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No Fixed Limit for Storing Simple Visual Features: Realistic Objects Provide an Efficient Scaffold for Holding Features in Mind

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Abstract

Prominent theories of visual working memory postulate that the capacity to maintain a particular visual feature is fixed. In contrast to these theories, recent studies have demonstrated that meaningful objects are better remembered than simple, nonmeaningful stimuli. Here, we tested whether this is solely because meaningful stimuli can recruit additional features—and thus more storage capacity—or whether simple visual features that are not themselves meaningful can also benefit from being part of a meaningful object. Across five experiments (30 young adults each), we demonstrated that visual working memory capacity for color is greater when colors are part of recognizable real-world objects compared with unrecognizable objects. Our results indicate that meaningful stimuli provide a potent scaffold to help maintain simple visual feature information, possibly because they effectively increase the objects' distinctiveness from each other and reduce interference.

Keywords

working memory capacity, object recognition, meaningfulness, color memory, open data, preregistered

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Decades of research have shown that the capacity of visual working memory—the cognitive system that holds visual information in an active state—is highly limited. However, it is still not well understood precisely what these limits are and how they arise. Although many theories of working memory postulate that the capacity is fixed—that is, in terms of fixed number of objects (Awh et al. (2007) or a fixed resource pool per visual feature (Bays et al., 2009)—recent findings have suggested that working memory capacity strongly depends on what type of information is being remembered and that capacity is increased for more meaningful stimuli (Asp et al., 2021; Brady & Störmer, 2020, 2022; Brady et al., 2016; Curby et al., 2009; Ngiam et al., 2019; Zimmer & Fischer, 2020). For example, real-world objects are better remembered than simple abstract shapes (e.g., colored squares, oriented lines; Brady et al., 2016; Brady & Störmer, 2022), and ambiguous face stimuli (i.e., Mooney faces) elicit higher memory capacity when they are recognized as a face (i.e., meaningful) relative to when they are perceived as arbitrary black-and-white shapes (Asp et al., 2021). On the basis of these findings, it has been hypothesized that recognizing a stimulus as meaningful allows the extraction and storage of additional conceptually meaningful features, effectively increasing working memory capacity (e.g., a face can be encoded not only by low-level shape features but also by features such as eye distance and head shape, and different object identities can be encoded not only in terms of their different visual features but also in terms of their affordances, e.g., sandal vs. tennis shoe, barstool vs. office chair). This is broadly consistent with models of working memory in which

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the presence of more features allows participants to store more information in memory (e.g., color vs. color/orientation; Luck & Vogel, 2013).

A critical question is whether meaningful stimuli can also support memory for visual features that are not themselves meaningful and in which no additional feature information can be extracted. Specifically, if participants are asked to remember the color blue, will it be better remembered when it appears as part of a real-world object or as an unrecognizable, nonmeaningful shape? Assuming memories are organized in a hierarchically structured way, where an individual memorandum comprises bundles of both feature and object-level representations (Brady et al., 2011), real-world objects could provide a particularly useful structure for lower-level visual features: Realistic objects connect to higher-order conceptual knowledge, introducing additional dimensionality and potentially reducing interference between the otherwise lower-level simple features (Cohen et al., 2014; Wyble et al., 2016). Thus, similar to how stimuli that are more distinct in location or orientation have less interference between them and lead to improved color memory performance (Brown et al., 2021; Emrich & Ferber, 2012; Oberauer & Lin, 2017), it is plausible that simple feature memory could benefit from being encoded as part of meaningful objects. This would be particularly important in the context of meaningful objects because it would also suggest that existing studies have consistently underestimated memory for simple visual features: In the real world, colors appear on meaningful real-world objects and not in isolation; thus, from an ecological perspective, it is crucial to characterize and understand feature memory and its capacity in more naturalistic conditions.

Across a series of experiments, we found that color memory is greater when colors are presented as part of realistic objects relative to unrecognizable shapes. Importantly, colors were always randomly paired with objects so that no preexisting long-term associations between certain colors and objects could explain the results. Furthermore, participants were never directly asked about the shapes or object identities but were always tested only on their color memory. Our findings demonstrate that naturalistic, real-world objects that connect to conceptual knowledge can improve simple color memory by serving as a particularly effective memory cue, aiding the encoding, maintenance, and retrieval of simple feature information.

Open Practices Statement

The hypotheses, analysis plans, and exclusion criteria for Experiments 1 through 3 were preregistered on AsPredicted (Experiment 1: https://aspredicted.org/5p4tt.pdf, Experiment 2a: https://aspredicted.org/5na6m.pdf, Experiment 2b: https://aspredicted.org/ce9ar.pdf, Experiment 3: https://aspredicted.org/cp3bd.pdf). All data and analysis code have been made publicly available via OSF and can be accessed at https://osf.io/mghr6/. The experiments were approved by the institutional review boards at the University of California San Diego and Dartmouth College.

Statement of Relevance

Understanding the limits of visual working memory is important because working memory is a core cognitive ability that relates to measures of intelligence and academic performance. Prior work investigating the limits of visual working memory has often asked participants to remember simple shapes, such as colored circles or oriented lines. However, in real life, we rarely encounter such visual features in isolation. Instead, we see and remember them embedded in naturalistic contexts, for example as part of real-world objects: a blue car, a red phone case, et cetera. Here, we demonstrated that working memory capacity for colors is greater when participants remember these colors as part of real-world objects compared with unrecognizable abstract shapes. This finding significantly changes how we ordinarily think about working memory capacity, demonstrating that working memory capacity for even simple features is strongly affected by the meaningfulness of the object.

Experiment 1: Sequential Presentation

We first tested whether working memory for simple features differs depending on whether colors appear on meaningful real-world objects or on unrecognizable (and thus nonmeaningful) scrambled versions of these objects.

Method

The hypothesis, analysis plan, and exclusion criteria for this experiment were preregistered (https://aspredicted.org/5p4tt.pdf).

Participants. Eighty-six participants were recruited from the subject pool at the University of California San Diego. All participants provided informed consent prior to beginning the experiment. Participants completed the experiment in a Web browser on their own devices. We

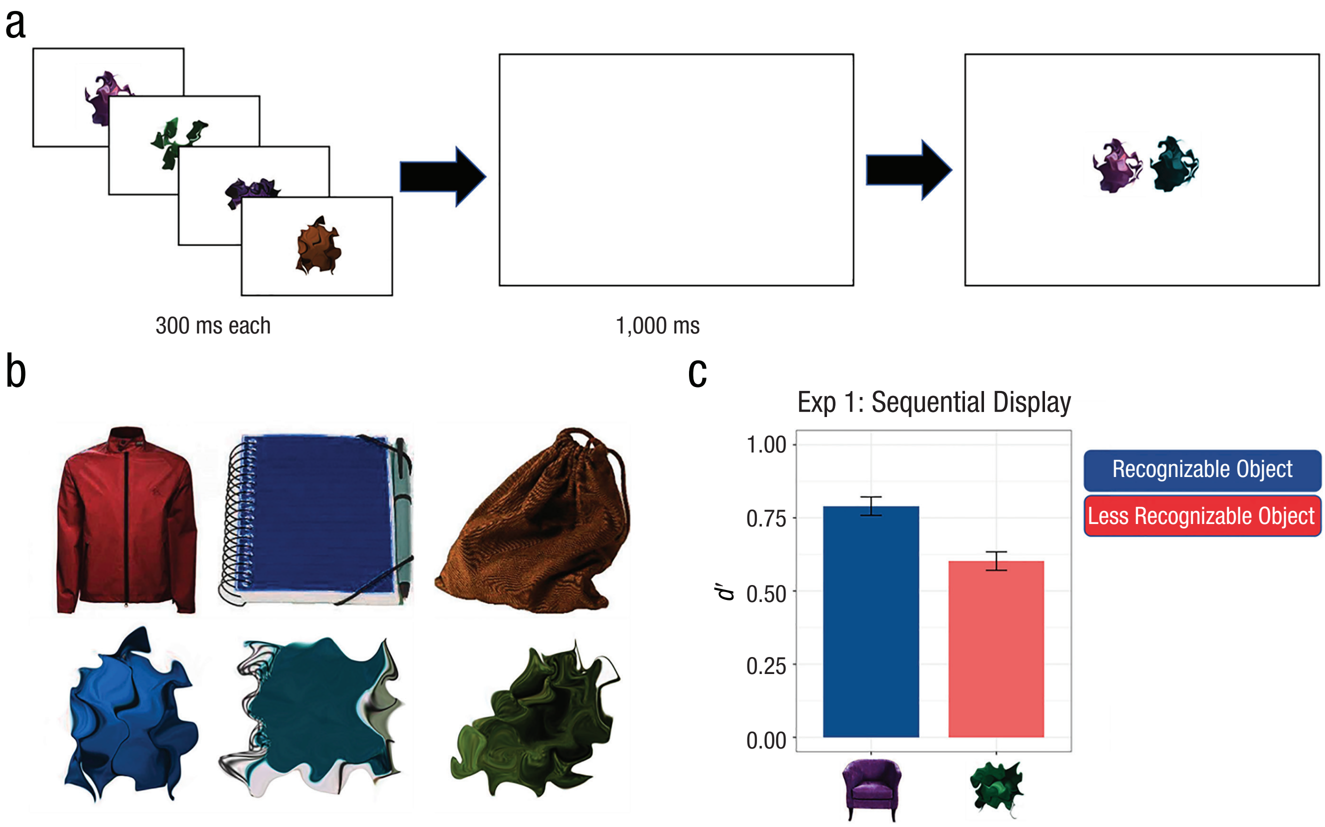

Fig. 1. Procedure, example stimuli, and results from Experiment 1. (a) Depiction of experimental procedure. Each stimulus was presented for 300 ms in the center of the screen with a 200-ms interstimulus interval. After a 1,000-ms delay, one of the stimuli reappeared in the center with two color options: one target color and one foil color (180° away on the color wheel). Participants were instructed to choose the color that matched the color from their memory. In the intact-object condition, all four stimuli were colored real-world objects, whereas in the scrambled-object condition, there were four scrambled objects. (b) Example stimuli. The top three images are examples of colored real-world objects, and the bottom three images are examples of corresponding scrambled objects in different colors. Scrambling was performed using diffeomorphic transformations as in Stojanoski and Cusack (2014). (c) Results of Experiment 1: sequential presentation. Average *d′* values are plotted separately for the intact-object condition (recognizable objects) and the scrambled-object condition (less recognizable objects). Error bars represent within-subject standard errors.

requested that the entire experiment be completed in full-screen mode on a computer. For analysis, we used data from the first 30 participants who fitted our exclusion criterion. Following our standard lab protocol and preregistered analysis plan, we excluded data from analysis if participants' overall *d′* value across all conditions was lower than 0.5 or if more than 10% of the trials were excluded. Individual trials were excluded if a response occurred less than 200 ms or more than 5 s after the response screen. On the basis of the *d′* criteria, we excluded 44 participants. Data from an additional 12 participants were excluded because more than 10% of their trials met the response time exclusion criteria. We chose 30 as the final number of participants in this study following similar protocols of previous studies investigating visual working memory (e.g., Asp et al., 2021; Awh et al., 2007; Brady & Alvarez, 2011; Brady & Störmer, 2020, 2022). The final sample of participants (N = 30) was between 18 and 31 years old. Because of an unusually high rate of exclusion following the preregistered analysis plan, we reanalyzed our data including all participants whose performance was above chance across all conditions (accuracy > .50), which resulted in 71 participants. All main findings reported here were replicated using these less strict exclusion criteria (see the Supplemental Material available online).

Stimuli. For object stimuli, we used the same 540 images as did Brady et al. (2013). Thus, these objects were designed to be largely made of a single arbitrary color—so they would be recognizable in any random color (see Fig. 1b for example stimuli). Following Miner et al. (2020), we rotated the stimuli in hue space using a Commission Internationale de l'Éclairage (CIE) L^*a^*b color wheel that approximately matched that used in previous work (Schurgin et al., 2020; Suchow et al., 2013), such that on a given trial, the object color was determined by using a random color value along the

360° color wheel with the constraint that the color images on each trial were at least 30° apart from each other. For the scrambled objects, these 540 object images were distorted using the diffeomorphic transformation technique (Stojanoski & Cusack, 2014) to be unrecognizable by the participants. This scrambling technique is particularly useful because it removes the meaningfulness of a stimulus while preserving basic perceptual properties.

Procedure. Participants remembered four colored stimuli on each trial. Stimuli were presented sequentially at the center of the screen, each appearing for 300 ms with a 200-ms interstimulus interval. We used a sequential presentation design in which items were shown one at a time at the same spatial location, which has previously been shown to maximize the benefit of meaningfulness on working memory performance (Brady & Störmer, 2022). Each of the memory stimuli was 150 pixels in width by 230 pixels in height. After a 1,000-ms memory delay, participants were presented with two differently colored versions of the same object at the center of the screen: one matching the encoded color (the target) and one maximally distinct from the target (i.e., 180° away on the color wheel; the foil). Participants performed a two-alternative forced-choice (2AFC) task, reporting which one of the colors they had previously seen by pressing the left or right arrow key on the keyboard (for an illustration, see Fig. 1a). Importantly, participants were never asked about the identity of the objects but only about which color they saw. After each response, participants received feedback in the form of a sound. Each participant completed 270 trials in total. Before the experiment, participants watched a 30-s example video of practice trials to familiarize themselves with the procedure.

Data analysis. Visual working memory performance was quantified using d' for a 2AFC task: $(z_{\text{hits}} - z_{\text{false alarms}})/\sqrt{2}$. We calculated d' values separately for the two conditions for each participant (intact-object condition vs. scrambled-object condition).

Results

Memory performance was higher when participants remembered colors that were part of realistic objects (mean $d' = 0.79$) relative to unrecognizable scrambled versions of these objects (mean $d' = 0.60$), $t(29) = 4.20$, $p = .0002$, Cohen's $d_z = 0.86$ (see Fig. 1c). The effect resulted in the same statistical decision when we included all participants whose performance was above chance ($N = 71$; see the Supplemental Material). This indicates that memorizing simple features, such as a particular set of colors, benefits from meaningful contextual information.

Experiment 2: Simultaneous Spatial Presentation

In Experiment 1, stimuli were presented at the same central location sequentially. Thus, object-identity information may have been particularly useful in segregating and remembering the different colors (essentially serving as an encoding or a retrieval cue). Because spatial information is thought to be a particularly strong cue to separate memoranda and reduce interference, even when task irrelevant (e.g., Cai et al., 2019; H. Chen & Wyble, 2015a, 2015b; Elsley & Parmentier, 2015), we next tested whether additional spatial information would eliminate the real-world-object benefit. In Experiment 2a, we presented all stimuli simultaneously at four different locations. In Experiment 2b, we also showed a spatial cue during the 2AFC, providing participants with an explicit spatial retrieval cue.

Method

The hypothesis, analysis plan, and exclusion criteria for this experiment were preregistered (Experiment 2a: https://aspredicted.org/5na6m.pdf, Experiment 2b: (https://aspredicted.org/ce9ar.pdf).

Participants. For Experiment 2a, 78 participants were recruited from the subject pool at the University of California San Diego. Data from six participants were excluded because more than 10% of their trials met the response time exclusion criteria. On the basis of the d' criteria, we excluded 42 participants. The final sample of participants ($N = 30$) for Experiment 2a was between 18 and 31 years old.

For Experiment 2b, data from 47 participants were collected from the subject pool at the University of California San Diego. Data from three participants were excluded because more than 10% of their trials met the response time exclusion criteria; data from an additional 14 participants were excluded because they did not meet the overall d' criterion. The final sample of participants ($N = 30$) for Experiment 2b was between 18 and 26 years old.

Given the high exclusion rate, as for Experiment 1, we reanalyzed all data with a less strict exclusion criterion including data from all participants whose performance was above chance and replicated the main findings ($N = 71$ for Experiment 2a, $N = 43$ for Experiment 2b; see the Supplemental Material).

Stimuli. Memory stimuli were identical to those in Experiment 1.

Procedure. All procedures were the same as in Experiment 1 except the stimulus presentation at encoding and

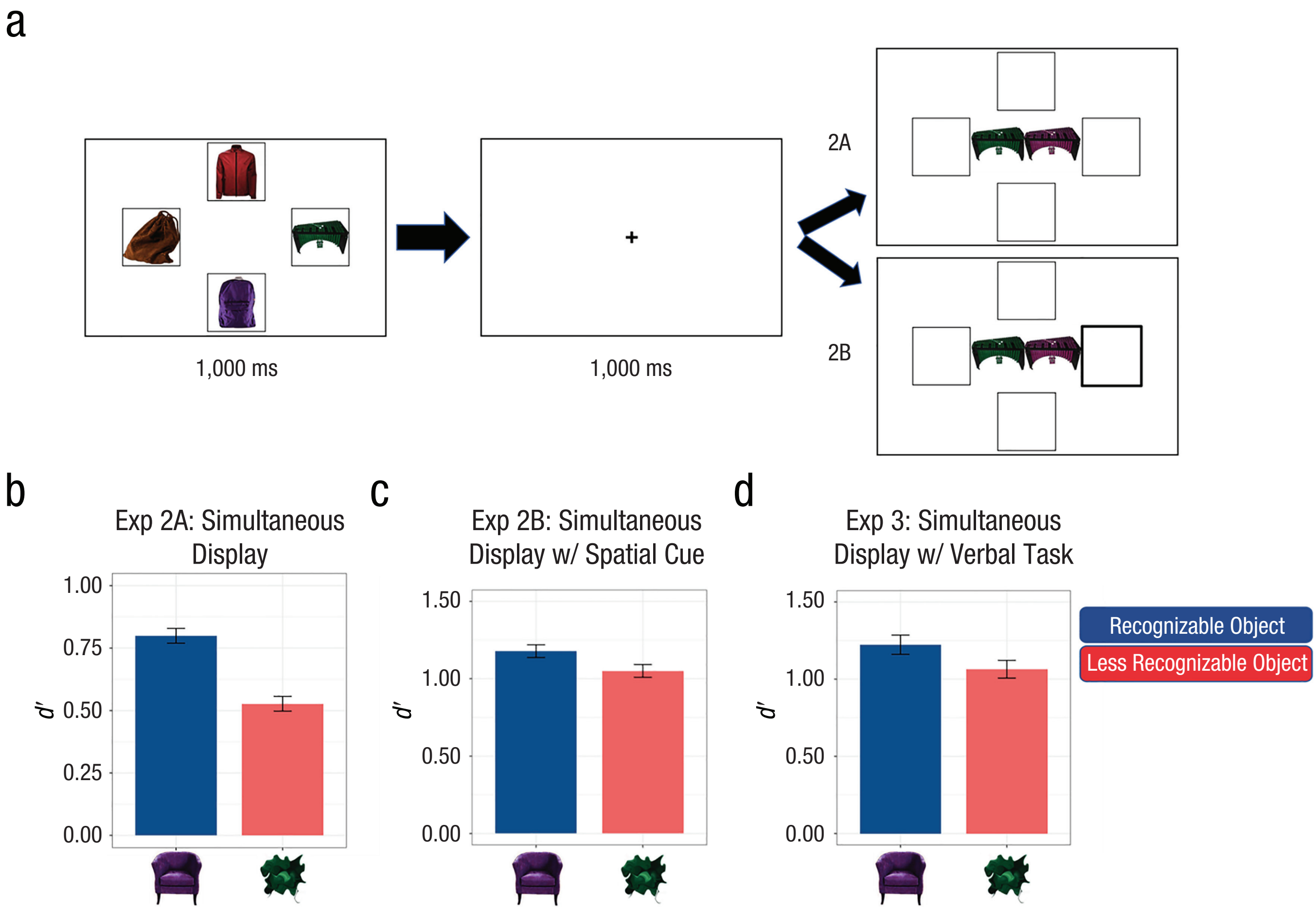

Fig. 2. Procedures and results from Experiments 2a, 2b, and 3. (a) Depiction of experimental procedures. All four stimuli were shown simultaneously for 1,000 ms, equally distributed around a central fixation cross. All other procedures were identical to those used in Experiment 1. In Experiment 2b, the placeholder for the target item's location was bolded on the response screen to indicate its location during encoding. In Experiment 3, a concurrent digit-repeating task was present during each trial. (b) Results of Experiment 2a: simultaneous presentation. (c) Results of Experiment 2b: simultaneous presentation with explicit spatial cue at retrieval. (d) Results of Experiment 3: simultaneous presentation with a verbal suppression task. In (b) through (d), average d' values are plotted separately for the intact-object condition (recognizable objects) and the scrambled-object condition (less recognizable objects). Note that results for Experiments 2b and 3 are shown using a different scale on the y-axis because overall performance was higher than in Experiment 2a. Error bars represent within-subject standard errors.

retrieval. On each trial, participants were presented with an array of four stimuli evenly distributed around the center of the screen for 1,000 ms, followed by a 1,000-ms delay period. After the delay, two test stimuli appeared in the center of the screen, and participants made a 2AFC, indicating which color they saw at encoding. During encoding and retrieval, placeholders were shown at the four locations. For Experiment 2b, the procedure was identical except that at the end of each trial, participants were shown an explicit location probe. The location probe was implemented by bolding the thickness of the placeholder box to indicate the location of the target object (for an illustration, see Fig. 2a).

Data collection and analysis. Data collection and analysis procedures were identical to those in Experiment 1.

Results

As in Experiment 1, we found a benefit for color memory when colors were presented on real-world objects relative to unrecognizable shapes both in Experiment 2a (mean d' = 0.80 for intact-object condition, mean d' = 0.53 for scrambled-object condition), $t(29) = 6.52$, $p < .001$, Cohen's $d_z = 1.53$, as well as Experiment 2b (mean d' = 1.18 for intact-object condition, mean d' = 1.05 for scrambled-object condition), $t(29) = 2.19$, $p = .037$, Cohen's $d_z = 0.30$. These results were replicated when we included all participants whose performance was above chance (see the Supplemental Material). These results show that even when spatial information is available at encoding and retrieval, colors are better stored when embedded in realistic objects relative to scrambled versions of them (Figs. 2b and 2c).

Experiment 3: Verbal Suppression

Real-world objects themselves are more verbalizable than scrambled stimuli, though it is unclear how labeling the objects would improve color memory (which were equally possible to verbally label in each condition). Nonetheless, to rule out the possibility that the meaningful object benefit on color memory arises from verbal labeling, we added a concurrent articulatory suppression task in Experiment 3.

Method

The hypothesis, analysis plan, and exclusion criteria for this experiment were preregistered (https://aspredicted.org/cp3bd.pdf).

Participants. Thirty-eight participants were recruited from the subject pool at the University of California San Diego. The first 30 participants whose data did not meet the exclusion criteria were analyzed. Data from participants with overall d' scores less than 0.5 (three participants) or overall verbal task accuracy lower than 80% (two participants) were excluded. Data from an additional three participants were excluded because more than 10% of their trials met the response time exclusion criteria. The final sample of participants was between 18 and 27 years old (two participants did not report their ages).

Stimuli. Stimuli were identical to those in Experiment 1.

Procedure. On each trial, three colored images were presented simultaneously around the center of the screen for 1,000 ms, two on the left and right sides of fixation and one below fixation. Prior to the stimulus presentation, participants were presented with four digits of numbers that they were instructed to verbally rehearse throughout the trial. After making a color 2AFC report, participants typed in the four digits they were repeating. Note that the set size was lower here than in previous experiments to ensure participants would be able to do the working memory task while also performing the difficult verbal suppression task. All other procedures were identical to those in Experiment 2a (simultaneous presentation).

Data analysis. For the verbal task, accuracy of the digit response was calculated. The data-analysis plan was otherwise identical to the plan used in Experiment 1.

Results

Average digit accuracy for participants was 95% correct. Replicating our previous experiments, analyses found a reliable real-world-object benefit (mean d' = 1.22 for intact-object condition, mean d' = 1.06 for scrambled-object condition), $t(29) = 4.16$, $p < .001$, Cohen's $d_z = 0.48$ (see Fig. 2d). Thus, verbal encoding strategies do not play a role in the meaningfulness advantage we found for color memory, consistent with previous work (e.g., Brady & Störmer, 2022) that showed no effects of verbal interference on working memory for real-world objects.

Experiment 4: Upright Versus Inverted Objects

Thus far, we used scrambled objects as our control condition to closely match visual complexity and retain lower-level feature information. Scrambled and intact objects have been shown to similarly activate early visual areas (e.g., Grill-Spector et al., 1998; Kanwisher et al., 1997), and the diffeomorphic transformation technique we used seems particularly effective in preserving low-level visual feature information (Stojanoski & Cusack, 2014). As another control condition, in Experiment 4, we used upside-down objects, which are less recognizable than upright objects but match the relative structural properties of real objects (e.g., Rossion & Curran, 2010; Yin, 1969).

Method

Participants. Forty-eight participants were recruited from the subject pool at the University of California San Diego. Data from the first 30 participants whose data did not meet the same exclusion criteria as in Experiment 1 were analyzed. Data from two participants were excluded because more than 10% of their trials met the response time exclusion criteria. Data from another 16 participants were excluded because they did not meet the overall d' criterion. The final sample of participants (N = 30) was between 18 and 29 years old. All results were replicated using data from all participants whose performance was above chance (N = 46; see the Supplemental Material).

Stimuli and procedure. All stimuli and procedures were identical to those used in Experiment 2a (simultaneous presentation) with the following exception: The scrambled-object condition was replaced by an inverted-object condition in which the intact object images were rotated 180°.

Data collection and analysis. Data collection and analysis procedures were identical to those in Experiment 1.

Results

We found that participants' color memory was significantly better in the upright-object condition (mean

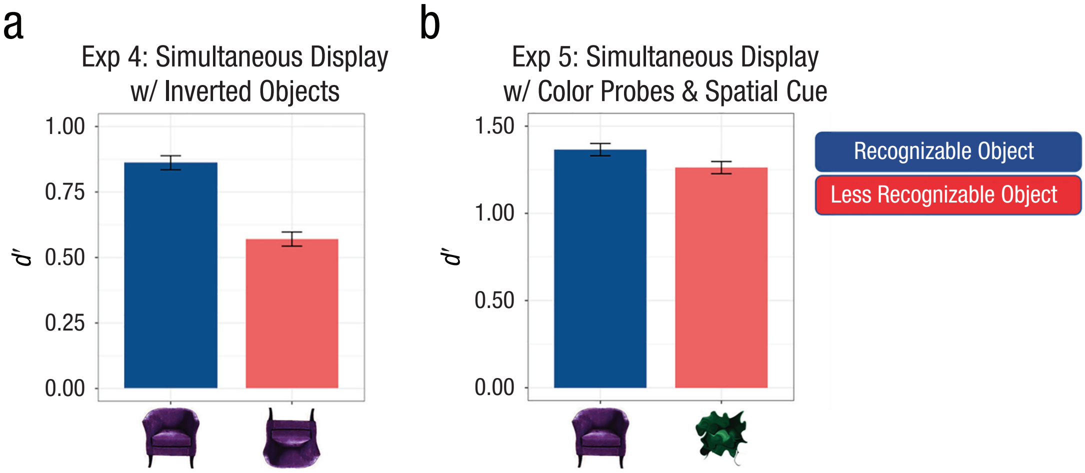

Fig. 3. Results of (a) Experiment 4: simultaneous presentation with upright versus upside-down objects and (b) Experiment 5: simultaneous presentation with color probes and spatial cue. Average d' values are plotted separately for upright and target colors (recognizable objects) and upside-down and foil colors (less recognizable objects). Error bars represent within-subject standard errors.

d' = 0.86) than the inverted-object condition (mean d' = 0.57), $t(29) = 7.68$, $p < .001$, Cohen's $d_z = 1.50$ (see Fig. 3a). These results remained reliable when all participants whose performance was above chance were included ($N = 46$; see the Supplemental Material).

Experiment 5: Nonobject Color Probes at Test

It is plausible that even though object identity was the same for the two probe stimuli during the 2AFC (e.g., one chair in the target color and the same chair in another foil color), participants interpreted the distinctly colored objects as different in identity and thus indirectly used this information to perform the task. To further test whether memory for colors per se was improved, we changed the 2AFC to contain no identity information whatsoever and presented two colored circles instead.

Method

Participants. Forty-two participants were recruited from the subject pool at the University of California San Diego. Data from five participants were excluded because more than 10% of their trials met the response time exclusion criteria. Data from seven participants were excluded because they did not meet the overall d' criterion. The final sample of participants ($N = 30$) was between 18 and 34 years old.

Stimuli and procedure. All stimuli and procedures were identical to those in Experiment 2b (simultaneous presentation with spatial cues) with the following exception: The color options for the 2AFC (target color and foil color) were presented as colored circles without the stimulus identity information.

Data collection and analysis. Data collection and analysis procedures were identical to those in Experiment 1.

Results

We replicated the real-world-object-feature-memory-benefit effect even when color memory was tested on colored circles at the end of the trial, thus eliminating identity information completely (mean d' = 1.37 for intact objects, mean d' = 1.26 for scrambled objects), $t(29) = 2.08$, $p < .05$, Cohen's $d_z = 0.26$ (see Fig. 3b). This effect was slightly smaller than in some of the previous experiments, which could be due to the spatial cue at retrieval (as in Experiment 2b), the fact that the test requires colors to be "unbound" from their object identity, or both (for additional analysis including all participants whose performance was above chance, see the Supplemental Material).

General Discussion

Theories of visual working memory have long assumed that the capacity to remember a set of visual features is fixed (e.g., Awh et al., 2007; Bays et al., 2009) and that this can be accurately measured in simple visual displays. Contrary to this, our study demonstrated that memory for simple features is stronger when those features are part of real-world objects relative to unrecognizable objects. This indicates that there is no rigid limit on working memory capacity for simple features but instead that memory capacity is more flexible and can be increased for basic features when they are part of real-world objects. These results place significant constraints on models of working memory and challenge accounts that assume a fixed storage limit, as they reveal that storing features in ecologically more valid contexts—colors of naturalistic objects instead of abstract shapes—can significantly increase the capacity to remember them.

Other recent work found increased working memory capacity for meaningful objects relative to simple and abstract shape stimuli (Asp et al., 2021; Brady et al., 2016; Brady & Störmer, 2022). In all this previous work, participants were asked to remember (and were tested on) object identities, demonstrating that meaningful objects can be better remembered than abstract stimuli. Our study significantly differed from this, as we found that memory for individual, simple features themselves is improved when these features are part of real-world objects. This effect was reliably found across all five experiments in the current study. Thus, our study reveals a novel role of semantics in feature working memory: Realistic stimuli provide an effective scaffold for simple features belonging to that object.

The current results also relate to other studies that have investigated the interactions between working memory and episodic long-term memory. For instance, other research in verbal working memory has found that performance increases when observers are remembering meaningful words compared with nonwords (e.g., Hulme et al., 1991), and more familiar digits are better remembered than less familiar digit strings (Jones & Macken, 2015). Similar types of long-term-memory effects on working memory have also been found in the visual domain (Bartsch & Shepherdson, 2022; Schurgin et al., 2018). However, one possibility of improved performance in these cases is that active working memory maintenance can be partially replaced by existing passive long-term memories of the specific items and thus not reflect changes in working memory capacity itself. In the current study, objects were never repeated throughout the experiment, preventing the use of any episodic long-term memory of specific objects. Thus, our results suggest a much broader role of conceptual knowledge on working memory by showing that even when no episodic long-term memories are available for a particular item, memory capacity for a simple feature is increased if it happens to be part of a conceptually meaningful object.

How might a realistic and meaningful object help you memorize its visual features, such as its color? Models of visual working memory that assume a distributed and hierarchical structure of memory representations naturally predict such interactions, as higher-level information can provide a useful structure for lower-level features to be stored (Brady et al., 2011). Specifically, lower-level features are bundled together to form objects at a higher level that, if meaningful, connect to conceptual information. Thus, because real-world objects interface with existing knowledge, they are stored not only in terms of their visual features but also in terms of their conceptual meanings. Such connections among multiple levels of hierarchical working and long-term-memory representations allow the memory items to be stored in a higher dimensionality (Asp et al., 2021; Brady & Störmer, 2022; Wyble et al., 2016), effectively reducing interference and supporting memory for their hierarchically linked lower-level features (Allen et al., 2021). To what extent the conceptual knowledge itself is maintained in working memory, or how it affects the representation of what is stored in working memory, remains to be determined. Either way, these semantically rich representations boost active working memory for their associated colors. Our results indicate that meaningful objects are particularly effective in providing a scaffold to maintain and access low-level visual feature information. Future research could explore how the present effects generalize across other meaningful stimuli and how they may be influenced by expertise in a specific object category.

The interpretation that realistic objects provide more relevant and potentially more distinct memory cues relates to other work that has demonstrated the importance of providing clear and distinct representations of objects in working memory tasks (e.g., Griffin & Nobre, 2003; Oberauer & Lin, 2017; Souza et al., 2016). However, previous studies used much more subtle manipulations of perceptual distinctiveness. For example, Brown et al. (2021) tested how well participants bind two visual features—color and orientation—and found higher memory performance when the cued dimension at retrieval was more distinct and more binding errors when they were less distinct, in line with previous work finding that binding errors may be the main result when items become less distinct from each other (Emrich & Ferber, 2012; Oberauer & Lin, 2017). Were binding errors the main cause of the current results? If the foil color during a 2AFC happens to match one of the nontarget items, a binding-failure account predicts that participants would be more likely to produce a false alarm in the scrambled-object relative to intact-object condition. However, additional analyses on these potential swap-error trials revealed that this was not the case (see the Supplemental Material). Work by S. Chen et al. (2021) has also shown that perceptual grouping of stimuli can improve working memory of their features. However, compared with the rather subtle effects of perceptual grouping or using multiple simple features, we found much more robust effects on overall memory performance when using naturalistic contexts. Thus, we suggest that real-world objects are particularly effective in increasing distinctiveness not only during retrieval but also during the encoding and maintenance of color information. This interpretation is supported by our finding that the object benefit on color working memory persists even when observers are given clear spatial information to retrieve the colors (Experiment 2) and when identity information is removed entirely at retrieval (Experiment 5).

Overall, our paradigm provides an ecologically more valid account of how memories are stored and supports models of working memory in which features are not stored as isolated unidimensional features but are bundled together with the objects they are part of in a hierarchically structured way. Most broadly, our results indicate that visual working memory capacity for features is not fixed: Simple features are better remembered when they appear in naturalistic and meaningful contexts.

Transparency

Action Editor: Angela Lukowski
Editor: Patricia J. Bauer
Author Contributions

Yong Hoon Chung: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing.

Timothy F. Brady: Conceptualization; Formal analysis; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing.

Viola S. Störmer: Conceptualization; Formal analysis; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing.

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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Supplemental Material

Additional supporting information can be found at http://journals.sagepub.com/doi/suppl/10.1177/09567976231171339

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