Sequential encoding aids working memory for meaningful objects' identities but not for their colors

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Abstract

Previous studies have found that real-world objects' identities are better remembered than simple features like colored circles, and this effect is particularly pronounced when these stimuli are encoded one by one in a serial, item-based way. Recent work has also demonstrated that memory for simple features like color is improved if these colors are part of real-world objects, suggesting that meaningful objects can serve as a robust memory scaffold for their associated low-level features. However, it is unclear whether the improved color memory that arises from the colors appearing on real-world objects is affected by encoding format, in particular whether items are encoded sequentially or simultaneously. We test this using randomly colored silhouettes of recognizable vs. unrecognizable scrambled objects which offer a uniquely controlled set of stimuli to test color working memory of meaningful vs. non-meaningful objects. Participants were presented with four stimuli (silhouettes of objects or scrambled shapes) simultaneously or sequentially. After a short delay, they reported either which colors or which shapes they saw in a 2AFC task. We replicated previous findings that meaningful stimuli boost working memory performance for colors (Exp. 1). We found that when participants remembered the colors (Exp. 2) there was no difference in performance across the two encoding formats. However, when participants remembered the shapes and thus identity of the objects (Exp. 3), sequential presentation resulted in better performance than simultaneous presentation. Overall, these results show that different encoding formats can flexibly impact visual working memory depending on what the memory-relevant feature is.

Introduction

Visual working memory is a capacity-limited cognitive process that allows the active maintenance and manipulation of visual information. Because an individual's working memory capacity — how much information they can actively maintain at a time — relates to other important cognitive abilities such as fluid intelligence (e.g., Unworth et al., 2014; Fukuda et al., 2010), many researchers have put great effort into accurately assessing individuals' visual working memory capacity. In doing so, many studies have used abstract, simple stimuli, such as colored circles or oriented bars (e.g., Zhang & Luck, 2008; Luck & Vogel, 1997), which helps ensure that they are tapping specifically into visual working memory, and not visual long-term memory, a passive storage system that has essentially unlimited capacity (Brady et al., 2008). Using these simple stimuli, studies have found performance limits that are consistent with relatively 'fixed' capacity models, either in terms of how many items people can remember or how much resources are available to store that information (Awh et al., 2007; Bays et al., 2009). Specifically, seminal studies have suggested that people can remember a fixed number of objects regardless of what these objects are (Luck & Vogel, 1997; Awh et al., 2007), and others have demonstrated that when stimuli are visually very complex, for example 3D cubes or complex polygons, performance is decreased relative to simple single-feature objects, presumably because more resources are needed to hold these stimuli in mind (e.g., Alvarez & Cavanagh, 2004; Delvenne & Bruyer, 2004).

However, more recent studies have found that visual working memory capacity is greater for pictures of real-world objects (e.g., a chair, keys, a plant) that connect to prior knowledge, despite these stimuli being visually complex (e.g., Brady & Störmer, 2022; Brady et al., 2016; Torres et al., 2023; Curby et al., 2009; Jackson & Raymond, 2008; Ngiam et al., 2019). Based on these findings, it has been hypothesized that recognizable and meaningful stimuli can be stored in visual working memory not only with respect to their lower-level visual features, but also in terms of their semantic features (Brady et al., 2016; Asp et al., 2021), effectively increasing their representational dimensionality and thereby making them particularly robust to interference (Wyble et al., 2016; Brady et al., 2023). In line with this interpretation, and of particular interest to the present study, studies using recognizable and meaningful stimuli have consistently used relatively long encoding times (1s or more), reasoning that this longer encoding enables recognizing the objects and allowing for deeper semantic processing of the stimuli – a prerequisite for the meaningfulness benefit to arise (i.e., if you cannot recognize a stimulus as meaningful and connect it to prior knowledge, it may not be remembered better than a non-meaningful stimulus; Brady et al., 2016; Brady & Störmer, 2022).

Encoding format modulates memory performance

A recent study by Brady and Störmer (2022) tested the hypothesis that *how* stimuli are encoded into working memory critically modulates the real-world object benefit in visual working memory. In that study, participants encoded 6 stimuli either all presented simultaneously[1], as is often done in visual working memory studies, or sequentially (one by one), while matching the presentation time of each stimulus. Sequential presentation was thought to encourage participants to encode each object separately, one at a time, with focused, item-based attention, which would presumably increase the depth of processing for each of these stimuli; whereas simultaneous presentation of all 6 objects was thought to shift people toward processing all the items at once, leading to less individualized object processing and thus less deep processing of each individual stimulus. The results were consistent with this: Visual working memory performance was always increased for real-world objects relative to colored circles, but this benefit was more pronounced during sequential encoding than simultaneous encoding (Brady & Störmer, 2022). Interestingly, the opposite was true for colored circles: participants performed better in the color memory task when these were presented simultaneously, not sequentially, possibly because ensemble, chunking, and global feature-based attention processes that are engaged most during simultaneous presentations of many items can help support memory in the case where the location of many simple features must be remembered (Brady & Störmer, 2022; Chunharas & Brady, 2023). Overall, this work indicated that how items are encoded into memory plays a critical role in visual working memory tasks, modulating performance in important ways depending on stimulus type (see also Quirk et al., 2020; Li et al., 2020).

[1] In Brady & Störmer (2022), encoding time for simultaneous displays was always relatively long (1.2s). In regards to how varying encoding time can impact visual working memory, a previous study found that longer encoding time can selectively benefit real-world objects working memory (Brady & Störmer 2016), while there's more mixed evidence for simple features: some reports show no effects of encoding time (Vogel et al., 2006; Alvarez & Cavanagh, 2004; Bays & Husain, 2008; Luck & Vogel, 1997) but more recent reports show that encoding time also modulates working memory performance for simple features (Quirk et al., 2020; Li et al., 2020; Schurgin et al,. 2020).

Real-world objects support memory for associated low-level features

In the studies discussed thus far, visual working memory capacity was always compared for drastically different stimuli and features: Participants were asked to remember either sets of colored circles, or an array of real-world objects. These differ in a large number of ways, and these studies do not make clear which are critical.

One possibility is that the benefit participants have in representing real-world objects compared to simple features arises because recognizing a stimulus as meaningful allows participants to extract more relevant high-level visual and conceptually meaningful features. That is, recognizing the image of a car will allow an observer to store circular shapes as *wheels* or *headlights*, and not just as arbitrary geometric shapes, and recognizing a stimulus as a face allows observers to memorize visual features as meaningful units such as eye distance, hair, mouth, and nose etc., and not just shape and orientation blobs (Asp et al., 2021; for review, see Brady et al., 2023).

Do meaningful stimuli have an effect beyond extracting additional relevant and meaningful features? In a recent study, we investigated whether real-world objects can support memory for simple features that are not themselves meaningful, such as color. We asked participants to remember a set of colors that were either superimposed on intact real-world objects, and thus embedded in a conceptually meaningful context, or to remember the colors of scrambled versions of these objects that were not recognizable or meaningful. We found that performance on the color memory task was better for the colors that were superimposed on real-world objects (Chung et al., 2023a). This demonstrates that the effects of meaningfulness can go beyond extracting more relevant features: pre-existing conceptual knowledge can also serve as an effective scaffold to encode and maintain simple, non-meaningful features in working memory (see also Allen et al., 2021). Critically, in that study, colors were randomly paired with different color-neutral objects (e.g., a ball, a couch, a jacket, etc.), eliminating any effect of long-term memories for the specific color-object pairs. Thus, the colors needed to be linked to the real-world objects on each trial, and linking them to these objects seemed to provide a more effective means of maintaining them in working memory.

Following the task design of other research using real-world objects in working memory, this study also used relatively long encoding times (1 second for set size 4); however, it is unclear whether long encoding and deeper processing of the stimuli would modulate the color memory benefit for meaningful objects in this particular task. In particular, this design combines two tasks (color and real-world objects) that have previously been found to have opposite results: while memory for colored circles has been found to exhibit better performance when these colors were presented simultaneously relative to sequentially, memory for the identity of objects – a picture of a chair, an apple, or a cat, – was stronger when these items were presented sequentially (Brady & Störmer, 2022). Thus, it is not obvious how memory for colors that are presented as part of meaningful objects or as part of non-meaningful shapes would be modulated by encoding format. One possibility is that how participants encode the stimulus depends on what information participants are trying to remember, rather than the stimulus itself: maintaining object identities might rely more strongly on focused, item-based encoding to allow the extraction of additional visual features that are relevant to do the task (i.e., recognizing the tail of a dog will be useful if the task is about remembering the dog itself); memorizing color, however, regardless of whether these colors are presented as parts of meaningful objects or not, might not benefit from this item-based encoding as added time to extract additional features might not necessarily be useful here (i.e., recognizing the tail of a dog is not critical when just remembering its color). In this case, participants may be relying on similar strategies for both sequential and simultaneous presentations when doing a color working memory task (Zhao & Vogel, 2023). Thus, it is an open question whether and how encoding format influences color memory for meaningful vs non-meaningful objects, and how this might differ for memory for object identity.

The present study: The role of encoding format on color and object identity memory

In the present study we test whether the color-memory benefit for meaningful objects is modulated by encoding format, and compare this to a working memory task focused on object identity. Specifically, we varied whether participants encoded all stimuli at once (simultaneously) or whether they encoded them one-at-a-time (sequentially). Furthermore, instead of using colorful real-world objects as in our previous study (Chung et al., 2023a), we used silhouettes of objects (e.g., a shirt, a microscope) and scrambled versions of these silhouettes. These stimuli better control for variation in lighting and color values which are necessarily present in images of real-world objects, and thus provide a more controlled stimulus set (while removing some ecological validity). Using this stimulus set also allowed us to test whether recognizing a stimulus as a particular object alone is sufficient to support color memory. That is, is recognizing a relatively abstracted version of an object – the silhouette of a dog – sufficient to scaffold memory for its color? Or are the richer visual details of real object pictures required for this benefit to arise?

We first replicated our previous results of better color memory for meaningful stimuli relative to non-meaningful stimuli using these more abstract silhouettes (Exp. 1). Then, we examined how sequential or simultaneous presentations of memory items at encoding influenced performance when participants were asked to remember colors (Exp. 2) or object identities (Exp. 3) of these stimuli. We found an overall increase in memory performance for colors superimposed on meaningful relative to non-meaningful stimuli as well as better performance for meaningful object identities relative to non-meaningful objects, confirming previous studies that meaningfulness can increase memory strength. Interestingly, we found that sequential presentation benefits only emerged when observers were asked about object identities, but these effects disappeared when colors were the only memory-relevant visual feature. Overall our results suggest that encoding strategies can flexibly impact visual working memory performance depending on what features are to be remembered, even for identical stimuli.

Experiment 1: Working Memory for Color in Intact vs. Scrambled Silhouettes

Experiment 1 investigates whether color memory is improved for colors presented on silhouettes that are recognizable as meaningful objects, compared to colors presented on scrambled and unrecognizable shapes. Thus, this experiment tests whether identifying a shape as conceptually meaningful is sufficient to support memory for its arbitrarily associated color, thus examining how generalizable our previous results of increased color memory for real-world objects are (Chung et al., 2023a).

Methods

Participants

Seventy-two participants were recruited from the SONA participants pool at the University of California, San Diego. All participants gave informed consent prior to the experiment as approved by Internal Review Boards at the University of California, San Diego and Dartmouth College. Participants completed the experiment in a Web browser on their own devices. We requested that the experiment be completed in full-screen mode on a computer. The first 30 participants who did not meet our exclusion criteria were included in the final data analysis. Following our lab protocol and previous investigation (Chung et al., 2023a), data from participants were excluded if the 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 response time was shorter than 200 ms or longer than 5,000 ms. Based on the d' criterion, data from thirty-nine participants were excluded. Based on trial number criterion, data from an additional three participants were excluded. We chose thirty as the sample size following procedures from Chung et al. (2023a). The final sample (N = 30) was between 18-34 years of age.

While a large number of excluded participants is not uncommon in online data collection (e.g., Chung et al., 2023a; Addleman & Störmer, 2022), to ensure that the observed effects were not dependent on our exclusion criteria we replicated all analysis using a more lenient d' criterion (see Supplement). Results did not differ from the results reported in the main paper.

Stimuli

Stimuli were selected from 310 silhouette images of real-world objects (e.g., a t-shirt, a mask, a football, etc., see Fig. 1B) from Sutterer & Awh (2016) and randomly rotated in hue space using a CIE L*a*b color wheel that approximately matches that of previous work (Suchow et al., 2013; Schurgin et al., 2020; Chung et al., 2023a; Chung et al., 2023b). On each trial, stimuli were at least 30 degrees apart from each other on the color wheel. For the non-meaningful shape stimuli, these colored silhouette images were scrambled using the diffeomorphic transformation technique (Stojanoski & Cusack, 2014) to be less recognizable while preserving visual properties of the original shapes.

Procedure

On each trial, participants were simultaneously presented with an array of 4 stimuli for 1,000 ms, evenly distributed around the center of the screen. On half of the trials, participants were presented with 4 colored, intact silhouettes of objects, and on the remaining half of the trials participants were presented with 4 colored, scrambled shapes. These trials were randomly intermixed trial-by-trial. Each memory stimulus was 150 pixels width by 150 pixels height. After a 1,000 ms delay, participants were presented with a two-alternative-forced-choice (2-AFC) with two different colors, each presented on the exact same shape (e.g., a green and a pink microscope, see Fig. 1A); one color matched the encoded color (target) and the other one was maximally distinct, 180° away from the target color on the color wheel (foil). Participants were instructed to report which of the two colors they had previously seen by clicking on it with their mouse. Throughout the task, participants were only asked about the colors they saw, and never about the identity of the shapes. After each response participants received auditory feedback. Each participant completed 270 trials in total. Prior to the experiment, participants were given a 15-second example video of practice trials. The procedure of Experiment 1 is illustrated in Fig. 1A.

Data Analysis

To assess memory performance, d' values for a 2-AFC task were calculated separately for the 2 conditions for each participant (intact silhouettes vs. scrambled silhouettes) as a measure of working memory strength ($[zH - zFA]/\sqrt{2}$). These d' values were then analyzed using a within-subject paired t-test.

Results

We found that participants were significantly better at remembering colors when these colors were presented as part of intact silhouettes (d' = 0.82) compared to scrambled silhouettes (d' = 0.68; $t(29) = 2.45$, $p = 0.02$; Cohen's $d_z = 0.53$; see Fig. 1C). This replicates our previous work using a much more controlled stimulus set.

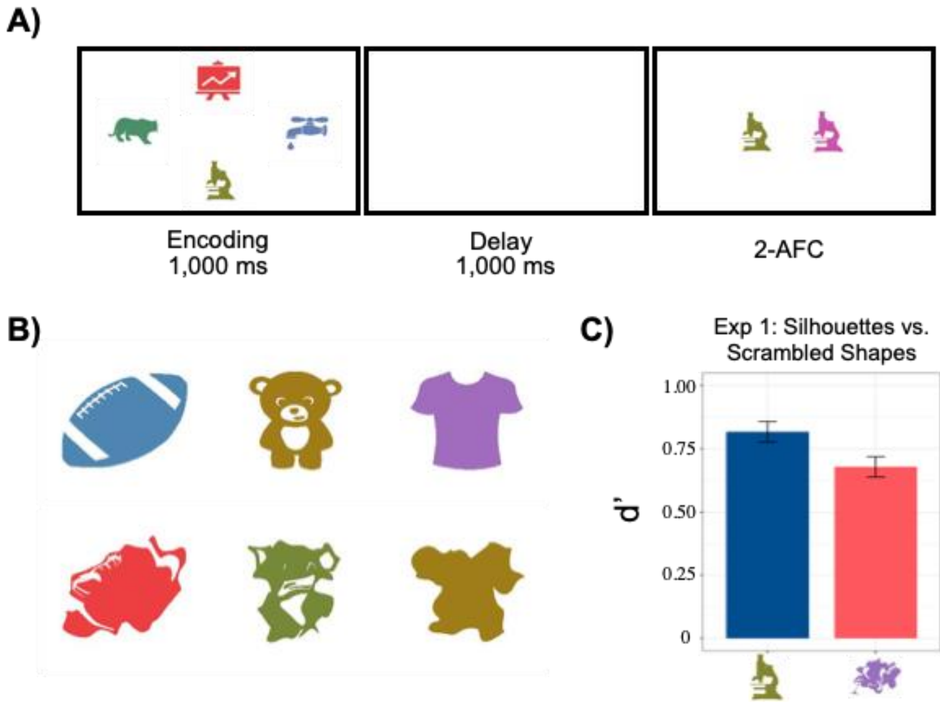

Figure 1. Procedure, stimuli, and results of Experiment 1. A) On each trial, four colored stimuli were presented for 1,000 ms. In the meaningful condition, these four colored stimuli were recognizable silhouettes, whereas these stimuli were scrambled and unrecognizable in the non-meaningful condition. After a 1,000-ms delay period, participants were given two color options: one that matched the previously seen color (target), and one that was maximally different from the target on the color wheel (foil). **B)** The stimuli were 310 silhouettes of objects sampled from Sutterer & Awh (2016), each colored randomly (top row). For the non-meaningful condition, they were scrambled using a diffeomorphic scrambling method (Stojanoski & Cusack, 2014) to render them unrecognizable (bottom row). **C)** Results from Experiment 1 (left/blue shows intact silhouettes, and right/red shows scrambled silhouettes) show that color working memory performance was improved for meaningful intact silhouettes compared to non-meaningful scrambled silhouettes, consistent with previous findings (Chung et al., 2023a).

Experiment 2: Working Memory for Color during Simultaneous vs. Sequential Presentation

Experiment 1 demonstrates that remembering a set of random colors results in better performance when these colors are superimposed on recognizable silhouettes relative to scrambled shapes. This provides strong support for our recent hypothesis that conceptually meaningful stimuli can serve as an effective scaffold to support the maintenance of simple visual features (Chung et al., 2023a; Allen et al., 2021). In Experiment 2, we asked whether this meaningfulness color benefit is modulated by encoding format. Specifically, Brady and Störmer (2022) showed that sequential encoding boosted the real-world object benefit in visual working memory, whereas simultaneous encoding benefitted color memory for simple colored circles.

This dissociation suggests that encoding format can have differential effects on working memory performance depending on exactly which stimuli are used and what features participants are asked to remember (e.g., real-world objects vs. colored circles). Here we aimed at honing in on the question of how encoding format would impact memory performance for colors vs. object identities by using the exact same stimulus set and only changing *what* participants were asked to remember: the object's color (Exp. 2) or the entire object (Exp. 3).

Methods

Participants

144 participants were recruited from the SONA participants pool at the University of California, San Diego. Data from 18 participants were excluded due to more than 10% of their trials being excluded. Data from an additional 66 participants were excluded due to their overall d' being lower than 0.5. The size of the final sample (N = 60) was determined based on the previous study that investigated an interaction between two different encoding formats and stimulus types (Brady & Störmer, 2022). The final sample of participants was between 18-34 years of age.

Given the high exclusion rate of participants, we replicated the same analysis and results using more lenient d' exclusion criteria (see Supplement).

Stimuli

Stimuli were identical to Experiment 1.

Procedure

Procedures were similar to Experiment 1 except for the following: Across experimental blocks, the encoding display was varied so that stimuli were either presented simultaneously at locations evenly distributed around the center of the screen for 1,200 ms (as in Exp. 1), or they were presented sequentially at the central location of the screen for 300 ms each followed by a 200 ms inter-stimulus-intervals. Encoding format (simultaneous vs. sequential) was blocked, but stimulus type (recognizable vs. unrecognizable) was varied randomly on a trial-by-trial basis, just like in Experiment 1. There were four blocks (2 simultaneous blocks and 2 sequential blocks) of 67 trials each, totaling 268 trials per participant. Starting block order was randomized for each participant with alternating block orders afterwards. All other procedures were identical to Experiment 1. Different encoding displays are illustrated in Fig. 2A.

Data Analysis

To assess memory performance, d' values were calculated as a measure of memory strength for each of the 4 conditions (sequential intact silhouettes, simultaneous intact silhouettes, sequential scrambled silhouettes, & simultaneous scrambled silhouettes). Memory strength across conditions was compared using a 2x2 repeated-measures ANOVA with stimulus type (intact vs. scrambled) and encoding display (simultaneous vs. sequential) as factors.

Results

A 2x2 repeated measure ANOVA yielded a significant main effect of stimulus type ($F(1, 59) = 42.26$, $p < 0.001$, $\eta_p^2 = 0.42$), but no significant effect of encoding format ($F(1, 59) = 0.04$, $p = 0.84$), and no interaction ($F(1, 59) = 0.30$, $p = 0.59$; Fig. 2B). These results indicate that the colors of intact, recognizable silhouettes were better remembered than colors of scrambled, unrecognizable shapes, regardless of encoding format.

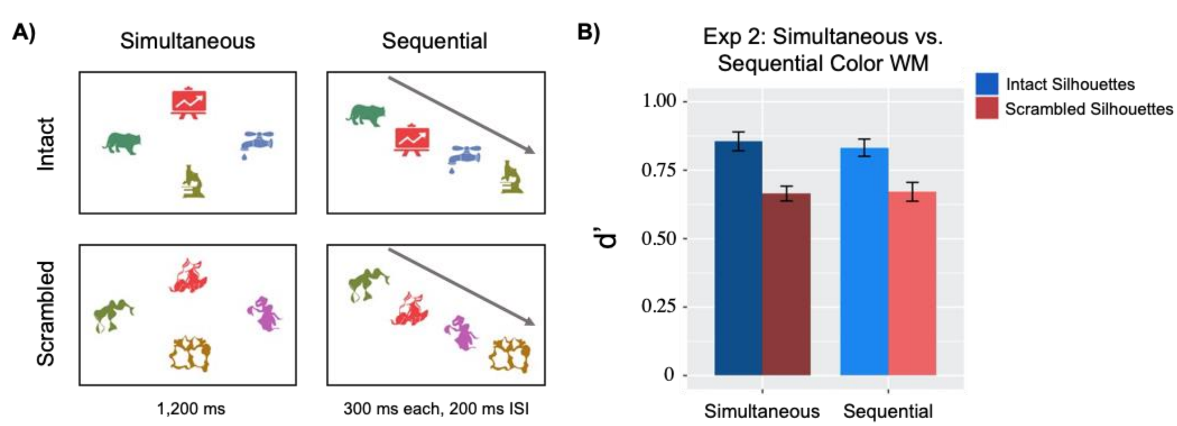

Figure 2. Encoding conditions and results of Experiment 2. A) Depending on the experimental block, stimuli were either presented simultaneously (left) or sequentially (right). Stimuli could either be intact or scrambled silhouettes. All other procedures were identical to Experiment 1. **B)** Results of Experiment 2 show that color working memory performance was improved for meaningful intact silhouettes compared to non-meaningful scrambled silhouettes (blue vs. red bars), consistent with Experiment 1. There was no significant difference in performance between the two encoding formats (left, darker colors: simultaneous; right, lighter colors: sequential).

Experiment 3: Working Memory for Object Identity during Simultaneous vs. Sequential Presentation

Experiment 2 replicated the pattern of Experiment 1, showing better color memory performance for meaningful relative to non-meaningful stimuli; however, we did not observe any effects of encoding format. Thus, where previous work showed a simultaneous benefit for colors alone and a sequential benefit for object identity (Brady & Störmer, 2022), the combination of the two showed no difference in either direction. It seems conceivable that item-based encoding (here promoted by sequential presentation at encoding) does not benefit memory for surface-level features, such as an object's color. Another possibility is that other differences between the studies and tasks, such as the stimuli used, variation in set size (4 vs. 6), or other small differences between tasks, could explain the differential effects. To directly test this, in Exp. 3, we used the exact same stimuli and set-up as in Exp. 2, but asked participants to remember the identities of the objects, not their colors, and examined whether encoding format would modulate the meaningful object benefit here.

Methods

Participants

Sixty-nine participants were recruited from the SONA participants pool at the University of California, San Diego. Data from 5 participants were excluded due to more than 10% of their trials being excluded. Data from an additional 4 participants were excluded due to their overall d' being lower than 0.5. The final sample (N = 60) was between 18-23 years of age.

Stimuli

Stimuli were identical to Experiment 1 except all stimuli were grayscale to ensure that participants would not use colors to do the identity memory task.

Procedure

Procedures were similar to Experiment 2 except for the following: at the 2-AFC test participants were given two shape choices (the target shape and a foil shape) and asked to choose the target *shape*, thus making this an identity working memory task. Following the previous findings of Brady & Störmer (2020), we chose the foil shapes to be maximally different from the target for both conditions, determined by features extracted from convolutional neural networks (see Supplement: Stimulus Validation). There were 50 trials per each of 4 blocks, totaling 200 trials per participant. There were fewer trials in Experiment 3 than Experiment 2 due to the foil objects being excluded from being memory stimuli. Procedure of Experiment 3 is illustrated in Fig. 3A.

Data Analysis

Data analysis was identical to Experiment 2.

Results

Participants had higher memory performance for intact meaningful silhouettes relative to scrambled shapes; they also showed an increase in performance when items were presented sequentially relative to simultaneously at encoding. These observations were statistically confirmed with a 2x2 repeated-measures ANOVA, which yielded a significant main effect of stimulus type ($F(1, 59) = 423.09$, $p < 0.001$, $\eta_p^2 = 0.88$), a significant main effect of encoding display ($F(1, 59) = 62.97$, $p < 0.001$, $\eta_p^2 = 0.52$), and no significant interaction between the two factors ($F(1, 59) = 1.71$, $p = 0.20$; Fig. 3B). Thus, asking about identity rather than color did lead to a sequential encoding benefit, and did so for both intact and scrambled silhouettes.

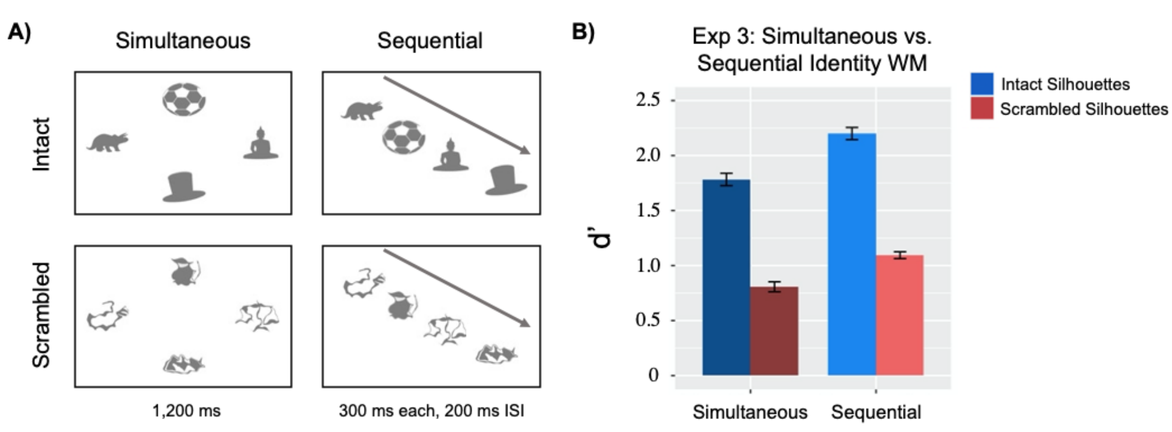

Figure 3. Stimulus displays and results of Experiment 3. A) Stimuli were greyscale, and could be presented simultaneously or sequentially at encoding. During the 2AFC test, two different objects were presented, and participants were asked to choose the object they remember. All other procedures were identical to Experiment 2. **B)**

Results showed that performance was higher for meaningful intact silhouettes compared to non-meaningful scrambled silhouettes (blue vs. red bars). At the same time, sequential presentation (left, lighter colors) also resulted in overall better performance than simultaneous presentation (right, darker colors). No reliable interaction was observed.

General Discussion

Visual working memory capacity for simple features can be increased if these features are encoded and maintained as part of real-world objects (Chung et al., 2023a). Here, we demonstrate that this meaningfulness advantage in color memory extends to silhouettes of objects, indicating that a relatively abstracted version of an object (a shape outline) is sufficient to drive these effects. Thus, our previous results generalize to other kinds of stimuli that can be considered 'meaningful' in a relatively broad sense – namely, it appears sufficient that the to-be-remembered colors appear on recognizable shapes that connect to prior conceptual knowledge. Furthermore, the stimulus set used in the current study, while losing some ecological validity, controls much better for color and lighting variations compared to the real-world objects used in the previous set of experiments (Chung et al., 2023a). This indicates that our previous results are robust and generalize across stimulus sets.

The way this advantage in memory for colors on real objects interacts with known encoding differences between real-world objects and colors (Brady & Störmer, 2022) was also unclear, with the color vs. real-world object aspects of the task appearing to suggest opposite possibilities. To address this, in Experiment 2, we found that when colors were the only task-relevant feature, there was solely an effect of meaningfulness but no difference in performance between simultaneous and sequential encoding formats. However, when shapes and thus the identities of objects were task-relevant (Exp. 3), sequential presentation resulted in better memory performance compared to simultaneous presentation for both meaningful and non-meaningful object shapes, with overall better memory for meaningful silhouettes. Thus, encoding format had differential effects depending on what participants were instructed to remember – suggesting that encoding strategies can impact memory performance fluidly depending on task relevance and task demands.

Semantic meaning can benefit color working memory

The current study adds to increasing evidence suggesting that visual working memory capacity is not 'fixed', but flexibly varies depending on what information is being maintained actively in mind. Our results show that even working memory for simple, low-level features such as the color of items is affected by prior knowledge stored in people's minds. Critically, this prior knowledge does not refer to item-specific knowledge, such as long-term associations between a particular color and an object (e.g., a yellow banana). Instead, it is about the fact that the conceptual knowledge that gets activated by seeing a recognizable, meaningful object can structure working memory representations 'on the fly', by quickly building and maintaining new associations with a low-level feature, such as color. The present findings replicate our previous study (Chung et al., 2023a) using a simpler and more controlled stimulus set. While the object images used in our previous work (Chung et al., 2023a; adapted from Brady et al., 2013) are ecologically more valid as they are images of real-world objects, they are also particularly visually complex, introducing a lot of variances in lighting and thus color values across the objects (different shades result in non-uniform color distributions such that one object may have different shades of blue, for example). This could have potentially introduced additional variance in the surface-level features, especially for the non-meaningful stimuli (scrambled or upside-down objects), as lighting cues could not be used by the visual system to discount shades and thus color variation in these cases (Chung et al., 2023a). In the current study we avoid these issues by using silhouettes of objects (from Sutterer & Awh, 2016) that allow for one uniform color to be used in each stimulus, distributed equally across the whole shape with no variation in lighting. Given that we found the same meaningfulness benefit using these silhouettes, we conclude that variations of color across the real-world object images (and their scrambled counterparts) in the previous study do not explain differences in performance. Instead, how meaningful an object is to an observer aids color working memory. The silhouettes used in the present study also offer a window into understanding what kind of "meaningfulness" is critical - or sufficient - in driving memory benefits for color. Specifically, the silhouettes are relatively simplified and abstracted versions of objects we encounter in the real world, removing a lot of the perceptual complexities and idiosyncratic features found in natural images, while still retaining their conceptual meaning through their global shapes. Thus, the present results demonstrate that recognizing what an object is – regardless of whether it is an image of a real-world object or just the abstracted shape of it in the form of a silhouette – is sufficient in scaffolding memory for its color.

Sequential presentation at encoding benefits complex shape working memory

Across Experiments 2 and 3, we found that sequential presentation selectively boosted working memory performance when remembering shape identities, but not when remembering their colors, even though both experiments used identical stimulus sets. One explanation for the benefit of sequential presentation for the objects is that serial processing can promote the extraction of additional features for complex stimuli that can be particularly useful in the object identity working memory task. A previous investigation by Brady and Störmer (2022) found that the sequential presentation resulted in better memory performance for real-world objects. These results were interpreted such that sequential presentation at encoding reinforces participants to focus on each item at once, encouraging deeper processing of each individualized object and its detailed features. This type of focused object-based processing would help especially when the goal of the task is to discriminate the target object in the subsequent 2AFC task. By contrast, the simultaneous (but still long) presentation of all stimuli at once could lead to a mixture of object-based and also global, parallel processing of the display, which may be less advantageous when remembering object identities. Thus, serial processing may allow for more features to be extracted, whether they are high-level visual and semantically meaningful features (i.e., recognizing a cat's ears) or lower-level complex but semantically non-meaningful shape features (i.e., specific contours of a scrambled shape), improving the observers' ability to remember and distinguish the stimulus identities at test. These additional features that can be best encoded during sequential presentation, however, may not be as useful when observers are only asked to remember and report a simple surface feature – such as the colors of the stimuli.

Interestingly, we found that sequential presentation improved working memory performance not only for meaningful stimuli but also for non-meaningful scrambled shapes, diverging in some ways from Brady and Störmer (2022) that reported no sequential encoding benefit for fully scrambled real-world objects, though they did find a sequential benefit for lightly scrambled real-world objects. There are two possible explanations for this. First, unlike Brady and Störmer (2022) who used real-world objects and scrambled objects that retained surface-level features such as their colors, we here used stimuli that were all grayscale in the object-identity task (Exp. 3), which prevented observers from utilizing colors to perform the task, especially when the stimuli were unrecognizable and thus harder to remember. Instead, in Experiment 3, participants had to rely on remembering the complex shape information to perform the object identity task. Thus, the sequential presentation that allows for extraction of additional complex features could have been especially helpful in our design for both conditions, and removing colors may have especially reduced potential benefits of simultaneous encoding. This would open up the possibility that the sequential presentation benefit may not be selective to meaningful stimuli per se, but could exist for any working memory task where task-relevant features are complex and can benefit from deeper perceptual or conceptual processing at encoding. Some features, such as color and other surface-level features that can be extracted quickly and in parallel, on the other hand, might not (always) benefit from the sequential encoding. A second possibility is that the scrambled silhouettes may not be as meaningless as the scrambled real-world object images used in the previous study. It's possible that in our task observers inferred some meaning from the scrambled silhouette shapes, maybe especially when processed serially. This is consistent with Experiment 3 of Brady and Störmer (2022), which found sequential presentation benefits for lightly scrambled real-world objects were similar to those for intact objects, suggesting that participants possibly recognized some of the scrambled objects, or parts of them, or at least thought to have recognized them (even if they were incorrect). Together, this pattern of data suggests that sequential presentation benefits may appear in a graded form, scaling with how meaningful the stimuli can be interpreted by the observer.

No sequential presentation benefit in color working memory

We observed that the two encoding formats did not differentially affect working memory performance when participants were asked only about the color of the stimuli (Exp. 2). Yet, we found a clear and reliable effect of meaningfulness such that intact silhouettes enhanced color memory relative to the scrambled silhouettes. This result is consistent with our previous study that used real-world objects, in which we found a benefit for color memory both when objects were presented sequentially (Exp. 1) and simultaneously (Exp. 2a; Chung et al., 2023a). However, this previous study lacked a systematic within-subject comparison between the two encoding formats, making it difficult to interpret how the two encoding formats may impact memory performance.

Why does sequential encoding not help color memory, even when color memory itself is supported by recognizing a stimulus as meaningful? There could be several reasons for this. First, as mentioned above, the additional features that can be extracted more easily in the sequential presentation may not be useful in the color working memory task. That is, recognizing the general shape and its associated color – both things that can presumably be done easily enough in the long simultaneous presentation condition (at least for set size 4 and the silhouettes used here) – is sufficient to perform the subsequent color 2AFC task. Knowing additional detailed features of the objects is – at least in our version of the task where the shapes are always relatively distinct from one another – not particularly useful or necessary for the color memory test. Furthermore, processing colors one-by-one in a focused item-based way is not necessarily useful for color memory more generally. In fact, previous work suggests the opposite, namely that the simultaneous presentation of colored circles can facilitate the use of ensemble information and global feature-based attention processes, thereby improving color working memory performance (Brady & Störmer, 2022; Chunharas & Brady, 2023). Thus, it could also be the case that simultaneous presentation of the stimuli in our task enhanced color memory due to global feature-based processes, while at the same time sequential encoding supported memory due to more focused encoding of each individual item and thus stronger memory hooks to the shapes – which ultimately led to equivalent performance across the two encoding conditions.

One notable additional difference between the two encoding formats is that stimuli were presented at distinct spatial locations for the simultaneous presentation whereas they were all presented at the center for the sequential presentation. As spatial information is known to play a privileged role in indexing visual working memory contents and binding visual features (Chen & Wyble, 2015a; Chen & Wyble 2015b; Tam & Wyble, 2022; Chung et al., 2023b; Schneegans & Bays, 2019; Mandler et al., 1977; Schulman, 1973), the usage of spatial information could have been especially helpful when observers were asked to remember simple features, even though they were never provided with explicit spatial cues at retrieval. However, to what extent spatial information would play a role in the current design is unclear as our previous study showed robust meaningfulness benefits in color working memory even when clear spatial cues were given (Chung et al., 2023a; Exp. 2b & 5). Additionally, Brady and Störmer (2022) used sequential presentations both where stimuli were presented centrally but also where they were presented at different locations and found no significant differences in the pattern of data in these two situations. Thus, it is unlikely that the difference in spatial location information alone can explain the present results.

Meaningfulness benefit in visual working memory

Across all experiments, we replicate the meaningfulness benefit for both color and identity working memory tasks across both sequential and simultaneous presentations. This demonstrates that the role of meaningfulness in visual working memory is pervasive and robust across different stimulus sets and encoding formats. Importantly, our results are consistent with the idea that when items are presented sequentially at encoding, more features can be extracted from complex stimuli, and this can be beneficial for an object identity working memory task, but perhaps not for a color working memory task. This may suggest that how much semantic and conceptual information can improve color working memory is limited compared to how useful this is when remembering object identity. This is also supported by the overall performance difference between the meaningful and non-meaningful conditions, which is much more nuanced in the color working memory task ($\eta_p^2 = 0.42$) compared to the identity working memory task ($\eta_p^2 = 0.88$).

The effect of meaningfulness in visual working memory also aligns with other recent research showing that meaningful object shapes are more likely to be represented incidentally in working memory relative to non-meaningful shapes, even if they are not task-relevant (Chung et al., 2023b; Sasin et al., 2023). However, exactly how these meaningful features, and at what level of detail or abstraction, are represented in working memory, is still unknown. It seems likely that this is strongly task-dependent, though there might be a “default” state that could be uncovered using these incidental memory tasks. Some initial data suggests that real-world objects are incidentally represented at the level of exemplars: For instance, Sasin et al. (2023) showed that incidental memory of meaningful objects was sensitive to exemplars (i.e., people knew which cookie they saw); however, information of the object states seemed lost (i.e., a cookie that has a bite on it vs. not). Similarly, Brady et al. (2016) showed a benefit for real-world objects in an explicit working memory task both when the task required an across-category discrimination (e.g., a shoe vs an apple), but also when the memory test required to discriminate between exemplars (i.e., object with detail, a mug from a different mug). Future studies could further address this question by systematically varying the levels of semantic distinctiveness in the stimulus set and mapping the impact on visual working memory performance for different task-relevant features. For instance, to what extent distinct objects from the same category (i.e., four different cars) relative to objects from different categories (as in the present study) affect color working memory, and how the effect size compares to identity working memory, is of future examination.

Conclusion

In conclusion, we found that sequential presentation at encoding selectively boosted working memory for complex shape identities, but there was no performance difference between sequential and simultaneous presentations when colors were the task-relevant feature, despite using the same exact stimulus set. We replicated the memory advantage for meaningful stimuli both when participants were asked about the object identity but also when asked just about their color. Our results demonstrate that encoding format can play an important role in driving working memory performance, and critically, that different encoding formats have different consequences depending on what the task goals are for the participant: remembering simple surface features like color vs. remembering object identities. Moving forward, it is thus important to consider how participants are using different encoding strategies, or control for them when comparing memory performance across different tasks.

Open Practices Statement

All data reported in the paper are publicly available here: https://osf.io/juvks/
The hypotheses, methods, analysis plans, and data exclusion criteria of Experiment 3 were pre-registered (https://aspredicted.org/7mh2w.pdf).

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Supplementary Materials

Re-analyses of data using a less strict performance exclusion criteria

Following the previous work (Chung et al., 2023a), we excluded all participants' data with overall d' < 0.5 from the main analysis. This led to a large number of exclusions in Experiment 1 and Experiment 2. To ensure that the observed effects are not simply due to our specific performance exclusion criterion, we replicated the analyses of Experiments 1 and 2 including all data from participants with an overall d' above-chance.

Experiment 1 Analysis and Results:

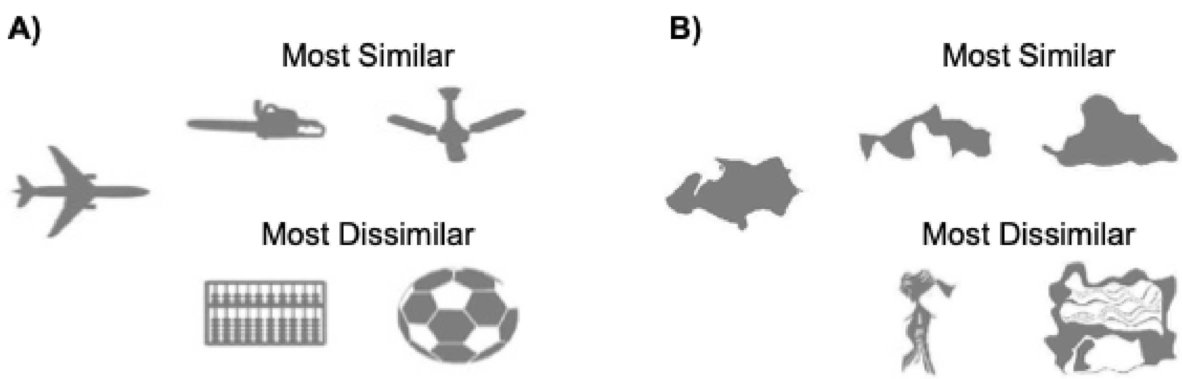
Data from two participants were excluded due to their overall d' being lower than 0. Additional data from three participants were excluded due to more than 10% of the trials meeting the response time exclusion criteria. Using the remaining 67 participants' data, we replicated the main effect of higher memory performance for the meaningful intact silhouette condition (d' = 0.56) relative to non-meaningful scrambled silhouette condition (d' = 0.48) (t(66) = 2.60, p = 0.01, Cohen's d_z = 0.27).

Experiment 2 Analysis and Results:

Data from two participants were excluded due to their overall d' being lower than 0. Additional data from 18 participants were excluded due to more than 10% of the trials meeting the response time exclusion criteria. Using the remaining 124 participants' data, we reran the same analysis as Experiment 2. Replicating the findings, a 2x2 repeated measure ANOVA yielded a significant main effect of stimulus type (F(1, 123) = 42.25, p < 0.001, η_p^2 = 0.26), but no significant main effect of encoding display (F(1, 123) = 0.02, p = 0.88) and no significant interaction (F(1, 123) = 0.84, p = 0.36).

Stimulus Validation for Experiment 3

A previous report by Brady & Störmer (2020) demonstrated that comparing memory performance across different stimulus types requires the 2AFC task to have maximally dissimilar foils in order to ensure that differences in performance do not simply arise from varying levels of difficulty in perceptual comparisons between the items during test. Following the same logic, we picked the foil objects for the 2AFC in Experiment 3 to be maximally different from the target object for both intact silhouettes and scrambled silhouettes. To do so, we evaluated the silhouette stimulus set using deep convolutional neural networks as used in Brady & Störmer (2020): the VGG16 convolutional neural network architecture pretrained on ImageNet (Simonyan & Zisserman, 2015). This allowed us to extract features of each image from the set of 310 silhouettes and the set of 310 scrambled shapes from the final max pooling layer. We then calculated the Euclidean distance between each pair of images, quantifying the similarities among all stimuli (see Supp Fig. 1). On each trial, the foil during the 2AFC test was chosen to be the most dissimilar object from the target object for each stimulus set.



Supplementary Figure 1. **A)** An example of a silhouette stimulus (the airplane, left) and the two most similar objects and two most dissimilar objects in the stimulus set determined by CNN. **B)** The same comparisons made for an example scrambled shape. The most dissimilar object from the target object was used as a foil during the 2AFC task in Experiment 3.