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, non-meaningful stimuli. Here, we test 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 (thirty young adults each) we demonstrate that visual working memory capacity for color is increased when colors are part of recognizable real-world objects compared to 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

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, etc. Here we demonstrate that working memory capacity for colors is increased when participants remember these colors as part of real-world objects compared to 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.

Introduction

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. While many theories of working memory postulate that the capacity is "fixed" (i.e., in terms of fixed number of objects; Awh et al., 2007; or a fixed resource pool per visual feature; Bays et al., 2009), recent studies have argued 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, 2022; Brady & Störmer, 2020; Curby et al., 2009; Ngiam et al., 2019; Zimmer & Fischer, 2020; Brady et al., 2016). For example, real-world objects are better remembered than simple abstract shapes (i.e., colored squares, oriented lines, etc.; 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 were perceived as arbitrary black-and-white shapes (Asp, Störmer, & Brady, 2021). Based on these studies 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 like eye distance and head shape; different object identities can be encoded not only in terms of their different visual features but also by their affordances, e.g., sandal vs. tennis shoe; bar stool vs. office chair, etc.). This is broadly consistent with models of working memory where more features being present allow 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 where no additional feature information can be extracted. Specifically, if asked to remember the color blue, will it be better remembered when it appears as part of a real-world object relative to an unrecognizable, non-meaningful 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, 2016). Thus, similar to how stimuli that are more distinct in location or orientation having less interference between them and leading to improved color memory performance (Emrich & Ferber, 2012; Oberauer & Lin, 2017; Brown et al. 2021), 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 find that color memory is increased when colors are presented as part of realistic objects relative to unrecognizable shapes. Importantly, colors were always randomly paired with objects so that no pre-existing 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 only tested 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.

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 unrecognizable (and thus non-meaningful) scrambled versions of these objects.

Methods

The hypothesis, analysis plan and exclusion criteria for this study were pre-registered (https://aspredicted.org/5p4tt.pdf). The experiments were approved by the Institutional Review Boards at the University of California, San Diego and Dartmouth College. All data and analyses code are available here: https://osf.io/mghr6/

Participants. Eighty-six participants were recruited from the subject pool at the University of California, San Diego. All participants provided informed consent prior to participating. Participants completed the experiment in a web browser on their own devices. We 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 fit our exclusion criterion. Following our standard lab protocol and preregistered analysis plan, data from participants were excluded from analysis if the overall d' value across all conditions was lower than 0.5 or if 10% or more of their trials were excluded. Individual trials were excluded if a response occurred less than 200ms or more than 5s after the response screen. Based on the d' criteria, we had to exclude forty-four participants. Data from an additional twelve participants were excluded due to more than 10% of the trials not meeting the response time exclusion criterion. 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; Brady & Störmer, 2022; Brady & Störmer, 2020; Awh et al., 2007; Brady & Alvarez, 2011). The final sample of participants (N=30) was between 18-31 years of age. Due to an unusually high rate of exclusion following the pre-registered analysis plan, we re-analyzed our data including data from all participants above chance level performance across all conditions (accuracy > 0.50), which resulted in 71 participants. All main findings reported here were replicated using these less strict exclusion criteria (Supplemental Material).

Stimuli. For object stimuli, we used the same 540 images as in Brady et al. (2013). Thus, these objects were designed to be made of largely a single arbitrary color – so that they would be recognizable in any random color (see Fig. 1B for example stimuli). Similar to Miner et al. (2020), we rotated the stimuli in hue space using a CIE L*a*b color wheel that approximately matched that of previous work (Suchow et al., 2013; Schurgin et al., 2020), such that on a given trial the object color was determined by using a random color value along the 360 degree color wheel with the constraint that the color images on each trial were at least 30 degrees 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 to remove 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 300ms with a 200ms inter-stimulus interval. We used a sequential presentation design where 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 width by 230 pixels height. After a 1,000ms memory delay, participants were presented with two different 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 degrees away on the color wheel (the foil). Participants performed a 2-alternative forced choice (2-AFC) task, reporting which one of the colors they had previously seen by pressing the left or right arrow key on the keyboard (for 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 second example video of practice trials to familiarize themselves with the procedure.

Data Analysis. Visual working memory performance was quantified using d' for a 2-AFC task: $[zH - zFA]/\sqrt{2}$. d' values were calculated 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 relative to unrecognizable scrambled versions of these objects (mean d'=0.79 for intact object condition and mean d'=0.60 for scrambled object condition: $t(29)=4.20$, $p=0.0002$; Cohen's $d_z=0.86$; see Fig. 1C). The effect resulted in the same statistical decision when including all participants above chance performance (N=71, see Supplemental Material). This indicates that memorizing simple features, like 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 retrieval cue). As spatial information is thought to be a particularly strong cue to separate memoranda and reduce interference, even when task-irrelevant (e.g., Chen & Wyble, 2015a; Chen & Wyble, 2015b; Elsley & Parmentier, 2015; Cai, et al., 2019), we next tested whether additional spatial information would eliminate the real-world object benefit. In Exp. 2a we presented all stimuli simultaneously at four different locations. In Exp. 2b, we also showed a spatial cue during the 2-AFC, providing participants with an explicit spatial retrieval cue.

Methods

The hypothesis, exclusion criteria and analysis plan were pre-registered (Exp. 2a: https://aspredicted.org/5na6m.pdf; Exp. 2b: (https://aspredicted.org/ce9ar.pdf).

Participants. For Exp. 2a, seventy-eight participants were recruited from the subject pool at the University of California San Diego. Data from six participants were excluded due to more than 10% of the trials not meeting the response time exclusion criterion. Data from 42 participants were excluded due to not meeting the overall d' criterion. The final sample of participants (N=30) for Exp. 2a was between 18-31 years of age.

For Exp. 2b, data from forty-seven participants was collected from the subject pool at the University of California San Diego. Data from three participants were excluded due to more than 10% of trials not meeting the response time exclusion criterion; data from an additional 14 participants were excluded due to not meeting the overall d' criterion. The final sample of participants (N=30) for Exp. 2b was between 18-26 years of age.

Given the high exclusion rate, as for Exp. 1, we re-analyzed all data with a less strict exclusion criteria including data from all participants above chance level performance and replicated the main findings (N=71 for Exp. 2a; N=43 for Exp. 2b; see Supplemental Material).

Stimuli. Memory stimuli were identical to Experiment 1.

Procedure. All procedures were the same as in Exp. 1 except the stimulus presentation at encoding and retrieval. On each trial, participants were presented with an array of four stimuli evenly distributed around the center of the screen for 1,000ms, followed by a 1,000ms delay period. After the delay, two test stimuli appeared in the center of the screen and participants performed a 2-AFC, indicating which color they saw at encoding. During encoding and retrieval, placeholders were shown at the four locations. For Exp. 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 illustration, see Fig. 2A).

Data Analysis. Data analysis was identical to 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 Exp. 2a (mean d'=0.80 for intact object condition and mean d'=0.53 for scrambled object condition: $t(29)=6.52$, $p<0.001$; Cohen's $d_z=1.53$) as well as Exp. 2b (mean d'=1.18 for intact object condition and mean d'=1.05 for scrambled object condition: $t(29)=2.19$, $p=0.037$; Cohen's $d_z=0.30$). These results were replicated when all participants above chance performance were included (see 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 (Fig. 2B & C).

Experiment 3: Verbal suppression

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

Methods

The hypothesis, exclusion criteria and analysis plan for this study were pre-registered (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' data within the exclusion criteria were analyzed. Data from participants with overall d' 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 due to more than 10% of the trials not meeting the response time exclusion criterion. The final sample of participants was between 18-27 years of age (two participants did not report their ages).

Stimuli. Stimuli were identical to Experiment 1.

Procedure. On each trial, three colored images were presented simultaneously around the center of the screen for 1,000ms, 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 which they were instructed to verbally rehearse throughout the trial. After making a color 2-AFC 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 Exp. 2a (Simultaneous Presentation).

Data Analysis. For the verbal task, accuracy of the digit response was calculated. All other data analysis was identical to Experiment 1.

Results

Average digit accuracy for participants was 95% correct. Replicating our previous experiments we found a reliable real-world object benefit (mean d'=1.22 for intact object condition and mean d'=1.06 for scrambled object condition: $t(29)=4.16$, $p<0.001$; Cohen's $d_z=0.48$; see Fig. 2D). Thus, verbal encoding strategies do not play a role in the meaningfulness advantage we find 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 vs. inverted objects

Thus far, we used scrambled objects as our control condition to closely match visual complexity and retain lower-level feature information. Scrambled objects have been shown to similarly activate early visual areas compared to intact objects (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., Yin, 1969; Rossion & Curran, 2010).

Methods

Participants. Forty-eight participants were recruited from the subject pool at the University of California San Diego. Data from the first 30 participants within the exclusion criteria as in Experiment 1 were analyzed. Data from two participants were excluded due to more than 10% of trials not meeting the response time exclusion criterion. Data from another 16 participants were excluded due to not meeting the overall d' criterion. The final sample of participants (N=30) was between 18-29 years of age. All data collection and analysis were identical to Experiment 1. All results were replicated using data from all participants above chance level performance (N=46; see Supplemental Material).

Stimuli & Procedure. All stimuli and procedures were identical to Exp. 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 degrees.

Data Analysis. Data analysis was identical to Experiment 1.

Results

We found that participants' color memory was significantly better in the upright object condition relative to the inverted object condition (mean d'=0.86 for upright-object condition and mean d'=0.57 for inverted object condition: $t(29)=7.68$, $p<0.001$; Cohen's $d_z=1.50$; see Fig. 3A). These results remained reliable when all participants with above-chance performance were included (N=46, see Supplemental Material).

Experiment 5: Non-object color probes at test

It is plausible that even though object identity was the same for the two probe stimuli during the 2-AFC (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 do the task. To further test whether memory for colors *per se* is improved, we changed the 2AFC to contain no identity information whatsoever and presented two colored circles instead.

Methods

Participants. Forty-two participants were recruited from the subject pool at the University of California San Diego. Data from five participants were excluded due to more than 10% of the trials not meeting the response time exclusion criterion. Data from seven participants were excluded due to not meeting the overall d' criterion. The final sample of participants (N=30) was between 18-34 years of age.

Stimuli & Procedure. All stimuli and procedures were identical to Exp. 2b (Simultaneous Presentation with Spatial Cues) with the following exception: The color options at 2AFC (target color and foil color) were presented as colored circles without the stimulus identity information.

Data Analysis. Data analysis was identical to Experiment 1.

Results

We replicated the real-world object feature memory benefit effect even when the 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 and mean d' = 1.26 for scrambled objects: $t(29)=2.08$, $p<0.05$; Cohen's $d_z=0.26$; see Fig. 3B). This effect is slightly smaller than in some of the previous experiments, which could be due to the spatial cue at retrieval (as in Exp. 2b), or the fact that the test requires colors to be “unbound” from their object identity, or both (For additional analysis including all participants above-chance level performance, see 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, we demonstrate that memory for simple features is enhanced when these 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 (Brady et al., 2016; Brady & Störmer, 2022; Asp et al., 2021). 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 differs 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 investigate 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 to non-words (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 (Schurgin et al. 2018; Bartsch & Shepherdson, 2022). 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, like 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 not only stored 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 (Wyble et al., 2016; Asp et al., 2021; Brady & Störmer, 2022), 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., Souza et al., 2016; Oberauer & Lin, 2017; Griffin & Nobre, 2003). 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 binding errors may be the main result when items become less distinct from each other (Emrich & Ferber, 2012; Oberauer & Lin, 2017). Are binding errors the main cause of the current results? If the foil color during a 2AFC happens to match one of the non-target items, a binding failure account predicts that participants should be more likely to false alarm in the unrecognizable relative to recognizable object condition. However, additional analyses on these potential swap-error trials revealed that this was not the case (see Supplemental Materials). Other work by Chen et al. (2021) has also shown that perceptual grouping of stimuli can improve working memory of their features. However, compared to the rather subtle effects of perceptual grouping or using multiple simple features, we find 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 (Exp. 2) and when identity information is removed entirely at retrieval (Exp. 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.

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Figure 1. **A)** Depiction of experimental procedures of Exp. 1. Each stimulus was presented for 300ms in the center of the screen with a 200ms inter-stimulus-interval. After a 1,000ms delay period, one of the stimuli reappeared in the center with two color options: One target color and one foil color (180 degrees away on the color wheel). Participants were instructed to choose the color that matches the color from their memory. In the real-world object condition all four stimuli were colored real-world objects while the unrecognizable object condition had four scrambled objects. **B)** Example stimuli. Top three images depict examples of colored real-world objects and bottom three images depict examples of corresponding scrambled objects in different colors. Scrambling was performed using diffeomorphic transformations as in Stojanoski & Cusack (2014). **C)** Results of Experiment 1: Sequential Presentation. Average d' values plotted separately for recognizable real-world objects (blue) and unrecognizable scrambled objects (red).

Figure 2. **A)** Depiction of experimental procedures of Exp. 2a/2b and Exp. 3. All four stimuli were shown simultaneously for 1,000ms, equally distributed around the central fixation cross. All other procedures were identical to Experiment 1. In Experiment 2b, the target item location placeholder was bolded during the response screen to indicate the location of the target item 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. Note that Experiments 2b and 3 are shown using a different scale on the y-axis due to overall higher performance than Experiment 2a.

Figure 3. **A)** Results of Experiment 4: Simultaneous Presentation with Upright vs. Upside Down Objects. **B)** Results of Experiment 5: Simultaneous Presentation with Color Probes and Spatial Cue.