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Grouping by semantic and color similarity in visual working memory:

An attentional mechanism, not compression mechanism

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Abstract

Few studies have examined whether semantic relatedness between objects can influence object grouping, thereby optimizing the efficiency of visual working memory (WM). Moreover, these studies have largely used real-world greyscale objects. Here, we sought to determine whether and how sharing object semantics and colors would benefit WM. Participants viewed six to-be-remembered objects, arranged as one semantically-related and/or perceptually-similar object pair plus four singletons, or as six singletons. Perceptually-similar pairs shared color, while semantically-related pairs included co-occurring objects. Our series of three experiments mainly showed redundancy advantages, with memory of related objects improved over that of singletons. This advantage was present for similarly colored objects in all experiments, and under conditions that allowed deeper information processing by facilitating access to knowledge (longer encoding or retention times), extended to semantically related objects. None of the experiments showed any redundancy-boost on overall WM performance, with memory for scenes comprising a related pair not differing from that for scenes comprising only singletons. The experiments also showed no capacity spillover for singletons in the presence of pairs. Overall, the results support the existence of an attentional encoding bias and rule out the compression hypothesis to explain the benefits of grouping by semantic and color similarity.

Keywords: Visual working memory, Perceptual grouping, Semantic relatedness, Attention, Real-world objects.

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In contrast to long-term memory, only a fraction of the massive visual input that humans face is retained in visual short-term memory (Baddeley, 2012; Cowan, 2001). Stimulus regularities can however be exploited for more efficient memory representations and thus greater capacity (Brady & Tenenbaum, 2013; Lin & Luck, 2009). It is also known that the capacity of visual short-term memory is greater for familiar or semantically meaningful objects than for abstract ones (e.g., Asp et al., 2021; Brady et al., 2016; Brady & Störmer, 2022; Conci et al., 2021; Reder et al., 2016; Sahar et al., 2020; Simmering et al., 2015; Xie & Zhang, 2017). While this ability to use semantic meaning to boost memory performance does not seem very surprising, it remains to be explained how meaning can overcome the limits of short-term capacity. In fact, a general improvement in recognition accuracy (i.e., a boost) can come from several sources. The nature of working memory (WM) capacity limits has catalyzed a strong debate as to whether capacity is constrained by a fixed number of discrete representations (e.g., Awh et al., 2007; Luck & Vogel, 1997) or by a fixed amount of divisible resources that can be allocated flexibly across stimuli (e.g., Bays et al., 2009). The exact mechanisms for why information load can be reduced for certain stimuli are still unknown, such as with real-world objects. One issue with this unknown is that over decades, most studies have focused on basic single-feature objects such as colored squares to estimate capacity, with the consequence that little is known about WM capacity for real-world objects.

But what is the exact WM bonus of the effect of real-world objects? Semantic knowledge of real-world objects is a critical factor boosting visual WM capacity (e.g., Asp et al., 2021; Starr et al., 2020). Consistent semantic relations among objects have been found to boost visual WM (e.g., a candle near a match versus near a hammer) (Kaiser et al., 2015; Liu et al., 2022; O'Donnell et al., 2018). Displaying objects belonging to a semantic category (e.g., clothing) has also been found to enhance visual WM capacity (Hu & Jacobs, 2021), but other work has not shown such capacity benefits (Quinlan & Cohen, 2016). Due to these conflicting results, the semantic-relatedness boost remains a contentious issue. On the other hand, the effects of perceptual grouping by similarity have been well established in the literature by a plethora of strong evidence confirming that single-feature objects that share a color can boost visual WM (e.g., Gao et al., 2011; Lin & Luck, 2009; Meyerhoff et al., 2021; Morey et al., 2015; Peterson et al., 2015; Peterson & Berryhill, 2013; Prieto et al., 2022; Quinlan & Cohen, 2012; Ramzaoui & Mathy, 2021; Shen et al., 2013). Results from a meta-analysis also showed that similarity-based grouping produces the strongest beneficial effects on visual WM compared to other perceptual grouping methods such as connectedness and closure, and that color produces a better grouping effect than features such as shape (Li et al., 2018).

The WM boost through perceptual grouping by color has been explained by two main competing mechanisms. Compelling evidence suggests that perceptual grouping serves the organization of visual information, by allowing related items to be integrated into a single representation (Gao et al., 2011; Peterson et al., 2015; Shen et al., 2013). This can be a form of memory compression, which consists of optimally recoding information in a compact way (Brady et al., 2009; Corbett, 2017; Nassar et al., 2018; Ngiam et al., 2019; Zhang & Luck, 2011). More importantly, the compression process increases storage space by freeing up resources that can be allocated to other items such as singletons in the display (Brady et al., 2009; Kowialiewski et al., 2022; Ngiam et al., 2019; Norris & Kalm, 2021; Ramzaoui & Mathy, 2021). Indeed, compression implies that the presence of related items allows the representation of the entire display to be encoded more efficiently, without any effect on the attentional resources allocated to each item (Corbett, 2017; Nassar et al., 2018). It is important to note that compression is by no means limited to materials for which there is perceptual similarity. In the verbal domain, it has been shown that semantic triplets (e.g., leaf-tree-branch) improve recall performance for unrelated items compared to a condition comprising only semantically unrelated items (e.g., wall-sky-dog) (Kowialiewski et al., 2021, 2022). If information of semantic regularities can be compressed, leading to the release of WM resources, this should also benefit singletons in the visual domain. Semantics can therefore be used to compress information.

In contrast to the compression hypothesis described above, other evidence suggests that the beneficial effect of perceptual grouping by color on visual WM arises from an encoding bias in favor of related items. Although information compression and encoding bias predict that displays containing related items will be easier to remember than those that do not, it is still possible to distinguish between these two hypotheses. Contrary to the compression hypothesis, encoding bias results from an attentional capture mechanism (Treisman, 1982; Vecera, 1994; Vecera & Farah, 1994) that lead to better recall of related items (Li et al., 2018; Peterson et al., 2015; Prieto et al., 2022). This redundancy advantage may result in no increase in singleton performance, or even, under certain conditions, a decrease in singleton performance (Prieto et al., 2022). Perceptual grouping by color similarity can therefore also serve the organization of information by biasing attentional allocation so that related items consume the main resources, leaving fewer resources available to store singletons. In the context of real-world objects, to our knowledge no prior visual WM study has explored whether semantically-related objects can be selectively encoded due to attentional capture. This gap in the literature deserves to be addressed, as real-world objects are rich in both perceptual and semantic information. As semantic information is well known to guide our attention in realistic scenes (for review see Wegner-Clemens et al., 2024), semantic similarity between objects could therefore attract attention and be prioritized in the same way as colors in WM tasks.

With regard to the semantic-relatedness boost in visual WM, although previous studies have shown this boost by comparing memory performance for pairs of semantically related objects in displays with that for singleton objects presented in other displays, this procedure cannot be used to test the theoretical hypothesis of compression, nor that of attentional encoding bias. To tackle the question of whether information compression could offer a general account of both semantic-sharing bonus and color-sharing bonus in visual WM, we tested whether the semantic-relatedness boost can be detected for both semantically related objects and singleton objects within visual displays. This memory benefit for encoding singletons due to the compressibility of the material has not been studied for real-world objects. Given that semantic regularities can be considered as redundant information learned across lifetime experience, semantics may allow information to be compressed the same way as colors do.

The present study

In this study, we sought to determine whether and how color and semantic sharing bonuses exist between real-world objects in visual WM, by testing two theoretical accounts, namely the attentional account (i.e., encoding bias) and the compression account described above. Although previous studies have provided important insights so far, the use of semantic similarity as a grouping process distinct from perceptual similarity between real-world objects may provide only a limited perspective on the capacity of visual WM in more realistic situations. In the real world, several grouping cues may indeed coexist. Possibly, perceptual grouping based on color and semantic similarity may jointly influence visual WM capacity for real-world objects. However, we remained exploratory, aiming to investigate whether the simultaneous application of these two grouping methods has an additive effect. A meta-analysis (Li, 2018) suggests that the combination of two grouping methods does not lead to an additive boost in visual WM, this on the basis of studies using simple feature stimuli combining proximity and similarity or connectedness and similarity methods. Thus, we considered this previous result insufficient to be sure we would observe an additive effect in our study.

Here, the perceptual similarity between objects was manipulated in terms of color (perceptually similar vs. perceptually dissimilar). The semantic relatedness between objects was manipulated in terms of co-occurrence in the real environment between objects (semantically related vs. semantically unrelated). Participants viewed scenes consisting of six to-be-remembered objects arranged into either one pair of semantically-related and/or perceptually-similar objects and four singleton (unrelated) objects, or six singletons in the baseline condition. Participants' memory was then probed for the scene objects using a central single probe. The probe tested either a singleton object, or an object from a related pair.

We tested three hypotheses. First, we expected that overall memory for scenes including a pair of perceptually and/or semantically related objects would be enhanced relative to scenes in the baseline condition comprising only singletons *(Hypothesis 1 of redundancy boost)*. This **redundancy-boost** could be expected by both the attentional account and the compression account. Indeed, the overall boost on WM performance may be due to the fact that the pairs are enhanced (attentional account) or that each stimulus is enhanced (compression account).

There are conditions under which the two theoretical accounts make different predictions. If the predicted redundancy-boost is confirmed and explained by the fact that pairs are encoded by compression, the advantage of related objects should spill over to singletons. Singleton memory should thus be improved in the conditions with a pair of related objects compared with the baseline condition *(Hypothesis 2 of spillover)*. If this **spill-over hypothesis** is confirmed, it will provide strong evidence that participants form compressed representations of related objects, as the concept of compression implies that the formation of compressed information frees up capacity that can be used to store more objects. Furthermore, if the related objects are better recalled than the singletons in the scene, this will suggest that related objects are selectively encoded due to an attentional capture at the expense of singletons *(Hypothesis 3 of redundancy advantage)*. The confirmation of this **redundancy-advantage hypothesis** will support the attentional account.

Experiment 1

Method

Participants

Fifty-seven volunteers participated in the study, in exchange for 10,00 € or course credits depending on the recruitment site. The study was conducted in person. Thirty participants were psychology students from Université Côte d'Azur (France), and the others were psychology students from Université Paris Cité (France). Two participants' data were excluded from all analyses: one due to a software malfunction, the other one due to an accuracy below 50%. A priori power analysis was conducted using G*Power version 3.1 (Faul et al., 2007) to determine the minimum sample size required to test the study hypotheses. The analysis indicated that the sample size required to achieve 95% power to detect a small-medium effect of $f = .20$, at a significance criterion of alpha = .05, were N = 55 for a one-way repeated measures ANOVA with a 4-level within-subject factor, and N = 43 for a two-way repeated measures ANOVA with 3-level by 2-level within-subject factors (see Results for the ANOVA structure). The recommended sample size of N = 55 was used. The final sample consisted of 55 participants (42 females, 13 males), aged between 18 and 38 years old ($M = 23.65$, $SD = 4.72$). None reported a history of psychological and/or neurological conditions, or color vision problems. All reported normal or corrected-to-normal visual acuity and were naive regarding the purpose of the experiment. This study was performed in line with the principles of the Declaration of Helsinki. All participants gave their informed written consent prior to starting the experiment. The experiment was approved by the ethic committee of CERNI Université Côte d'Azur: Avis-2018-3.

Materials

The experiment was coded using PsychoPy 2021.2.3 (Peirce, 2007). It was conducted on a Dell PC running Windows 10. The stimuli were presented on a 22-inch LCD screen. The stimuli were modified and created using GIMP 2.10 software, an image manipulation program (Free Software Foundation, Boston, MA). Visual objects were taken from Google Images, Hemara Photos-Objects database and public databases (Brady et al., 2008; Konkle et al., 2010).

Objects have been selected to be highly discriminable, whether manufactured or natural. Animals, faces and objects bearing inscriptions were not selected as stimuli.

The experimental stimuli consisted of 80 visual scenes containing colored real-world objects on a white background (RGB: 255, 255, 255). For the practice phase, two additional scenes were created. Each scene contained six to-be-remembered objects arranged in a circle at fixed locations (see Figure 1). The objects were placed at 5.5° eccentricity from the center of the screen. Each object occupied on average 0.46% of the scene area (SD = 0.12%; range = 0.21%–0.89%)[1]. An experimental scene consisted of objects arranged into one semantically-related and/or perceptually-similar pair of objects and 4 singleton (unrelated) objects. In the baseline condition, the scene was comprised of singleton objects, i.e. objects that are not typically semantically co-occurring and do not share their main color. In the experimental scenes, the perceptual similarity was manipulated in terms of color (perceptually similar *vs*. perceptually dissimilar). Object pairs were considered to be of similar color on the basis of the Delta E colour difference (ΔE for the perceptually similar pairs condition: $M = 8.14$, $SD = 7.08$, *range*: 0.23-23.88; ΔE for the semantically and perceptually similar pairs condition: $M = 8.99$, $SD = 6.75$, *range*: 0.85-19.23). ΔE is a standard calculation related to human visual assessment of the differences between two colors (based on L*a*b coordinates) that was introduced by the International Commission on Illumination (CIE). We used the CIE 2000 formula (Sharma et al., 2005). The color of the pair of perceptually similar objects was either red, grey, pink, black, blue, yellow, green, orange, or purple. The color of the pair of perceptually and semantically

[1] Baseline condition: M = 0.46%; SD = 0.13%; range = 0.21%–0.81%. Perceptually-similar pair condition: M = 0.48%; SD = 0.12%; range = 0.22%–0.89%. Semantically-related pair condition: M = 0.43%; SD = 0.12%; range = 0.21%–0.88%. Semantically- and perceptually-related pair condition: M = 0.46%; SD = 0.11%; range = 0.26%–0.86%.

related objects was either red, grey, brown, black, beige, blue, yellow, transparent grey, or purple.

The semantic relatedness between objects was manipulated in terms of co-occurrence between objects (semantically related vs. semantically unrelated). For example, a brush and a dustpan tend to co-occur in the real environment (see Figure 1). See in the Supplemental Material the pilot study for the evaluation of the object semantic relatedness. We did not use participant-judges to assess the semantic relatedness between 'singletons', as we did for 'semantically related objects', due to the large number of comparison judgments to be made. Instead, we used ConceptNet (Speer et al., 2017), a semantic network (with millions of nodes and edges) of word-meaning knowledge that is built from a variety of interconnected knowledge resources, including the Open Mind Common Sense corpus, WordNet, DBPedia, and OpenCyc. The API of ConceptNet 5.8.1 was executed in Python to measure the semantic similarity between two object labels with respect to each other. The measure gives a score between 0 and 1 (absolute value), with 0 meaning that the two words are not at all semantically similar, and 1 that they have almost the same meaning. Negative scores would mean low similarity. For each scene, all possible pairs of singletons were evaluated as being very weakly semantically related, with scores between -0.16 and 0.19 (M = 0.02, SD = 0.06). For scenes with a pair of semantically related objects, the semantic pairs were evaluated as semantically related, with scores between 0.30 and 1.0 (M = 0.60, SD = 0.21). See in the Supplemental Material Table 1 for a list of the objects used in our experiment.

In all type-pair conditions, the pair of objects was always placed near each other in the scene, but each object of the pair had a unique position in the scene. The position of the pair of objects in the scene was balanced as best as possible between the six possible positions for each type pair condition. For this first study of perceptual grouping in WM using real objects and manipulating both color and semantic similarity, we always placed the pairs adjacently to avoid potential noise arising from any possible differences in the sizes of similarity effects with differing proximity between similar objects. The results from a meta-analysis also suggest that the effect of similarity grouping does not depend on proximity (Li et al., 2018). Figure 1 shows examples of experimental and baseline scenes used in our experiments.

Figure 1. *Examples of scenes.*

Note. The pair of related objects is outlined in black in the scene for clarity and the stimuli do not reflect the exact dimensions as displayed during the experiment. Scene conditions: (1) Semantically and perceptually related pair: dustpan and brush are blue. (2) Semantically related pair: watering can and plant are of different colors. (3) Perceptually related pair: oven dish and flip-flops are green. (4) Baseline: only singleton objects. The online article shows the color version of the figure.

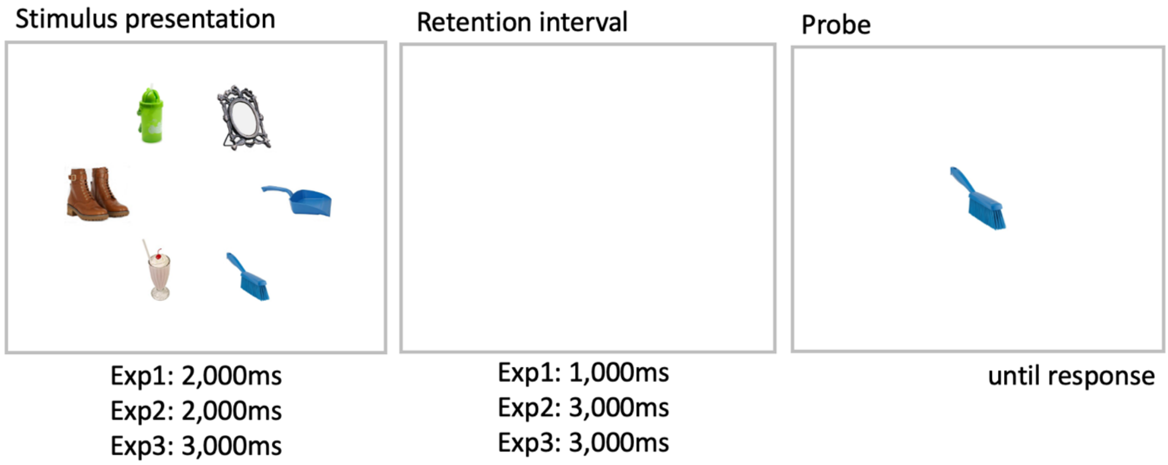
Procedure

The experiment was run collectively by groups of up to five participants, in an illuminated room. Participants were placed at a distance of approximately 57 cm away from the screen. The experiment used a classical change detection task. The participants viewed scenes consisting of to-be-remembered objects, and then their memory was probed for the scene objects. In each trial, a central black fixation cross (height: 2.1°) appeared for 4,000 ms before the study scene. The scene was then presented for 2,000 ms, followed by a 1,000 ms retention screen, during which the central fixation cross appeared. The test screen then followed, where the central single-object probe was presented until response, as in O'Donnell et al. (2018). The participants indicated whether the probed object was absent or present in the previous study scene. Without any time pressure, the participants were asked to respond as accurately as possible, by pressing "a" for "absent" or "p" for "present" on the azerty keyboard. The participant initiated the next trial by pressing the spacebar. Figure 2 shows an illustration of the trial procedure. The scenes were presented in random order and only once to each participant. The experiment lasted approximately 15 min.

The experiment consisted of a total of 80 scenes (plus 2 practice scenes) with 20 scenes in each of the 4 scene conditions: semantically-related pair condition, perceptually-related pair condition, semantically- and perceptually-related pair condition, baseline condition (see Figure 1). In each condition, there were 10 change trials and 10 same trials. In the same trials, half of the probes consisted of an object belonging to a related pair, while the other half consisted of singleton objects. Note that in the baseline condition, all same trials included a singleton object as a probe.

The experiment used 520 unique objects to create the 80 scenes and the 40 probes for the change trials (i.e. foils). The foils were chosen so that they do not typically co-occur with the objects to be memorized in the scene. However, to ensure that the participants did not attempt to reduce this task to a color-memory task, the foils were selected to match in color to one of the objects in the scene. Half of the foils replaced objects belonging to a related pair and the other half replaced singleton objects, with the exception of the baseline condition where all foils replaced singletons.

Figure 2. *Trial procedure.*



Note. The figure depicts an example of a same trial for a scene in the semantically- and perceptually-related pair condition. The pair of objects consists of the dustpan and the brush, and the object tested is the brush. Each trial started with a central fixation cross, which is not shown here. The stimuli do not reflect the exact dimensions as displayed during the experiment. The online article shows the color version of the figure.

Results

Statistical analyses were performed using R version 3.6.2 (The R Foundation's Project for Statistical Computing). Memory accuracy was analyzed using *d*', as in previous relevant studies (Kaiser et al., 2015; Liu et al., 2022; O'Donnell et al., 2018). The measure of detection sensitivity *d*' is independent of response bias. The formula is the following: *d*' = *Z*(hit rate) – *Z*(false alarm rate), where *Z*(hit rate) and *Z*(false alarm rate) are the *z*-transforms of hit rate and false alarm rate. To deal with extreme values representing hit ratios of 1 and zero false alarms for which the *z*-transforms cannot be performed, we transformed the data using a log-linear correction (Hautus, 1995). Hit and false alarm rates for each experimental conditions are presented in Tables 2 and 3 of the Supplemental Material. Data were excluded when the mean *d*' for all conditions was less than 0.465 (i.e. accuracy of 60%). Based on this criteria, three participants were excluded from the analyses, giving a final sample of 52 participants and an a posteriori power of 94-98% (effect size = 0.20, alpha = 0.05). Trials with excessively fast or slow responses were also excluded. Trials where the response occurred more than 5 seconds after the response screen appeared were excluded from the analyses (0.70% of the data). We did not observe responses faster than 300 ms. It should be noted that in all our experiments, we used exclusion criteria similar to those in Brady and Störmer's study (Brady & Störmer, 2022). Overall, the data pre-processing steps left 99.4% trials. Statistical analyses were performed using repeated measures ANOVAs. Post-hoc comparisons were assessed using the Tukey HSD test, when necessary. Bonferroni corrections were applied to compensate for multiple comparisons. Only *p* values below .05 were considered noteworthy. Effect size estimates were reported using Partial eta-squared.

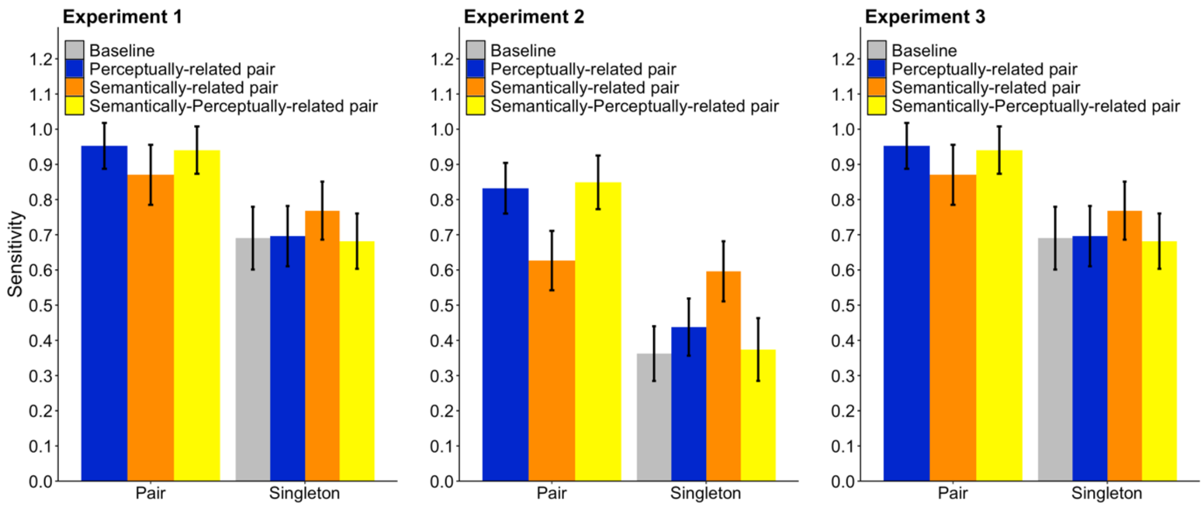
We conducted three ANOVAs. First, to test whether there were perceptual and semantic sharing bonuses, we performed a one-way ANOVA with scene type (baseline, perceptually-similar pair, semantically-related pair, perceptually- and semantically-related pair) as a within-subject factor and sensitivity as the dependent variable **(Model 1: Redundancy-boost hypothesis)**. To test the redundancy-boost hypothesis, we were particularly interested in sensitivity comparisons between the baseline and each pair type condition. Note that the baseline has been specified as the reference level in R. Second, we tested whether compression could explain any redundancy-boost effect. Specifically, we assessed singleton memory by performing a one-way ANOVA on singleton only trials, with scene type as a within-subject factor and sensitivity as the dependent variable **(Model 2: Spill-over hypothesis).** Note that even if Model 1 is not significant, we will still report the results of Model 2. Third, to test whether perceptual and semantic sharing bonuses lead to redundancy advantages, we performed a 3×2 repeated-measures ANOVA with pair type (perceptually-similar pair, semantically-related pair, perceptually- and semantically-related pair) and probe type (related object vs. singleton object) as within-subject factors and sensitivity as the dependent variable **(Model 3: Redundancy-advantage hypothesis)**. Overall, Model 1 aimed to test both the compression hypothesis and the attentional (encoding bias) hypothesis. Model 2 aimed to test the compression hypothesis, while Model 3 aimed to test the attentional hypothesis that larger advantages should be observed for objects in the pairs than singletons. Data from Experiment 1 are shown in the left-most panel of Figure 3.

Redundancy-boost hypothesis. A one-way ANOVA showed that the overall effect of scene type was not significant, $F(3, 153) = 1.99$, $p = .118$, $\eta_p^2 = 0.038$.

Spill-over hypothesis. A one-way ANOVA showed that the effect of scene type was not significant, $F(3, 153) = 2.45$, $p = .066$, $\eta_p^2 = 0.046$.

Redundancy advantage hypothesis. A two-way ANOVA showed that the effect of probe type was significant, $F(1, 51) = 6.20$, $p = .016$, $\eta_p^2 = 0.108$. The effect of pair type was not significant, $F(2, 102) = 1.67$, $p = .193$, $\eta_p^2 = 0.032$. However, there was a significant interaction between probe and pair type, $F(2, 102) = 4.41$, $p = .015$, $\eta_p^2 = 0.080$ (see Figure 3). Post hoc testing indicated that sensitivity was significantly higher ($p < .001$) for scenes with a pair of perceptually-similar objects and probed with a paired object ($M = 0.95$, $SD = 0.50$) than when probed with a singleton object ($M = 0.57$, $SD = 0.58$). This redundancy advantage was not found for scenes with a pair of perceptually- and semantically related objects or a pair of semantically related objects (*ps* > 1).

Figure 3. *Sensitivity as a function of scene type and probe type.*



Note. Scene type factor: baseline, perceptually-related pair, semantically-related pair, semantically- and perceptually-related pair. Probe type factor: related object from a pair, singleton object. Error bars indicate ± 1 standard error of the mean (SEM). See the online article for the color version of this figure.

Discussion

The results showed a redundancy advantage (memory for related objects vs. singletons), but no redundancy-boost on WM overall performance. This advantage appeared for related objects that shared only their color. The findings therefore support the redundancy advantage hypothesis. This suggests that the benefit in recall from the presence of related objects should not be taken as evidence that the input has been recoded into compressed representations in short-term memory. Rather, the color-sharing bonus restricted to the related pairs may reflect an attentional mechanism in which the perceptual group captures and consumes attentional resources at the expense of singletons (Prieto et al., 2022). The redundancy advantage did not translate into detectably increased performance for singletons, which is consistent with some previous studies using simpler stimuli (Peterson et al., 2015; Prieto et al., 2022; Quinlan & Cohen, 2012).

The lack of performance improvement in the presence of semantically related objects, regardless of color similarity, may be due to experimental conditions that do not allow for sufficiently in-depth processing. Recent evidence suggests that, compared to simple stimuli, real-world objects benefit from deeper processing by facilitating access to knowledge (Brady et al., 2016; Brady & Störmer, 2022). Furthermore, when a new object is seen, its low-level perceptual features are activated faster than higher-level semantic features (Linde-Domingo et al., 2019). Increasing the duration of the retention interval can be a way of encouraging semantic in-depth processing. Previous studies examining semantic effects among real-world objects have used a retention interval of 1,000 ms as in our experiment, but arrays composed solely of pairs of related objects (Kaiser et al., 2015; Liu et al., 2022; O'Donnell et al., 2018), which may have resulted in stronger grouping manipulation than in our experiment. We therefore carried out a second experiment, in which we increased the duration of the retention interval to 3,000 ms to see if this manipulation could modulate the semantic grouping effect. Manipulating the retention interval could also affect putative resource-sharing strategies. The potential effects of semantics may only become apparent after a longer delay, favoring the extraction of additional object-specific information.

Experiment 2

Method

Participants

Fifty-five volunteers participated online in the study (27 females, 28 males). They were recruited and paid 3.0 GBP through Prolific, an online participant platform. None of the participants in Experiment 2 took part in Experiments 1 and 3, or in the pilot study. The study was approved by the ethic committee of Cardiff University (EC17.09.12.4952G). The participants were native French speakers, aged between 20 and 32 years old (M = 25.17, SD = 3.28). Other recruitment criteria were the same as in Experiment 1.

Materials

The same stimuli were used as in Experiment 1 (see Figure 1).

Procedure

The change detection task was the same as in Experiment 1, except for the duration of the retention interval. The retention time was 3,000 ms instead of 1,000 ms. Figure 2 shows an illustration of the trial procedure. The experiment was built using PsychoPy Builder (PsychoJS) and hosted on Pavlovia (https://pavlovia.org/). Participants completed the task in a web browser on their personal computers. The recommended browsers were Mozilla Firefox and Google Chrome. Participation via mobile phone or tablet was not permitted. As we do not know prior to the experiment the exact dimensions of each participant's screen, all stimulus sizes were defined in PsychoPy's "height" units. This measure is useful in that it scales with window size.

Results

Data from Experiment 2 are shown in the central panel of Figure 3. The rejection criteria for invalid trials and the analyses plan followed the same rules specified in Experiment 1. Eleven participants' data were excluded from the analyses due to overall poor performance at the change detection task (d' for all conditions less than 0.465). Trials where the response occurred more than 5 seconds after the response screen appeared were also excluded from the analyses (0.70% of the trial data). We did not observe responses faster than 300 ms. Participants were excluded when more than 5% of their individual trials were excluded, which resulted in the exclusion of one participant's data. In Experiment 2, the final sample was therefore 43 participants, giving an a posteriori power of 88-95% (effect size = 0.20, alpha = 0.05). Overall, the data pre-processing steps left 99.6% trials.

Redundancy-boost hypothesis. A one-way ANOVA showed that the effect of scene type was not significant, $F(3, 126) = 0.37$, $p = .774$, $\eta_p^2 = 0.009$.

Spill-over hypothesis. A one-way ANOVA showed that the effect of scene type was not significant, $F(3, 126) = 1.90$, $p = .133$, $\eta_p^2 = 0.043$.

Redundancy advantage hypothesis. A two-way ANOVA showed that the effect of probe type was significant, $F(1, 42) = 43.69$, $p < .001$, $\eta_p^2 = 0.510$. The effect of pair type was not significant, $F(2, 84) = 0.12$, $p = .888$, $\eta_p^2 = 0.003$. However, there was a significant interaction between probe and pair types, $F(2,84) = 5.34$, $p = .006$, $\eta_p^2 = 0.114$ (see Figure 3). Post-hoc testing indicated that sensitivity was significantly higher ($p = .001$) for scenes with a pair of perceptually-similar objects and probed with a related object ($M = 0.85$, $SD = 0.47$) than when probed with a singleton object ($M = 0.41$, $SD = 0.52$). The results also indicated that sensitivity was significantly higher ($p < .001$) for scenes with a pair of perceptually- and semantically-related objects probed with a related object ($M = 0.84$, $SD = 0.51$) than when probed with a singleton object ($M = 0.35$, $SD = 0.58$). This redundancy advantage was not found for scenes with a pair of semantically related objects (*ps* > 1).

Discussion

In Experiment 2, we observed further evidence in favor of the redundancy-advantage hypothesis, with memory for related objects again improved over that for singletons. This redundancy advantage was present for objects sharing similar color regardless of semantic relatedness. Once again, evidence is in favor of the encoding bias hypothesis and not the compression hypothesis. Moreover, the results suggest that objects of similar color may have attracted attention during scene presentation, and that a longer retention time allows to process the objects semantic relatedness, enabling more WM resources to be used.

The lack of memory gain in Experiment 2 in the presence of object pairs that were only semantically related (but not perceptually related) may be due to the length of the encoding time, which may not have allowed for sufficiently in-depth processing. Recent studies have indeed shown that real-world objects in particular benefit from a longer encoding time, probably by facilitating access to semantic knowledge (Brady et al., 2016; Brady & Störmer, 2022). In Experiment 2, the stimulus presentation duration was 2,000 ms as in Experiment 1. Previous studies examining semantic effects have used a stimulus presentation duration ranging between 2,000 and 4,000 ms (Kaiser et al., 2015; Liu et al., 2022; O'Donnell et al., 2018). Even if the stimulus presentation duration (2,000 ms vs. 4,000 ms) has been found to have no effect on the magnitude of the grouping per semantic (Kaiser et al., 2015, 2019; Liu et al., 2022). We therefore carried out a third experiment, in which we increased the stimulus presentation duration to 3,000 ms as in the semantic grouping study of O'Donnell et al. (2018). Will this result in a redundancy advantage for semantically related objects?

Experiment 3

Method

Participants

Fifty-five volunteers participated in the study. The study was conducted online, as in Experiment 2, and participation was unpaid. The participants were native French speakers recruited from the community by internet advertisements and word-of-mouth communication. None of the participants in Experiment 3 took part in Experiments 1 and 2, or in the pilot study. Two participants' data were excluded from all analyses due to incomplete data files. The final sample consisted of 53 participants (39 females, 14 males), aged between 18 and 42 years old (M = 22.93, SD = 5.63). Other recruitment criteria were the same as in Experiments 1 and 2.

Stimuli

The same stimuli were used as in Experiments 1 and 2 (see Figure 1).

Procedure

The task and procedure were the same as in Experiment 2, except for the duration of the stimulus presentation. The duration was of 3,000 ms instead of 2,000 ms. Figure 2 shows an illustration of the trial procedure.

Results

Data from Experiment 3 are shown in the right most panel of Figure 3. The rejection criteria for invalid trials and the analyses plan followed the same rules specified in Experiments 1 and 2 (see Results subsection of Experiment 1). Two participants' data were excluded from the analyses due to overall poor performance at the change detection task (d' for all conditions less than 0.465). Trials where the response occurred more than 5 seconds after the response screen appeared were also excluded from the analyses (3.40% of the trial data). We did not observe responses faster than 300 ms. Data were excluded if greater than 5% of individual trials were excluded, which resulted in the exclusion of ten participants. The final sample was therefore 41 participants, giving a posteriori power of 86-94% (effect size = 0.20, alpha = 0.05). Overall, the data pre-processing steps left 98.2% trials.

Redundancy-boost hypothesis. A one-way ANOVA showed no significant effect of scene type, $F(3, 120) = 0.79$, $p = .499$, $\eta_p^2 = 0.020$.

Spill-over hypothesis. A one-way ANOVA showed no significant effect of scene type, $F(3, 120) = 0.28$, $p = .840$, $\eta_p^2 = 0.007$.

Redundancy advantage hypothesis. A two-way ANOVA showed that the effect of probe type was significant, $F(1, 40) = 10.81$, $p = .002$, $\eta_p^2 = 0.213$ (see Figure 3). Sensitivity was higher for a related object ($M = 0.92$, $SD = 0.46$) than for a singleton object ($M = 0.71$, $SD = 0.53$). There was no significant effect of pair type, $F(2, 80) = 0.02$, $p = .981$, $\eta_p^2 = 0.0004$, nor was there a significant interaction between probe and pair types, $F(2, 80) = 0.84$, $p = .433$, $\eta_p^2 = 0.021$. Overall, the results of Experiment 3 showed a redundancy advantage for all related pairs. Furthermore, as in Experiments 1 and 2, the results showed no overall performance improvement due to the presence of related objects, nor any capacity spillover for singletons.

General discussion

The statistical structure of the environment and semantic sense of objects within our field of vision are known to influence what and how much we can remember. Though we generally remember little moment-to-moment, these stable regularities somehow allow us to remember a little more. This study is the first to investigate how both perceptual and semantic similarities might be exploited to boost limited memory capacity. The present series of three experiments mainly showed redundancy advantages, with memory of related objects improved over that of singleton objects. This advantage was present for similarly colored objects, and under conditions allowing for deeper information processing, extended to semantically related objects. We manipulated the depth of information processing by varying the encoding and retention times, with the longer times allowing for deeper processing of real-world objects (Brady et al., 2016; Brady & Störmer, 2022). None of our three experiments showed a redundancy-boost on overall WM performance, with memory for scenes comprising a pair related items in terms of color or semantics not differing from that for scenes comprising only singletons. Nor did the experiments show any capacity spillover for the remaining singleton objects in the scene. The results of the present study therefore support the attentional encoding bias hypothesis and rule out the compression hypothesis to explain the color and semantic sharing bonuses between real-world objects in visual WM. Unlike the compression hypothesis, the encoding bias hypothesis states that the grouping effect influences the organization of visual information by biasing the allocation of attentional resources, so that more resources would be available to store related objects to the detriment of singletons. On the other hand, compression enables more efficient processing of the information to be stored without any effect on the attentional resources allocated to each item in the scene.

This study suggests the existence of attentional capture derived from perceptual and semantic grouping processes. The fact that there were redundancy advantages suggests a lower probability of encoding singleton objects due to the lower attentional resources allocated to them (Prieto et al., 2022). Consistently, redundancy advantages have also been found in perceptual grouping studies using simple colored features (Morey, 2019; Morey et al., 2015; Peterson et al., 2015; Peterson & Berryhill, 2013; Prieto et al., 2022; Quinlan & Cohen, 2012). For example, Morey et al. (2015) recorded eye movements when participants performed a change detection task similar to ours and found that attention was captured by repeated colors during encoding. They also found that, during retention, participants' attention was more focused on the locations where singleton colors were presented. This strategic allocation of attention explain the two advantages found in their study for repeated colors over singleton colors and for singletons in arrays with repetitions over arrays with only singletons. Contrary to our study, though encoding the perceptual groups was prioritized, more capacity remained for encoding the remaining singletons when repetitions were present than when they were absent (Morey et al., 2015). This spillover effect was very small, but genuine and robust as it was replicated later by Morey (2019). This small spillover effect has been interpreted by suggesting that the excess resource made available due to perceptual grouping would be distributed across all the remaining singletons in the display (Morey et al., 2015). Since real-world objects recruit additional WM resources compared with simple stimuli (Brady & Störmer, 2022), our interpretation of the lack of benefit for singletons in our study is that there are not enough resources left to allocate to better singletons encoding. Related objects appear to enable more efficient WM processing due to greater attention allocation to them at the expense of singletons. Altogether, our findings support the encoding bias hypothesis and rule out the compression hypothesis to explain the color and semantic sharing bonuses between real-world objects. This study also indirectly supports theories of visual memory that assume a flexible resource account of storage based on attentional resources allocated to items (e.g., Bays et al., 2009), with a greater proportion of resources allocated to items prioritized for storage in visual WM. Compatible with flexible resource models, it has also been shown that grouped items are stored with greater precision than dissimilar items (Son et al., 2020). But this last point remains an open question, namely whether the redundancy advantages for real-word objects may be also due to the quality of the representation and not just to the increased likelihood of related objects entering WM.

Critically, our study has led us to conclude that the recent idea put forward by Kowialiewski et al. (2022) of a domain-specific compression mechanism to deal with item similarity does not extend to more complex visual stimuli such as real-world objects. Kowialiewski et al. (2022) conducted a series of experiments offering compelling evidence that grouping eases memory load via color and semantic similarity. The authors showed that item similarity improves recall performance for similar items themselves, but also for less compressible items (i.e., singletons) in the same list/array, in a variety of domains. This proved to be the case in the visuospatial and visual domains using simple stimuli, and in the semantic and phonological domains using verbal stimuli. The results of the present study suggests that the stimuli used can be one limit of the recent proposal that similarity grouping in any domain can impact WM via a compression mechanism (Kowialiewski et al., 2022). As far as compression is concerned, it must have a cost and therefore cannot be at play in all scenarios, as this mechanism requires active recoding and decoding processes to recover the original information (Norris & Kalm, 2021), and imply a slow retrieval process to access the compressed memories (Huang & Awh, 2018). Moreover, similar items such as stimuli sharing a color appear to be represented with higher precision than dissimilar items (Son et al., 2020). Since there is a trade-off between the level of compression and the precision of the recovered signal, the greater the compression, the less accurately the signal can be recovered (Norris & Kalm, 2021). Our study could possibly suggest that compression is not an optimal mechanism for dealing with real-world objects and has been avoided so as not to lose too much information. Our study thus also highlights the importance for future studies to paying more attention to the properties of WM in relation to realistic stimuli, as factors such as stimulus types could lead to differences in the grouping effect and the underlying mechanisms at play.

This study allows us to draw other important conclusions about the mechanisms involved in the perceptual and semantic grouping in visual WM. The results of our series of experiments suggest that color and semantic sharing bonuses between real-world objects in visual VWM come from different processes. Indeed, the results showed that the color-sharing bonus outweighed the semantic-sharing bonuses, with the presence of color redundancy advantages in all three experiments. We can thus conclude that visual WM appears to not utilize resource intensive semantics unless given time to do so. Our results are consistent with recent data showing that perceptual information such as color of real-world objects influences visual WM capacity more than conceptual structure (Li et al., 2023). In our experiments, conditions that allowed time for deeper processing resulted in semantic-sharing bonuses. More specifically, we manipulated the depth of information processing by varying the encoding and retention times, with the longer times allowing for deeper processing of real-world objects, as seen previously (Brady et al., 2016; Brady & Störmer, 2022). This increase in processing possibly facilitated access to object semantic knowledge, in line with models postulating a close interaction between WM and long-term memory (e.g., Cowan, 2001; Oberauer, 2002). Indeed, previous work that has not shown same semantic category boost on WM capacity had used too short of encoding and retention times (Quinlan & Cohen, 2016), suggesting typical change detection tasks may not always permit the semantic activation of real-world objects. The present study is, to our knowledge, the first to show that the duration of the retention interval can modulate the grouping effect, shedding light on how the grouping effect can change during the maintenance phase. Our results suggest that, although there appear to be situations where participants adapt their encoding and maintenance strategies to the semantic relationships in the scene, semantic guidance requires more time to access knowledge. Furthermore, perceptual grouping by color and semantic grouping may have both increased the physical salience of related objects and thus induced their priority access to visual awareness (Ding et al., 2019; Li et al., 2018). This priority access led to attentional prioritization of related objects during encoding, in line with WM studies showing that highly salient objects in a visual scene enhance recall of these objects (Fine & Minnery, 2009; Melcher & Piazza, 2011; Ravizza et al., 2016). Though semantic guidance is considered a top-down factor, and thus, may be less automatic than color guidance. A recent study has shown that certain features such as color guide attention in an automatic parallel-like fashion, resulting in a memory advantage for items that share this feature regardless of task relevance in pre-cued change detection tasks (Qian et al., 2020). In our experiments, involuntary color-based attention compared to semantic-based attention facilitated visual WM independently of the duration of the memory or retention screen, presumably reflecting different attention-guiding potencies of the two types of groupings, and possibly different encoding and maintenance efficiency. Our findings suggest therefore that grouping of typically co-occurring objects appears to be qualitatively different from the perceptual color grouping mechanism.

In line with studies using simple stimuli, our results provide further evidence that perceptual grouping based on color can lead to strong beneficial effects on visual WM compared to other grouping methods (Li et al., 2018). In contrast to the few studies examining the effects of semantic grouping on visual WM for real-world objects, none of our experiments showed a relatedness boost on overall performance. Indeed, memory for scenes comprising a pair of related items in terms of color or semantics did not differ from that for scenes comprising only singletons. Previous studies had made extensive use of the same set of pairs of related objects presented several times during the experiment both in the study array and as a probe, so a possible effect of repetition on memory performance and hence on the grouping effect cannot be totally ruled out (Kaiser et al., 2015; Liu et al., 2022; O'Donnell et al., 2018). To our knowledge, our experiments are the first to use objects that are not repeated throughout the experiment. In these previous studies, each pair of related objects was also assigned to one of the available locations in the display, which may have greatly facilitated the semantic grouping process compared with our experiments in which each object in a pair had its own position in the scene. However, it would be interesting to carry out a study similar to ours and test the possible effects of spatial proximity between related objects. Our study is also the first to test whether and how color and semantic sharing bonuses exist between real-world objects in visual WM.

Conclusion

We show that there are semantic and perceptual sharing bonuses between real-world objects in visual WM, and that these bonuses cannot be explained by a compression mechanism, but rather by an attentional encoding bias for perceptual and semantic groups. Indeed, we show that the effects of perceptual and semantic groupings favor only the recall of related objects. Our interpretation of the results is that related objects enable more efficient

WM processing due to greater attention allocation to them at the expense of unrelated singleton objects. These redundancy advantages indirectly support the theories of visual memory that assume a flexible resource account of storage based on the attentional resources allocated to the items, and on attentional capture by salient stimuli. Future research using real-world objects is needed to understand whether grouping biases attention during encoding and maintenance, and whether it increases recall precision. Importantly, we also show that color sharing bonuses outweigh semantic sharing bonuses, suggesting that visual WM does not always utilize resource-intensive semantics, at least not as rapidly. The conditions that allowed deeper processing resulted in semantic sharing bonuses by facilitating access to object knowledge, supporting models postulating that semantic effects in WM are explained by a close interaction between WM and LTM knowledge, but stressing that these links require time to develop. Semantic guidance may also be less automatic than color guidance. Our findings have important implications for our understanding of the fundamental processing involved in WM and attention and encourage future research into the process of semantically grouping real-world objects to more systematically control for perceptual influences, particularly color.

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