.html) created by Brady and colleagues. The stimuli could appear at six locations, evenly distributed along the circumference of one invisible circle centered at the display center with the radius of 4°.

Procedure and design. The procedure was exactly the same as in Experiment 1 of Brady et al. (2016). Participants were required to memorize a set of either real-world objects or simple colors while performing a simultaneous verbal task (rehearsing two digits) to ensure visual memory, rather than verbal memory, was activated (see Figure 1). First, two digits were presented for 1 s, followed by a 1-s interval. Then, six to-be-memorized materials (i.e., color squares or real-world objects) were presented for 0.2 s, 1 s, or 2 s. After another 0.8-s interval, a retro-cue (i.e., a thick dot) was presented for 0.5 s to indicate the to-be-probed item. In the probe display, two items were presented slightly above or below the probed item location, and participants were required to indicate which one was shown in the sample display by pressing the "up arrow" or "down arrow" key (i.e., made a [Two-alternative Forced

[1] This is an unpublished study that was presented during a poster presentation at the Vision Science Society, May, 2017.

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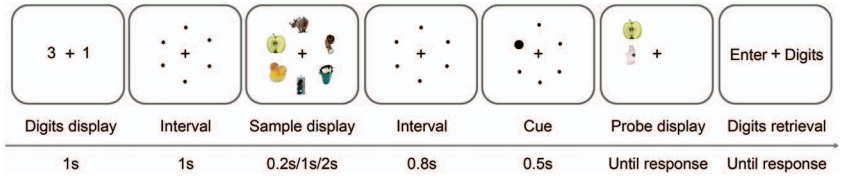


Figure 1. The procedure adopted in the present study. See the online article for the color version of this figure.

Choice] judgement). Finally, they were required to input the sum of the two digits shown in the beginning by pressing the corresponding number key in the keyboard.

When color was tested, we chose a novel probe color, a color that was categorically distinct from the original color (defined as the distance on the CIELAB color space between these two colors of 180°; see Figure 2, left panel, for an example) and did not appear on the original display. For real-world objects, two conditions were tested: (a) An object was tested against another categorically distinct object (e.g., an apple you had seen vs. a backpack; see Figure 2, middle panel, for an example), and (b) an object was tested against another exemplar from the same category (e.g., a bread vs. another bread; see Figure 2, right panel, for an example). Thus, a 3 (*encoding time:* 0.2 s, 1 s, and 2 s) × 3 (*probe type:* color, objects, and objects with detail) within-subject design was adopted. For each encoding time and each probe type, participants were tested in different blocks, with each including 7 practice trials and 33 testing trials. The order of nine blocks was counterbalanced across participants.

Analysis. Memory capacity (K) was calculated for N to-be-memorized items according to the method adopted in Brady et al. (2016). It was assumed that participants could correctly answer the [Two-alternative Forced Choice] test in p (percent correct) trials. They would definitely remember the tested items in K/N trials or could correctly guess the answer in $(N - K)/N \times 50\%$ trials (chance = 50%) when they could not remember the tested items. Thus, by simplifying the equation for percent correct, $p = (K/N) + (N - K/N) \times 0.5$, the formula for capacity is as follows: $K = N \times (2p - 1)$.

Results

There were no effects on mean accuracies for digits report task in all experiments. The results of this task for all experiments are provided in the Appendix.

The mean VWM capacities for each probe type as a function of encoding time are shown in Figure 2. A repeated-measures analysis of variance (ANOVA) on the mean capacities with variables *probe type* (color, objects, and objects with detail) and *encoding time* (0.2 s, 1 s, and 2 s) showed that there were significant main effects for encoding time, $F(2, 34) = 30.96$, $p < .001$, partial $\eta^2 = .65$, and probe type, $F(2, 34) = 6.76$, $p = .003$, partial $\eta^2 = .29$. Also, a significant interaction was observed, $F(4, 68) = 3.96$, $p = .006$, partial $\eta^2 = .19$. Planned follow-up comparisons revealed that the mean VWM capacities increased as the encoding time was prolonged for colors, $F(2, 34) = 24.66$, $p < .001$, partial $\eta^2 = .59$; for objects, $F(2, 34) = 25.42$, $p < .001$, partial $\eta^2 = .6$; and for objects with detail, $F(2, 34) = 4.55$, $p = .018$, partial $\eta^2 = .21$.

We also used the linear slope to quantify the systematical process of the encoding time benefit. Subsequent planned comparisons showed that the slope for colors (0.95) and that for objects (1.05) were not statistically different, $t(17) = 0.57$, $p = .565$, $d = 0.16$, but the slope for objects with detail (0.45) was statistically smaller compared to that for colors, $t(17) = 3.56$, $p = .002$, $d = 0.81$, and that for objects, $t(17) = 3.0$, $p = .008$, $d = 0.89$.

Discussion

Our findings regarding real-world objects and objects with detail perfectly replicate the findings of Experiment 1 in Brady et al. (2016). However, while Brady et al. did not observe the encoding time benefit for simple colors, our results unequivocally show such an effect (see also Quirk & Vogel, 2017). In fact, there was no reliable difference in encoding time benefit between real-world objects and simple colors, suggesting visual memory benefits from prolonged encoding time regardless of stimulus type.

To ensure that the current failure to replicate is not accidental, we sought to replicate the results in Experiments 2 and 3. In addition, we observed another interesting finding that the encoding time benefit was reduced in the condition of objects that contained

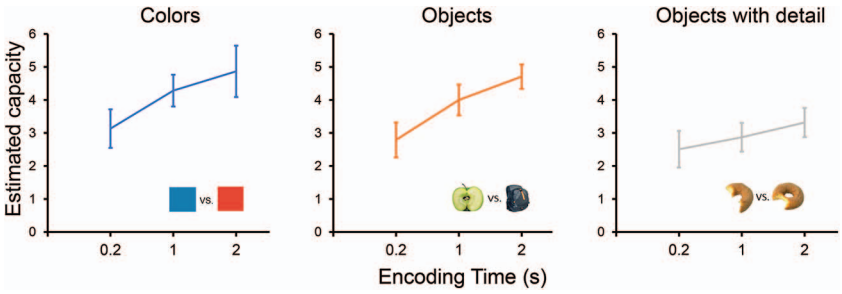


Figure 2. Experiment 1: Estimated capacity as a function of ending time for colors, objects, and objects with details. Error bars denote within-subjects 95% confidence intervals. See the online article for the color version of this figure.

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details. One might argue that this reduction is due to the fact that more details need to be encoded into visual memory. That is, due to the prolonged encoding time, in each condition, a high-fidelity memory representation has been formed, yet in the condition of objects that contained details, the memory representation is of a lower fidelity than in the condition without details, because with details, more has to be encoded. However, it should be noted that the details of objects for encoding were the same in both conditions. The only difference between the two conditions is that a higher fidelity memory representation was required to make a judgment during retrieval for the objects with detail condition than the objects condition. Thus, we argue that the scale of the original encoding time benefit is the same between those two conditions, but the benefit is reduced when the task requires a high-fidelity representation during retrieval in the condition of objects that contain details. In Experiments 2 and 3, we examined whether the task requirements during retrieval play a role in the reduction in encoding time benefit.

Experiment 2

For replication purposes, in one condition, we adopted the same difference between two color probes (i.e., 180° difference in CIELAB color space) as used in Experiment 1; in the other condition, we reduced the difference between two color probes (i.e., 20°), forcing participants to use a high-fidelity representation to make a judgment in the discrimination task. Yet, we used the same color set as in the "replication" condition to ensure that participants encoded the same colors. Therefore, in this experiment, what needed to be encoded was the same; the only difference was that in one condition, the task required only a relatively low fidelity, while in the other condition, a high fidelity was required.

Method

Eighteen new participants (two males; mean age: 20.4 years) participated in Experiment 2. The task procedure was identical to that of Experiment 1, except participants were only required to memorize a set of simple colors with different *probe* difference (180° vs. 20°). The 180° difference was defined as the distance on the CIELAB color space between two probe colors of 180°; 20° difference was defined as the distance on the CIELAB color space between two probe colors of 20°. Thus, a 3 (*encoding time:* 0.2 s, 1 s, and 2 s) × 2 (*probe difference:* 180° vs. 20°) within-subject design was adopted.

Results

The mean VWM capacities for each probe difference as a function of encoding time are shown in Figure 3A. A repeated-measures ANOVA on the mean VWM capacities with variables probe difference (180° vs. 20°) and encoding time (0.2 s, 1 s, and 2 s) showed that there were significant main effects for encoding time, $F(2, 34) = 16.1$, $p < .001$, partial $\eta^2 = .49$, and probe difference, $F(1, 17) = 247.91$, $p < .001$, partial $\eta^2 = .94$. Also, there was a significant interaction, $F(2, 34) = 9.45$, $p = .001$, partial $\eta^2 = .36$. Planned follow-up comparisons revealed that for 180° probe difference, the mean VWM capacities increased as the encoding time was prolonged (slope: 0.95), $F(2, 34) = 25.37$, $p < .001$, partial $\eta^2 = .69$; however, for 20° probe difference, there were no such benefits from prolonged encoding time (slope: 0.28), $F(2, 34) = 1.62$, $p = .212$, partial $\eta^2 = .08$.

Discussion

With large probe difference (180°), we replicated the findings from our Experiment 1, showing that the mean VWM capacities for simple colors increased as the encoding time was prolonged. However, with small probe difference (20°), such benefits were no longer found, suggesting that the encoding time benefit is compromised for simple colors as well when more fidelity of the representation is required in the discrimination task.

Experiment 3

To further confirm our previous findings, in Experiment 3, we added a medium probe difference (60°) to Experiment 2. If the previous findings were really due to the task requirement for the representation fidelity, we expect that the scale of the encoding

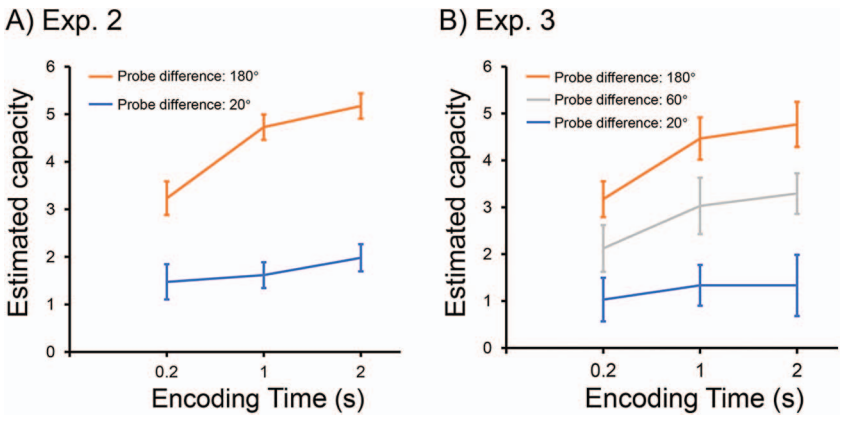


Figure 3. Estimated capacity as a function of ending time for different probe differences in Experiment 2 (A) and in Experiment 3 (B). Error bars denote within-subjects 95% confidence intervals. See the online article for the color version of this figure.

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time benefit from this medium probe condition (60°) should fall in between the 20° and 180° condition.

Method

Eighteen new participants (one male; mean age: 20.2 years) took part in the experiment. The procedure was identical to that of Experiment 2, except for adding a medium probe difference (60°). Thus, a 3 (*encoding time:* 0.2 s, 1 s, and 2 s) × 3 (*probe difference:* 180°, 60°, and 20°) within-subject design was adopted.

Results

The mean VWM capacities for each probe difference as a function of encoding time are shown in Figure 3B. A repeated-measures ANOVA on the mean VWM capacities with variables probe difference (180°, 60°, and 20°) and encoding time (0.2 s, 1 s, and 2 s) showed that there were significant main effects for encoding time, $F(2, 34) = 12{,}47$, $p < .001$, partial $\eta^2 = .42$, and probe difference, $F(2, 34) = 87.91$, $p < .001$, partial $\eta^2 = .84$. The interaction was marginally significant, $F(4, 68) = 2.27$, $p = .071$, partial $\eta^2 = .12$. Planned follow-up comparisons revealed that, for 180° and 60° probe differences, the mean VWM capacities increased as the encoding time was prolonged with the slopes of 0.86, $F(2, 34) = 19.07$, $p < .001$, partial $\eta^2 = .53$, and 0.64, $F(2, 34) = 5.45$, $p = .009$, partial $\eta^2 = .24$, respectively. Again, however, for 20° probe difference, there was no such benefit from prolonged encoding time (slope: 0.16), $F(2, 34) = .45$, $p = .644$, partial $\eta^2 = .03$.

Discussion

Not being surprised, again, we replicated the critical findings from our Experiment 1, showing that the mean VWM capacities for simple colors increased as the encoding time was prolonged with large probe difference (180°). With three independent replications, we provide compelling evidence that memory performance for simple colors is also improved when the encoding time is extended. That is, visual memory benefits from prolonged encoding time regardless of stimulus type.

Consistent with Experiment 2, we found that when adopting the same color sets, the encoding time benefit was eliminated when the difference between two probes was substantially reduced from 180° on the color wheel to 20°. Once the probe difference increased to 60°, the size of the encoding time benefit recovered and fell in between the 20° and 180° conditions. It suggests that the scale of the encoding time benefit is impacted by how much the fidelity of the memory representation is required by the task.

Experiment 4

As mentioned above, compared to simple colors, real-world objects not only have additional conceptual information but are also perceptually more complex. In previous experiments, we found the same effects for simple colors as for real-world objects, indicating that neither the conceptual information nor the perceptual complexity is linked to the encoding time benefit. However, one might still argue that there are different mechanisms underlying the benefits for real-world objects and for simple colors. As outlined earlier, the involvement of VLTM is one factor that may play a crucial role in driving the encoding time benefit. Previous studies have shown that real-world objects with different conceptual information barely interfered with each other in VLTM, suggesting that conceptual information is one important factor to help memorize real-world objects into VLTM (Konkle et al., 2010). Thus, it is quite feasible that the conceptual information associated with real-world objects still plays a critical role in obtaining the benefits from prolonged encoding time.

The current experiment examined this possibility. In this study, participants had to memorize real-world objects that were either familiar (generating additional conceptual information) or unfamiliar (not generating additional conceptual information), with more or less the same perceptual complexity. To determine which objects were familiar or unfamiliar, we first conducted Experiment 4a, in which participants had to indicate whether they recognized the object that was shown and indicated on a 5-point scale how confident they were in their answer. On the basis of these data, we selected real-world objects that were indicated as being very familiar and real-world objects that were considered very unfamiliar. In Experiment 4b, we used these stimuli to create two conditions: Participants had to memorize familiar real-world objects in one condition and unfamiliar real-world objects in the other condition. We used the same procedure as in Experiment 1. If the encoding time benefit depends on stimulus familiarity (which is assumed to generate additional conceptual information), we expect to see an increase in memory performance for familiar objects but not for unfamiliar objects when the encoding time is prolonged. If this effect is not found, we have to conclude that the encoding time benefit has nothing to do with stimulus familiarity.

Experiment 4a

Method. Twelve new participants (two males; mean age: 20.4 years) took part in the experiment. A new set of 210 images of real-world objects (subtended by 2° × 2°) were selected from the same database as in Experiment 1. In each trial, an image of the real-world object was present for 5 s, and participants had to indicate whether they could recognize what it is or not. If yes, they pressed "left arrow"; otherwise, they pressed "right arrow" on the keyboard. Following this response, participants indicated their confidence about their answers on 1–5 confidence scale test (1 represented very sure and 5 represented very unsure). There was no time limit for their responses.

Results. As illustrated in Figure 4A, we randomly selected 15 familiar objects and 15 unfamiliar objects from one array of objects with which all participants were completely familiar (with the answer of "yes" and the confidence of "very sure") and the other array of objects with which all participants were completely unfamiliar (with the answer of "no" and the confidence of "very sure"), respectively.

Experiment 4b

Method. Twenty-four new participants (one male; mean age: 20.1 years) took part in the experiment. The procedure was identical to that of Experiment 1, except that participants were only required to memorize real-world objects with different familiarity. Thus, a 3 (*encoding time:* 0.2 s, 1 s, and 2 s) × 2 (*familiarity:* familiar vs. unfamiliar) within-subject design was adopted.

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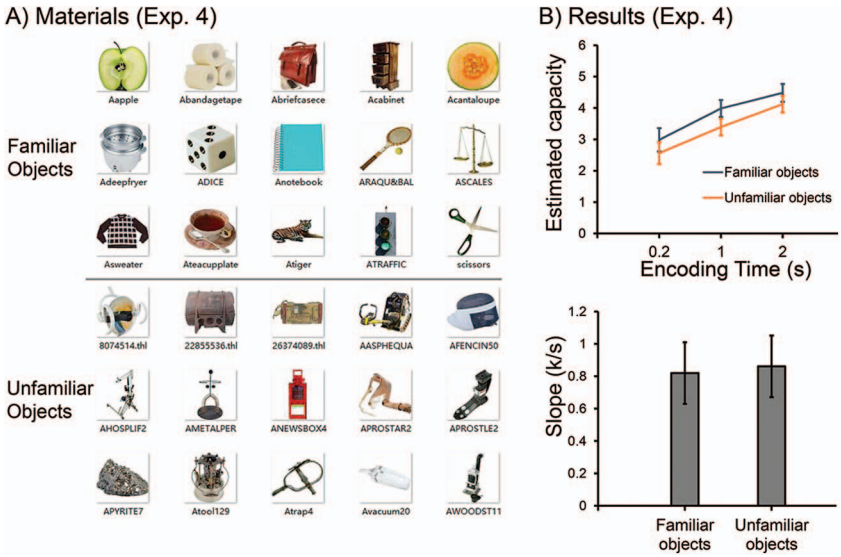


Figure 4. (A) Familiar and unfamiliar objects used as memory materials in Experiment 4b were selected based on the results of Experiment 4a. (B) Upper panel shows estimated capacity as a function of encoding time in Experiment 4b, and bottom panel shows the estimated slopes for familiar and unfamiliar objects. Error bars denote within-subjects 95% confidence intervals. See the online article for the color version of this figure.

Results. The mean VWM capacities for different familiarities as a function of encoding time are shown in Figure 4B. A repeated-measures ANOVA on the mean VWM capacities with variables familiarity (familiar vs. unfamiliar) and encoding time (0.2 s, 1 s, and 2 s) showed significant main effects for encoding time, $F(2, 46) = 40.36$, $p < .001$, partial $\eta^2 = .64$, and familiarity, $F(1, 23) = 10.07$, $p = .004$, partial $\eta^2 = .31$. No interaction was observed, $F(2, 46) = 0.28$, $p = .755$, partial $\eta^2 = .01$, Bayes factor [BF] = 0.14. Planned follow-up comparisons revealed that the mean VWM capacities increased as the encoding time was prolonged for both familiar objects, $F(2, 34) = 19.07$, $p < .001$, partial $\eta^2 = .53$, and unfamiliar objects, $F(2, 34) = 5.45$, $p = .009$, partial $\eta^2 = .24$. Statistically, the slope for familiar objects (0.82) and that for unfamiliar objects (0.86) were also the same, $t(23) = .23$, $p = .823$, $d = 0.06$, BF = 0.22.

Discussion

The current results showed that the overall memory performance for familiar objects was better than that for unfamiliar objects, but the encoding time benefit was the same regardless of whether participants were familiar or unfamiliar with these objects. This indicates that, similar to what has been shown regarding the perceptual complexity, the additional conceptual information related to the real-world objects is not critical for obtaining benefits from prolonged encoding time.

General Discussion

Recently, Brady et al. (2016) found that the memory performance for real-world objects was improved when the encoding time was prolonged while this effect was not found for simple stimuli such as colors. On the basis of this, Brady et al. argued that the richer conceptual information of real-world objects enabled observers to exploit the extended encoding time to store a larger number of items in working memory. This important result challenged the standard view that the storage capacity of VWM is limited (Adam, Vogel, & Awh, 2017; Awh et al., 2007; Cowan, 2001; Luck & Vogel, 1997; Zhang & Luck, 2008). However, inconsistent with Brady et al., the current study unequivocally shows that the encoding time benefit does not depend on the type of stimuli employed: There were encoding time benefits for both real-world objects (Experiments 1 and 4) *and* for simple colors (Experiments 1, 2, and 3; see also Quirk & Vogel, 2017, for similar results). We also show that this benefit is not the result of perceptual complexity or the presence of conceptual information (Experiment 4). As shown in Experiments 2 and 3, one of the factors that impacted the encoding time benefit was the task requirement: If a higher fidelity memory representation was required, the encoding time benefit was reduced.

Brady et al. (2016) found an increased CDA amplitude for real-world objects when observers had to memorize five objects instead of three objects, suggesting that more than three real-world objects could be stored in VWM. This might indicate that VLTM does not play a crucial role. However, Quirk and Vogel (2017), who used more participants and more trials to increase statistical power, were not able to replicate this effect on the CDA and reported no reliable difference in CDAs between three and five real-world objects. Therefore, it is difficult to decide whether or not real objects are exclusively stored in VWM (as argued by Brady et al., 2016) and whether VLTM plays a role in the encoding time benefit. Regardless of this specific discussion, our conclusion is the same: Visual memory benefits from prolonged encoding time regardless of stimulus type.

So, one question that needs to be answered is why visual memory benefits from prolonged encoding time. There are several possibilities, for example: (a) The items are stored in VWM, but

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with the involvement of (or the interaction with) VLTM storage, the memory capacity is temporally increased (see also Endress & Potter, 2014; Hollingworth, 2005; Hollingworth & Hollingworth, 2004; Shoval, Luria, & Makovski, 2019); (b) the items are not stored in VWM but instead in VLTM, which basically has a very large storage space (see also Brady et al., 2008); and (c) the items are stored in both VWM and VLTM by chunking information from different memory types, resulting in larger memory capacity (see also Ngiam, Khaw, Holcombe, & Goodbourn, 2019). Therefore, it seems that, if anything, the involvement of VLTM might be a critical factor in driving the benefits from prolonged encoding time. However, it should be noted that none of the explanations support the notion that VWM capacity is extended.

It has been argued that relative to simple colors, real-world objects have additional conceptual information (which is related to VLTM), which in turn may be the reason for encoding time benefits of real-world objects (Brady et al., 2016; see also Curby, Glazek, & Gauthier, 2009; Olsson & Poom, 2005). However, compared to simple colors, real-world objects not only have additional conceptual information but also have additional perceptual complexity. Here, we found that the encoding time benefit existed both for simple colors and for real-world objects, which indicates that neither the conceptual information nor the perceptual complexity is necessarily linked to the encoding time benefit. Critically, while controlling for the perceptual complexity, our Experiment 4 further showed that the encoding time benefit for real-world objects did not depend on whether participants had any conceptual knowledge about real-world objects as the benefits were the same for familiar and unfamiliar objects. Therefore, it is unlikely that conceptual information has any potential impact on obtaining the encoding time benefit.

In Experiment 4, we found that the overall memory performance for familiar objects was better than that for unfamiliar objects. There is some controversy in the literature regarding this effect. On the one hand, using Pokémon figures as memory materials, Xie and Zhang (2017a, 2017b, 2018) found no increase in memory capacity due to stimulus familiarity but only found an effect on memory consolidation. On the other hand, using alphabet letters as memory materials, Ngiam et al. (2019) reported an increase in memory capacity due to stimulus familiarity. Ngiam et al. argued that the degree of familiarity between first-generation (familiar) and recent-generation (unfamiliar) Pokémon is too small to generate an effect on memory capacity. Indeed, Ngiam et al. (2019) used English letters as familiar stimuli and novel characters as unfamiliar stimuli, which generates a large difference in familiarity. Under those conditions, a difference in memory capacity was found. This is consistent with our Experiment 4, in which there was a large difference between familiar and unfamiliar objects because the unfamiliar real-world objects we chose were completely unknown to observers while the familiar ones were well known to the observers.

In summary, we conclude that visual memory benefits from prolonged encoding time regardless of stimulus type employed. Our study shows that neither the presence of conceptual information nor the perceptual complexity of the stimuli plays a critical role in obtaining the encoding time benefit. This implies that factors other than those related to conceptual information and perceptual complexity associated with VLTM might be critical in obtaining the benefits from prolonged encoding time.

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Appendix

Analysis for the Digits Report Task

The mean accuracies for digits report task in all experiments are shown in Table A1. In Experiment 1, a repeated-measures ANOVA on the mean accuracies with variables *probe type* (color, objects, and objects with detail) and *encoding time* (0.2 s, 1 s, and 2 s) showed that there were no significant main effects for encoding time, $F(2, 34) = 2.17$, $p = .129$, partial $\eta^2 = .11$, and probe type, $F(2, 34) = 1.86$, $p = .171$, partial $\eta^2 = .1$. Also, no significant interaction was observed, $F(4, 68) = 0.13$, $p = .97$, partial $\eta^2 = .01$.

Table A1
Mean Accuracies for Digits Report Task in the Present Study

Variable	0.2 s, *M* (*SD*)	1 s, *M* (*SD*)	2 s, *M* (*SD*)
Experiment 1			
Colors	.98 (.03)	.98 (.03)	.99 (.01)
Objects	.98 (.04)	.97 (.05)	.99 (.03)
Objects with detail	.97 (.04)	.97 (.06)	.98 (.03)
Experiment 2			
Colors 20°	.97 (.03)	.97 (.04)	.99 (.06)
Colors 180°	.99 (.03)	.98 (.03)	.97 (.06)
Experiment 3			
Colors 20°	.97 (.05)	.95 (.08)	.96 (.06)
Colors 60°	.96 (.08)	.97 (.04)	.97 (.05)
Colors 180°	.96 (.07)	.96 (.07)	.96 (.06)
Experiment 4b			
Familiar objects	.98 (.04)	.97 (.04)	.98 (.03)
Unfamiliar objects	.98 (.03)	.97 (.03)	.98 (.04)

In Experiment 2, a repeated-measures ANOVA on the mean accuracies of digits report task with variables *probe difference* (180° vs. 20°) and *encoding time* (0.2 s, 1 s, and 2 s) showed that there were no significant main effects for encoding time, $F(2, 34) = 0.33$, $p = .719$, partial $\eta^2 = .02$, and probe difference, $F(1, 17) = 1.03$, $p = .324$, partial $\eta^2 = .06$. Also, no significant interaction was observed, $F(2, 34) = 1.4$, $p = .26$, partial $\eta^2 = .08$.

In Experiment 3, a repeated-measures ANOVA on the mean accuracies of digits report task with variables *probe difference* (180°, 60°, and 20°) and *encoding time* (0.2 s, 1 s, and 2 s) showed that there were no significant main effects for encoding time, $F(2, 34) = 0.1$, $p = .909$, partial $\eta^2 = .01$, and probe difference, $F(2, 34) = 0.25$, $p = .781$, partial $\eta^2 = .01$. Also, no significant interaction was observed, $F(4, 68) = 0.79$, $p = .536$, partial $\eta^2 = .04$.

In Experiment 4b, a repeated-measures ANOVA on the mean accuracies of digits report task with variables *familiarity* (familiar vs. unfamiliar) and *encoding time* (0.2 s, 1 s, and 2 s) showed that there were no significant main effects for encoding time, $F(2, 46) = 1.07$, $p = .352$, partial $\eta^2 = .04$, and familiarity, $F(1, 23) = 0.06$, $p = .809$, partial $\eta^2 < .01$. Also, no interaction was observed, $F(2, 46) = 0.62$, $p = .543$, partial $\eta^2 = .03$.

Overall, participants performed the digits report task quite well in all conditions in all experiments.

Received August 27, 2019
Revision received March 6, 2020
Accepted March 25, 2020 ■