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The Role of Perceptual Similarities in Determining the Asymmetric Mixed-Category Advantage

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Considering working memory capacity limitations, representing all relevant data simultaneously is unlikely. What remains unclear is why some items are better remembered than others when all data are equally relevant. While trying to answer this question, the literature has identified a pattern named the mixed-category benefit in which performance is enhanced when presenting stimuli from different categories as compared to presenting a similar number of items that all belong to just one category. Moreover, previous studies revealed an asymmetry in performance while mixing certain categories, suggesting that not all categories benefit equally from being mixed. In a series of three change-detection experiments, the present study investigated the role of low-level perceptual similarities between categories in determining the mixed-category asymmetric advantages. Our primary conclusion is that items' similarity at the perceptual level has a significant role in the asymmetric performance in the mixed-category phenomenon. We measured sensitivity (d') to detect a change between sample and test displays and found that the mixed-category advantage dropped when the mixed categories shared basic features. Furthermore, we found that sensitivity to novel items was impaired when presented with another category sharing its basic features. Finally, increasing the encoding interval improved performance for the novel items, but novel items' performance was still impaired when these items were mixed with another category that shared their basic features. Our findings highlight the significant role low-level similarities play in the asymmetric mixed-category performances, for both novel and familiar categories.

Public Significance Statement

Our visual environment is a diverse collection of stimuli sourced from various categories. Research has shown that memory performance is better when different categories of stimuli are combined, rather than when a single category is presented. However, recent studies have revealed that not all combinations of stimuli produce comparable memory enhancement, which has resulted in an unresolved asymmetry in the mixed-category advantage. Our findings, in contrast to previous interpretations that primarily rely on high-level cognitive processing, demonstrate that low-level encoding processes also impact memory enhancement. Specifically, our study provides evidence that the perceptual similarities between stimuli derived from different categories have an effect on the extent of the mixed-category advantage.

Keywords: visual working memory, perceptual similarity, mixed-category effect

Preparing for dinner, you start scanning the fridge; the dairy has expired, few vegetables are left in the drawer, and only one egg is lying in the carton. Keeping all products that are about to perish active in mind, you are heading toward the grocery store. Replacing the expired products with new ones back home, you realize that you forgot to buy several desired items. Given the idea of limitations across working memory's functions, representing all relevant data simultaneously is unlikely. What is not clear is why some items were better remembered than others when all data were equally relevant. In this study, we sought to investigate the role of early perceptual processing, in directing memory to encode and maintain a specific stimulus over another.

Several studies (outlined below) have identified a mixed-category benefit such that performance is enhanced when presenting stimuli from different categories as compared to presenting a similar number of items that all belong to one category. The current study will further investigate this effect and, in particular, the impact of perceptual similarities between categories on this mixed-category asymmetric effect.

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A mixed-category improvement was found in a functional magnetic resonance imaging study by Cohen et al. (2014), who examined the relationship between behavioral performance and neural activation. The results indicated that participants performed better when the displayed items belonged to different categories than when the items were taken from the same category. They found that the amount of division between neural response patterns, particularly within the occipitotemporal cortex, is strongly connected to the behavioral benefit. In the study of Cohen et al., high-level visual categories were used (faces, bodies, scenes, and objects) to examine the competition for visual working memory (VWM) representations in a change-detection task. According to Cohen et al., the observed increase in performance resulted from the increase in the availability of neural resources since different categories tap distinct neural activations.

The use of familiar and ecological categories (faces, bodies, scenes, and objects) limits Cohen et al. (2014) ability to identify the stage in which the representations overlap, as same-category items share similarities across several processing stages (e.g., two faces share low perceptual similarities but also share higher perceptual structure). Thus, in the context of having only familiar categories, the mixed-category benefit can be generated by tuning up different perceptual encoding maps (Reynolds & Desimone, 1999) or/and by holding different high-level encoding patterns (Kanwisher, 2010; Moores et al., 2003).

Follow-up studies found that while the mixed-category advantage has a pronounced effect on some categories, it may have only a negligible effect on the parried category, revealing an asymmetrical categorical preference (Avital-Cohen & Gronau, 2021; Jiang et al., 2016). For instance, Jiang et al. (2016) paired different categories (faces, bodies, scenes, and objects), showing an advantage for faces and bodies only, such that both showed better performance when paired with objects or scenes, while this advantage was not observed for the other paired category. This asymmetrical improvement was explained by arguing that faces and bodies create large within-category interference (due to an automatic averaging of multiple exemplars or difficulty in remembering the spatial configuration of features and parts); thus, displaying faces or bodies with another category decreased this interference resulting in a better performance.

Moreover, Jiang et al. (2016) found a mixed-category benefit when mixing faces and bodies; however, this observed advantage was weaker relative to a condition in which faces or bodies were mixed with either objects or scenes. These asymmetric advantages were interpreted as evidence of within-category interference for faces and bodies such that mixing each with items from different category resulted in a smaller demand on memory.

Avital-Cohen and Gronau (2021) proposed an explanation for the observed asymmetry, attributing it to an imbalance in the distribution of attentional resources between two or more competing categories. In their study, they found that categories other than faces and body poses, such as highways, exhibited a mixed-category advantage. This suggests that the mixed-category effect may not necessarily align with a category-specific interference account. Instead, Avital-Cohen and Gronau (2021) put forward a central resource allocation account, suggesting that the asymmetric mixed-category effect likely arises from an inherent attentional bias toward one of the two categories.

While each theory interpreted the mixed-category phenomenon differently—such as lesser categorical neural overlap, variation in within-category interference, and inherent attentional biases, they all lean on high-level processing mechanisms. Interestingly, considering early perception processes may explain a portion of the mixed-category phenomenon. As was mentioned by Cohen et al. (2014), neural overlaps can emerge at any processing level, such as in the stage where low-level features are encoded. Furthermore, the argument that bodies and faces display strong within-category interference was suggested to be most salient when increasing the within-items similarity (Jiang et al., 2016). Thus, the present research aimed to examine the role of low-level perceptual similarities in the asymmetric mixed-category effect.

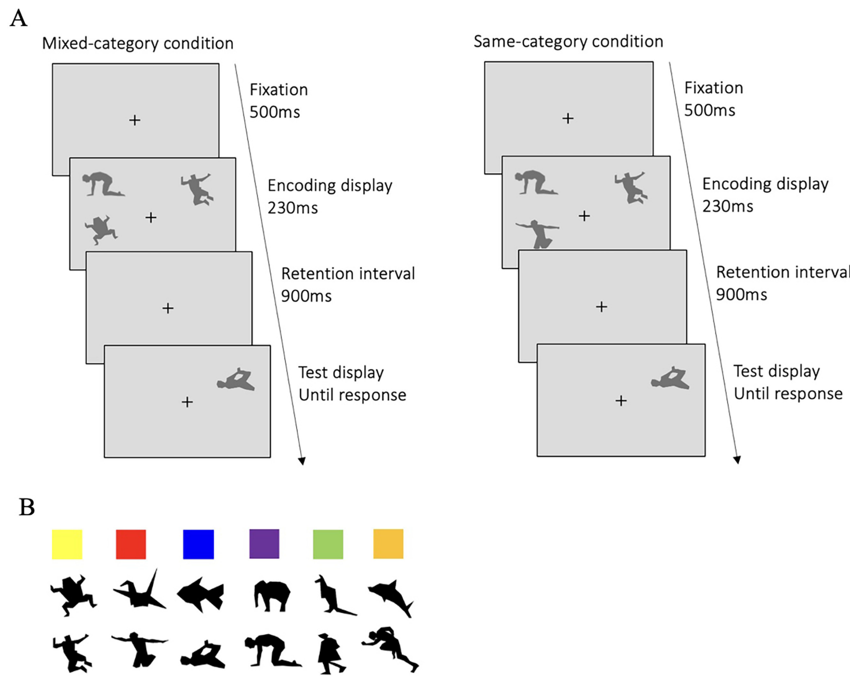
In a series of three change-detection experiments, in which performance was measured by calculating sensitivity (d'), the present study sought to extend the scope of knowledge regarding the asymmetry in the mixed-category effect. Our findings replicated the broad mixed-category benefit in which mixing two different categories yields better performance as compared to performance in the same-category condition; moreover, the asymmetric advantage among bodies was also replicated. Importantly, this study revealed asymmetric performance in mixed conditions that resulted from pairing categories that shared similarities in perceptual features. In our study, we manipulated the perceptual features of color and shape. When two categories shared perceptual similarities, it indicated that the items within those categories had the same color (black) and exhibited similar orientations (see Figures 1B and 3B). We chose colors and shapes since their use as stimuli in VWM research has provided valuable insights. For example, Luck and Vogel (1997) demonstrated that memory capacity for objects defined by a single feature, such as color or orientation, was comparable to capacity for objects with multiple features. In contrast, Alvarez and Cavanagh (2004) demonstrated that the shape complexity played a significant role in VWM capacity, as subjects showed superior performance for certain categories, such as colored squares, compared to other categories such as Chinese characters or random polygons. Additionally, Luria et al. (2010) concluded that encoding and maintaining complex shape information, such as polygons, in VWM required more storage capacity compared to simpler features like color.

By creating perceptual similarities between two of three distinct categories (body-pose silhouettes, animals' silhouettes, and colors), Experiment 1 revealed a significantly stronger mixed-category advantage when the mixed categories did not share low-level similarities compared to when the categories shared low-level similarities. To further examine the impact of low-level perceptual similarities on the mixed-category effect, Experiment 2 examined the effect of perceptual similarities among novel items (black-colored polygons). We found a performance cost to novel stimuli when these were paired with familiar items sharing similar basic features. Consequently, in Experiment 3, we examined the assumption that complex stimuli require a prolonged encoding interval (Alvarez & Cavanagh, 2004; Luria et al., 2010), by giving participants more time to encode the stimuli. Experiment 3 showed that a prolonged interval did not change the pattern already observed in Experiment 2, suggesting another interpretation for the asymmetry in the mixed-category performance.

Experiment 1

In Experiment 1, we presented three categories—colors, animals' silhouettes, and body poses' silhouettes, in either same-category or

Figure 1
Trial Sequence and Stimuli in Experiment 1



Note. Panel A: examples of trials in the two main conditions: mixed and same-category conditions. In mixed-category trials, display contained three stimuli taken from two different categories that were presented for 230 ms followed by 900 ms retention interval. Test array included single stimulus presented in one of the three previous locations which could be the same stimulus presented in the memory array or a different one taken from the same category. Panel B: stimulus types: colors, animals' silhouettes, and body poses' silhouettes. See the online article for the color version of this figure.

mixed-category conditions. Regarding the body poses category, both the cortical resource theory (Cohen et al., 2014) and the within-category interaction (Jiang et al., 2016) theory predict a mixed-category advantage when mixed with either colors or animals. The reason is that, according to Cohen et al., displaying distinct categories cause different neural activations, which lead to enhanced memory for each; according to Jiang et al., body poses show mixed-category benefit due to their strong within-category interference, which is reduced when fewer items from this category are presented.

Importantly, to investigate the role of perceptual similarities in the mixed-category benefit, we used two categories sharing perceptual similarities (body poses and animals, see Figure 1, panel B). While these categories are semantically distinct, the stimuli that were used in the present experiment were black silhouettes, resembling each other. Importantly, if perceptual similarities affect the mixed-category advantage, both animals and poses should benefit more from being mixed with colors than with each other. Therefore, we expected to observe a mixed-category asymmetry between body poses and animals, such that the mixed-category advantage should be reduced in the perceptually similarity mix as compared to the perceptually distinct mix. Additionally, we expected an equal increase in performance for colors when mixed with either body poses or animals, as both combinations lack perceptual similarities.

Method

Transparency and Openness

We report how we determined our sample size for all three experiments, all data exclusions (none), all manipulations, and all measures in the study, and we follow JARS (Kazak, 2018). All data and research materials are available for request. Data were analyzed using Excel, Version 16.71, and were plotted using RStudio, Version 2023.03.0 + 386, and the package ggplot2, Version 3.4.1 (Wickham et al., 2019). This study's design and its analysis were not preregistered.

Participants

Twenty-seven undergraduate students from Tel Aviv University (21 females, six males, ages 19–35) participated in the experiment that was conducted in the year 2021. The participants either received course credit or 40 NIS (approximately $13) per hour for participation. A consent form was obtained, and all participants had normal or corrected-to-normal vision. The sample size for all three experiments was determined through an a priori power analysis using the G*Power tool (Faul et al., 2009). We used the smallest effect size of the main effect of display type (same-category/mixed-category) observed in the Jiang et al. (2016) and Avital-Cohen and Gronau (2021) studies as the basis for our analysis. Using the partial

η^2 of .07, with a power of .95, resulting in 18 participants. All three experiments were conducted with larger sample sizes than required by conservative estimates.

Procedure and Materials

The experiment was conducted in an experimental room at Tel Aviv University, where a 23-in. computer screen (resolution 1,920 × 1,080) was used to display the task. The assessment was performed using a modified version of the change-detection task. The task consisted of arrays of one, two, or three stimuli presented in one of two conditions (same-category/mixed-category, for the results of the same-category arrays with set size of 1–3 stimuli, please see Appendix). The stimuli could be colors, body poses' blacked silhouettes, and animals' blacked silhouettes selected randomly in each trial (with replacement) from sets of six colors (magenta, red, yellow, green, cyan, and blue), six body poses' blacked silhouettes, and six animals' blacked silhouettes. Each color square subtended approximately 1.1° × 1.1° of visual angle, and each pose and animal subtended approximately 1.2° × 1.2° of visual angle.

All stimuli were displayed on a gray background, from a viewing distance of approximately 60 cm, within a 7.4° × 13.7° rectangle. The spatial positions of the stimuli were randomized for each trial. Each trial began by presenting a fixation point ("+") in the center of the screen for 500 ms, then the memory array was presented for 230 ms, whereby subjects were instructed to memorize the entire array. After a blank retention interval of 900 ms, in one of the memory array locations, an item (the test probe) was presented until receiving a response. The subjects were presented with all possible stimuli arrays during the instructions and were asked to indicate their familiarity with them. It is noteworthy that all subjects recognized all three categories. The subjects were asked to indicate whether the stimulus remained the same or changed from the initial presentation. A nonspeeded keyboard response was requested ("*z*" and "/" keys for "same" and "different," respectively). During the "different" trials, the probed stimulus could be any stimuli from the category set beside the one already displayed in the memory array (Figure 1, panel A).

Nine conditions were conducted in the task. Among them, three provided a baseline performance in an array of three items taken from the same category (e.g., same conditions). The remaining six conditions had a set size of three stimuli, comprising the different categories together. The mixture form was (x, $2y$), a combination of two categories at a 1:2 ratio. Each test probe could be one of the two presented categories. In each trial, a randomly selected probe item was used. An eight-trial practice block was followed by 18 experimental blocks with 50 trials each.

Results and Discussion

The mean accuracy rate in arrays with a set size of three stimuli was 0.85 ($SD = 0.35$). Figure 2 presents d' for the nine experimental conditions (three same-category, and six mixed-category conditions). A repeated-measures analysis of variance (ANOVA) with d' means as the dependent variable revealed a significant effect of display types, $F(8, 208) = 42.07$, $p < .001$, $\eta_p^2 = .62$. To further examine these differences, pairwise comparisons were conducted for each category between the mixed-category and the same-category conditions. We used the false discovery rate correction across all comparisons, across all three experiments (Benjamini & Hochberg, 1995).

The Mixed-Category Advantage

Replicating previous findings, sensitivity was higher in most mixed conditions compared to the same-category conditions. Each combination of stimuli resulted in a significant increase sensitivity for body poses compared to when only body poses were displayed; when body poses were mixed with animals, $F(1, 26) = 10.47$, $p = .005$, $\eta_p^2 = .29$, and when they were mixed with colors, $F(1, 26) = 48.15$, $p < .001$, $\eta_p^2 = .64$. The same pattern was observed for colors in the mixed conditions compared to the same-category condition. Specifically, when colors were mixed with animals, $F(1, 26) = 11.49$, $p = .004$, $\eta_p^2 = .30$; and similar results were obtained when they were mixed with body poses, $F(1, 26) = 5.31$, $p = .04$, $\eta_p^2 = .17$. As for animals' silhouettes, a significant improvement was observed when animals were paired with colors, comparing to animals-only condition, $F(1, 26) = 28.91$, $p < .001$, $\eta_p^2 = .52$. In addition, animals showed no benefit from being mixed with body poses as compared to performance in animals' same-category condition, $F(1, 26) < 0.01$, $p = .92$.

The Effect of Perceptual Similarities in the Mixed-Category Advantage

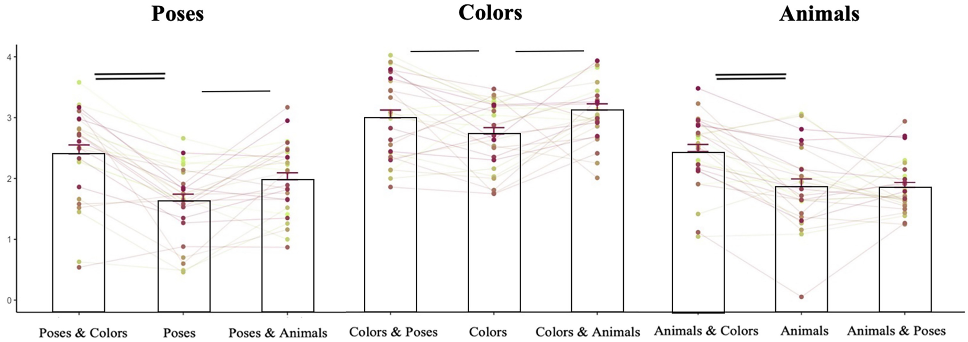
Similar to the pattern found in Jiang et al. (2016) of asymmetric advantage, we found that the mixed-category advantage for poses was significantly higher when these were mixed with colors than with animals, $F(1, 26) = 21.29$, $p < .001$, $\eta_p^2 = .45$, see Figure 2, left panel. Moreover, we found that the mixed-category advantage for animals was significantly higher when these were mixed with colors than with body poses, $F(1, 26) = 35.44$, $p < .001$, $\eta_p^2 = .58$, see Figure 2, right panel. Here, we replicated the asymmetry for the bodies' category observed by Jiang et al. (2016). This time, the weaker advantage emerged when pairing bodies with a category other than faces (i.e., silhouettes of distinct animals). Lastly, corresponding to our hypothesis, the mixed-category benefit for colors was similar when paired either with animals or body poses, $F(1, 26) = 1.36$, $p = .25$, $\eta_p^2 = .04$.

In Experiment 1, the asymmetric mixed-category advantages for body poses were replicated, showing that sensitivity was greater when bodies were presented alongside colors as opposed to when presented with animals. Similarly, animals also displayed an asymmetric advantage, gaining a benefit when combined with colors—a perceptually distinct category, but no performance benefit was observed when animals were paired with the perceptually similar category (i.e., bodies). Finally, the colors category, which differed from both animals and bodies in low-level features, exhibited an equivalent advantage when combined with either animals or bodies.

Experiment 1 showed that low-level similarities reduced the mixed-category advantage. However, one could argue that both animals and body poses share a higher level of neural activation due to their common characteristic of being animate shapes. This shared activation may contribute to the observed asymmetric mixed-category pattern between the two categories. Moreover, it is worth noting that all stimuli used in the experiment belonged to familiar categories. It is possible that encoding the items at higher (i.e.,

Figure 2

Sensitivity (d′) in the Same and Mixed Conditions

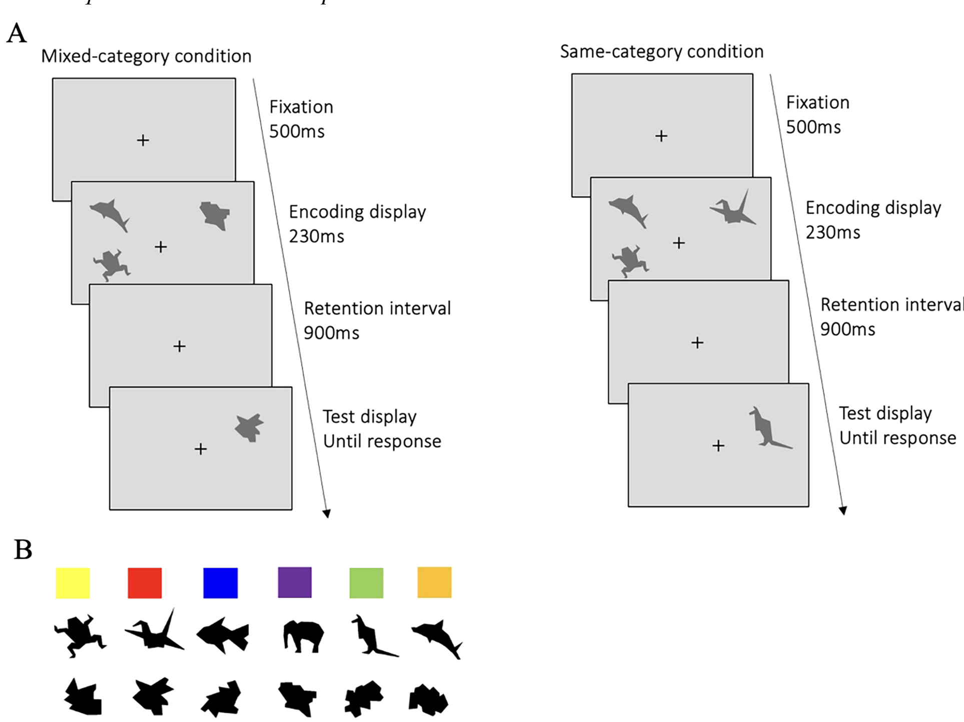


Note. Body poses, colors, and animals, respectively; each category holds three conditions: two mixed conditions and one (middle column) is the same-category condition. For each category, the mixed-condition headlines represent the averaged sensitivity for the category's probes when the memory display contained the relevant category alongside another category in all possible displays (i.e., one stimulus from the relevant category + two stimuli from the other category and two stimuli from the relevant category + one stimulus from the other category). Each condition holds mean d' (box plots) + *SE* along with the subject trend separated by color. The lines on top represent the significant differences between the conditions, where a double line represents $p > .001$, and a single line represents $.001 < p < .05$. See the online article for the color version of this figure.

semantic) levels may mitigate the effect of perceptual similarities since the items are represented not only by their basic features but also by their semantic representation. To overcome these limitations and to further investigate how sharing basic features affects the mixed-category advantage, In Experiment 2, body poses were replaced with black polygons, a novel category with low-level

Figure 3

Trial Sequence and Stimuli in Experiment 2



Note. Panel A: examples of trials in the two main conditions: mixed and same-category conditions. Panel B: stimulus types: colors, animals' silhouettes, black-colored polygons. See the online article for the color version of this figure.

features resembling animals' silhouettes. We reasoned that novel items are represented mainly by encoding their basic features, as they lack semantic representations. By using this novel category, we aimed to dissociate the shared higher level activation and examine whether the mixed-category advantage would be further reduced when basic features are shared between the polygons and the animals.

Experiment 2

Experiment 1 demonstrated that low-level perceptual similarities affected the mixed-category advantage by decreasing its magnitude. To further explore this possibility, Experiment 2 was designed to replace the familiar category of body poses with an unfamiliar category of black-polygons silhouettes. This allowed us to investigate the effect of low-level perceptual similarities on a novel category, which is mainly represented by its basic features. We expected to observe a greater improvement in performance for polygons when they were mixed with the perceptually distinct category (i.e., colors) compared to the perceptually similar category (i.e., animals).

Method

Participants

Twenty-seven undergraduate students from Tel Aviv University (24 females, three males, ages 20–35) participated in the experiment that was conducted in the year 2021. The participants either received course credit or 40 NIS (approximately $13) per hour for participation. A consent form was obtained, and all participants had normal or corrected-to-normal vision.

Procedure and Materials

The experiment was conducted in an experimental room at Tel Aviv University, where a 23-in. computer screen (resolution 1,920 × 1,080) was used to display the task. Experiment 2 procedure was identical to Experiment 1(for results of same-category arrays of 1–3 stimuli, please see Appendix), with two exceptions—first, the stimuli involved were: colors, black-colored polygons, and animals' silhouettes (Figure 3, panel B); second, all subjects recognized the colors and animals categories; however, for the polygons category, participants were not familiar with the stimuli except for acknowledging that these stimuli represent geometric shapes.

Results and Discussion

Change-detection accuracy rates were typical for the change-detection task containing a set size of three stimuli ($M = 0.84$, $SD = 0.07$). Figure 4 presents d' for the nine experimental conditions (three same-category and six mixed-category conditions). A repeated-measures ANOVA on the d' means as the dependent variable revealed a significant main effect of display types, $F(8, 208) = 6.64$, $p < .001$, $\eta_p^2 = .78$. To further examine these differences, pairwise comparisons were conducted for each category between the mixed-category and the same-category conditions.

The Mixed-Category Advantage

The mixed-category advantage among familiar categories was replicated: animals benefitted from being mixed with colors, $F(1, 28) = 27.32$, $p < .001$, $\eta_p^2 = .49$, or with polygons, $F(1, 28) = 9.7$, $p = .009$, $\eta_p^2 = .25$, relative to their same-category performance. Furthermore, performance for colors in both mixed conditions slightly increased, although not significantly: when the colors were mixed with polygons, $F(1, 28) = 2.02$, $p = .201$, $\eta_p^2 = .28$, and when they were mixed with animals, $F(1, 28) = 2.09$, $p = .204$, $\eta_p^2 = .27$. It is worth noting that the mixed-category advantages for colors became significant in both Experiment 1 and the subsequent experiment. As for polygons, no improvement in sensitivity was observed in both mixed conditions; when polygons were mixed with colors, the performance was similar to their same-category performance, $F(1, 28) = 0.88$, $p = .39$. When polygons were paired with animals the performance decreased below that of their same category, resulting in a performance cost (outlined below).

The Effect of Perceptual Similarities in the Mixed-Category Advantage

An asymmetric increase in performance was found between animals' two mixed conditions—significantly higher sensitivity for animals when mixed with colors compared to when mixed with polygons, although this difference was not significant, $F(1, 26) = 4.7$, $p = .07$, $\eta_p^2 = .15$. As for polygons, being mixed with animals actually resulted in an impaired performance, $F(1, 26) = 10.75$, $p = .01$, $\eta_p^2 = .28$; namely, presenting three polygons together (i.e., polygons' same-category setting) yielded better performance than presenting one or two polygons with two or one animals, $F(1, 26) = 17.01$, $p = .001$, $\eta_p^2 = .39$.

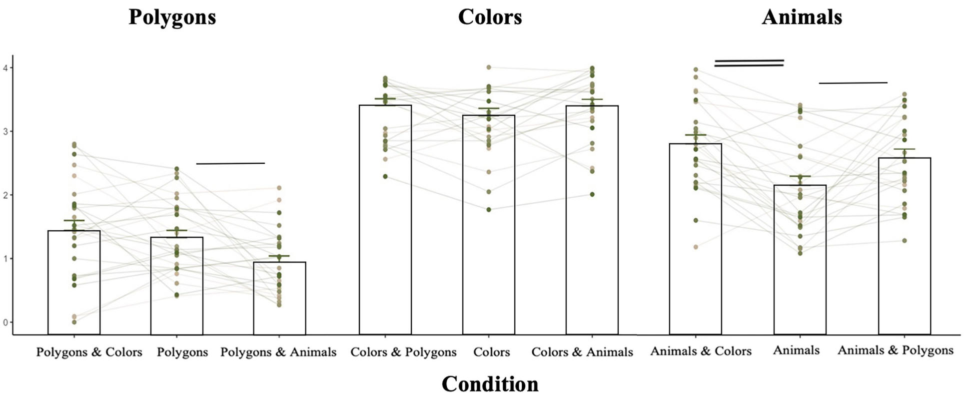
Experiment 2 yielded new insights into the mixed-category pattern by mixing a novel category (polygons) with a familiar category (animals) that share low-level features. When polygons shared basic features with the other category, their sensitivity was even impaired, causing their performance to decrease below that of their same category. As polygons lack semantic representation, these results provide further support for the notion that low-level similarities impact the mixed-category advantage.

A possible explanation for the asymmetric performance in the animals and polygons mixed conditions is that complex stimuli require extra encoding time (Alvarez & Cavanagh, 2004; Luria et al., 2010). If the reason for the poor performance of polygons and animals when they are mixed is insufficient encoding interval, then extending this interval should result in better performance in this mixed condition. When complex stimuli, such as random polygons, are combined with another category, participants may focus on encoding the other (simpler) category, leading to limited time available for encoding the complex polygons. However, when three polygons are presented, participants are compelled to encode all three polygons. As a result, participants had better memory performance for the condition with three polygons compared to conditions with one or two polygons. Therefore, we reasoned that allocating more time for encoding the stimuli would result in improved performance for polygons in the mixed conditions. Thus, Experiment 3 tested whether increasing the encoding interval improves performance for polygons, specifically—in their mixed conditions.

Experiment 3

In Experiment 3, participants had 500 ms to encode the stimuli in all conditions. According to the literature, increasing the encoding

Figure 4
Sensitivity (d′) in the Same and Mixed Conditions



Note. Polygons, colors, and animals, respectively; each category holds three conditions: two mixed conditions and one (middle column) is the same-category condition. For each category, the mixed-condition headlines represent the averaged sensitivity for the category's probes when the memory display contained the relevant category alongside another category in all possible displays (i.e., one stimulus from the relevant category + two stimuli from the other category and two stimuli from the relevant category + one stimulus from the other category). Each condition holds mean d' (box plots) + SE along with the subject trend separated by color. The lines on top represent the significant differences between the conditions, where a double line represents $p > .001$, and a single line represents $.001 < p < .05$. See the online article for the color version of this figure.

time should improve performance for complex stimuli (Alvarez & Cavanagh, 2004; Luria et al., 2010). As a result, we hypothesized that a longer time interval would lead to a general improvement in performance for the polygons. Additionally, we anticipated that sensitivity to the animals might also improve when combined with polygons as compared to the performance in Experiment 2, as more time would be available for the animals to be encoded.

Method

Participants

Twenty-nine undergraduate students from Tel Aviv University (23 females, six males, ages 19–31) participated in the experiment that was conducted in the year 2021. The participants either received course credit or 40 NIS (approximately $13) per hour for participation. A consent form was obtained, and all participants had normal or corrected-to-normal vision.

Procedure and Materials

Experiment 3 was identical to Experiment 2 (for results of same-category arrays of 1–3 stimuli, please see Appendix), with one exception, the memory array was presented for 500 ms instead of 230 ms, whereby participants were instructed to memorize the entire array. Similar to Experiment 2, subjects recognized the colors and animals' categories; however, for the polygons category, participants were not familiar with the stimuli except for acknowledging that these stimuli represent geometric shapes.

Results and Discussion

The mean accuracy rate in arrays with a set size of three stimuli was 0.85 ($SD = 0.13$). Figure 5 presents d' for the nine experimental conditions (three same-category and six mixed-category conditions). A repeated-measures ANOVA on the d' as the dependent variable revealed a significant main effect of display types (same-category, mixed-category) on participants' sensitivity to change, $F(8, 224) = 60.86$, $p < .001$, $\eta_p^2 = .68$. To further examine these differences, pairwise comparisons were conducted within each category, between the mixed-category and the same-category conditions.

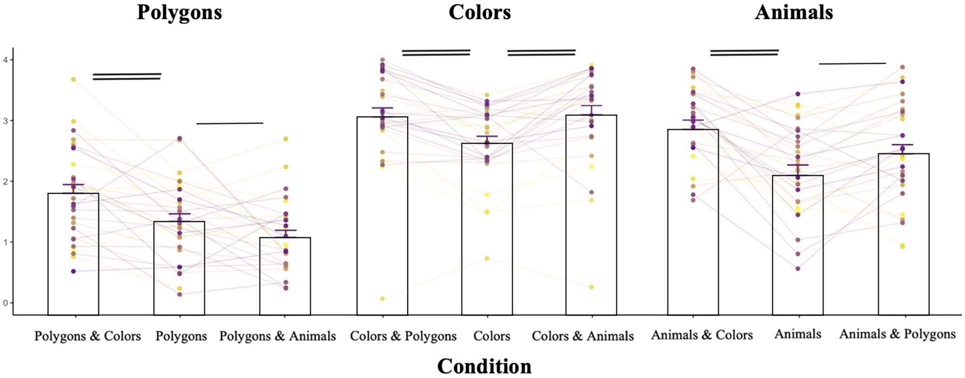
The Mixed-Category Advantage

The mixed-category advantage was found for both the familiar and the novel categories. Colors' performance improved in each mixed condition compared to their same-category performance; when were paired with polygons, $F(1, 28) = 24.7$, $p < .001$, $\eta_p^2 = .47$, and when they were paired with animals, $F(1, 28) = 20.61$, $p < .001$, $\eta_p^2 = .42$. There was no difference in the advantage size between the two colors' mixes, $F(1, 28) = 0.12$, $p = .73$. As for the animals, sensitivity was significantly improved in each mix compared to their same-category condition; when were mixed with colors, $F(1, 28) = 30.1$, $p < .001$, $\eta_p^2 = .52$, and when they were mixed with polygons, $F(1, 28) = 7.46$, $p = .013$, $\eta_p^2 = .21$. At last, polygons benefited only from being mixed with colors, $F(1, 28) = 14.63$, $p = .001$, $\eta_p^2 = .34$.

The Effect of Perceptual Similarities in the Mixed-Category Advantage

Although presenting the stimuli for 500 ms, the asymmetric pattern between the two mixed conditions was replicated for animals and for polygons; we found a smaller improvement for animals' probes in the animals & polygons mix relative to when animals were presented with colors, $F(1, 28) = 8.64$, $p = .009$, $\eta_p^2 = .23$ (see Figure 5, right panel). As for polygons, being paired with animals resulted in a performance cost for the polygons as compared to

Figure 5
Sensitivity (d′) *in the Same and Mixed Conditions*



Note. Polygons, colors, and animals, respectively; each category holds three conditions: two mixed conditions and one (middle column) is the same-category condition. For each category, the mixed-condition headlines represent the averaged sensitivity for the category's probes when the memory display contained the relevant category alongside another category in all possible displays (i.e., one stimulus from the relevant category + two stimuli from the other category and two stimuli from the relevant category + one stimulus from the other category). Each condition holds mean d' (box plots) + SE along with the subject trend separated by color. The lines on top represent the significant differences between the conditions, where a double line represents $p > .001$, and a single line represents $.001 < p < .05$. See the online article for the color version of this figure.

performance in polygons-only array, $F(1, 28) = 4.5$, $p = .047$, $\eta_p^2 = .13$.

Follow-up contrasts, that compared the mixed-category effects over Experiments 2 and 3 (i.e., 230 and 500 ms, respectively), revealed that time-extension improved sensitivity only for polygons when they were mixed with colors, $F(1, 54) = 14.63$, $p < .001$, $\eta_p^2 = .34$; conversely, in the animals & polygons mix, no difference in performance emerged neither for the polygons, $F(1, 54) = 0.48$, $p = .49$, nor for the animals, $F(1, 54) = 0.17$, $p = .68$. Moreover, no difference in performance was found for polygons between their same-category conditions, $F(1, 54) = 0.008$, $p = .92$. The reason for the improved sensitivity for polygons in the mixed condition, which involved two polygons, compared to the same-category condition, which had three polygons, may be attributed to the capacity limit for processing complex stimuli in the polygons' same-category condition.

Experiment 3 showed that sensitivity to complex stimuli improved when increasing the encoding time—this effect was evident for polygons in the polygons and colors mix. However, prolonging the encoding interval did not affect performance for the polygons when these were paired with animals—resulting in the same asymmetric pattern observed in Experiment 2 with a 230 ms encoding interval.

The interpretation put forth by Avital-Cohen and Gronau (2021) offers a potential explanation for the observed pattern when combining polygons and animals. According to their attentional account interpretation, animals may elicit greater attentional capture compared to polygons due to their meaningful nature. This differential attention allocation could result in a mixed-category advantage favoring animals while providing disadvantage for polygons. However, the intriguing finding of a significant performance improvement of colors when they were mixed with animals challenges this explanation. Given that animals are considered meaningful stimuli with biological or social inherent significance one would expect no improvement in memory for colors. However, we found significant advantages for colors when they were mixed with animals. Therefore, in the General Discussion, we propose a mechanism of deactivation of perceptual features to account for this effect.

General Discussion

The present study investigated the impact of feature similarities between categories on creating the asymmetric mixed-category effect. In three experiments, we presented three categories either separately or paired, and importantly, two of these categories shared similar "basic" features. Our primary conclusion is that items' similarity at the perceptual level has an important role in the determining the asymmetric performance in the mixed-category phenomenon, such that the mixed-category benefit decreased once the mixed categories shared basic features compared to when they were perceptually distinct and when the category lacked a semantic level of representation, we even observed a mixed-category cost. Our results highlight that the cognitive system relies on category division processes (arguably at various levels of processing) when maintaining information. The mixed-category effect is evidence that high-level category information could be used to increase memory performance, but once these categories share basic features, this low-level information is able to reduce and even eliminate this benefit.

Considering the viewpoint that working memory storage is feature-specific to some extent (as indicated by Honkanen et al., 2015; Wheeler & Treisman, 2002), one could argue that our manipulation primarily focused on the diagnostic feature upon which the task was performed (shape vs. color), rather than the perceptual similarity of the stimuli. Consequently, in the body-animals mixed condition, participants needed to engage in a task involving stimulus outlines, whereas when either of the two categories was intermixed with colors, the task involved fewer colors and shapes. Since poses and animals in Experiment 1 (as well as polygons and animals in

Experiments 2 and 3) shared similar basic features, this account predicts similar performance for mixed animals and poses compared to their same-category conditions. However, our results showed that memory improved for the mixed condition (for poses in Experiment 1 and for animals in Experiments 2 and 3), as compared to performance in the same-category condition. thus, this diagnostic feature account cannot fully explain our results.

When evaluating prior theories, the cortical overlaps theory (Cohen et al., 2014) offers a comprehensive explanation for the observed asymmetric advantages in the current research. It is possible that sharing basic features produces overlap in activation at low-level representations, which eventually reduces feature availability. Clearly, the unique category-specific interference theory (Jiang et al., 2016), which suggests that the mixed-category advantage is primarily determined by intercategory interference rather than between-category interference, fails to account for the results of the current study. This theory cannot explain why the mixed-category advantage increases once paired with a perceptually distinct category, compared to when both share basic features.

Interestingly, neither the cortical overlaps theory (Cohen et al., 2014) nor the unique category-specific interference theory (Jiang et al., 2016) can successfully account for the impaired performance of the novel category in both Experiments 2 and 3. Namely, performance for the novel items (i.e., polygons) was impaired when presented with stimuli sharing their basic features (i.e., animals) relative to their same-category performance. The cortical overlaps theory (Cohen et al., 2014) fails to explain this pattern because this theory argues that animals and polygons consume the same low-level resources, thus it does not matter from which category the items come from. As for the unique category-specific interference theory (Jiang et al., 2016), the prediction is the opposite outcome to what resulted. The reason is that according to Jiang et al., the sensitivity should have been higher for one or two polygons mixed with animals because there is less interference than when three polygons are presented. The theory that can account for the impaired performance of the polygons is the inherent attentional bias (Avital-Cohen & Gronau, 2021), which claims that participants' attention was biased toward the biologically significant category (i.e., animals). However, as mentioned before, this theory would face challenges in explaining the significant advantages for colors when they were combined with animals.

Since the current theories cannot account for the deceased sensitivity for polygons when they are presented with animals relative to when polygons are presented alone, in what follows, we suggest an additional process that aims to explain the nature of this effect. The current set of results demonstrated an interaction between the low-level and high-level representations; thus, we further specify such a potential mechanism. Specifically, we propose that the higher level (e.g., semantic) representation of the items elicits the deactivation of its basic features.

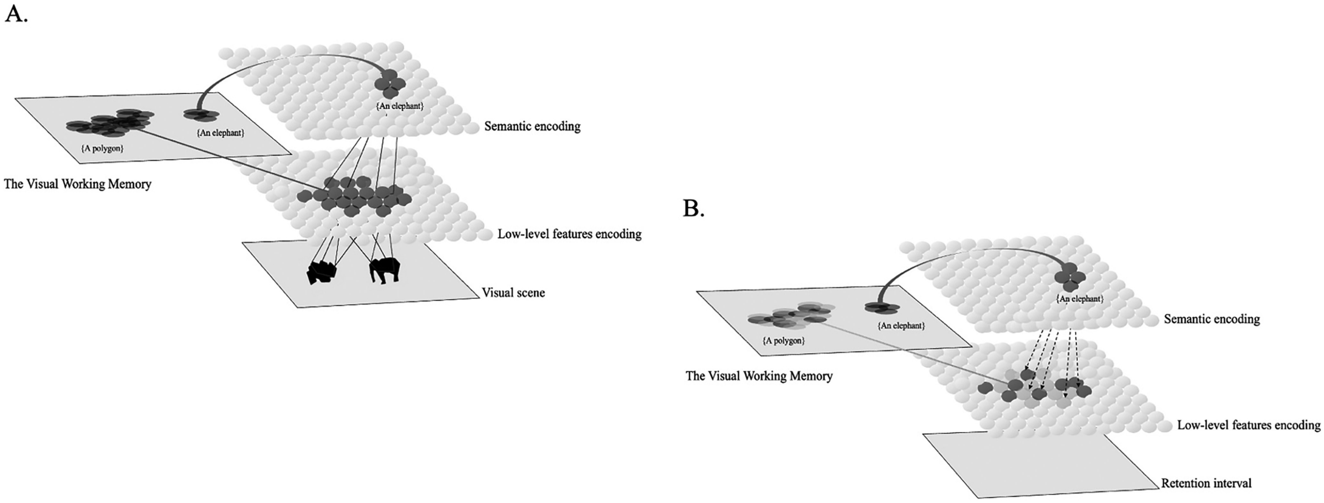
Deactivation plays part in cognitive processes such as inhibition in perception and selective attention (Tipper et al., 1994), memory (Johnson et al., 2009), and behavioral control (Logan & Cowan, 1984). Here, we suggest that deactivation of low-level features is involved when encoding to the VWM stimuli with high-level representations (e.g., semantic encoding). Namely, when participants capture a geometric shape of an elephant, VWM maintains its semantic representation, and in turn, its basic features are being turned off. According to this theoretical suggestion, when animals and polygons were paired, animals were maintained in VWM by their high-level representations, but their basic features (i.e., orientations, color) were deactivated. But why was sensitivity impaired for polygons in this condition? We reason that polygons lack semantic representation, so they are primarily maintained by their basic features. Accordingly, the poor memory for one or two polygons when mixed with animals is due to the deactivating effect of the animals on the polygons' representation. Namely, when polygons were mixed with animals, animals' high-level representations deactivated the animals' basic features, but importantly, these are the same features composing the polygons, thus this deactivation affected the polygons' performance as well (see Figure 6 for an illustration of the suggested mechanism). Thus, although fewer polygons were presented when mixed with animals than in their same-category condition, their representation suffered from the deactivation triggered by the animals' category. In the same-category condition of polygons, only items that lacked semantic representation were included, which resulted in the absence of deactivation of their basic features. As a result, the sensitivity was higher when presenting only polygons, compared to when polygons were paired with animals.

Interestingly, the same logic can explain part of the asymmetric advantages observed among animals and body poses across their mixed conditions—wherein the mixed-category advantage was more pronounced when paired with a category that differed in basic features, compared to when both shared low-level similarities. When body poses and animals were paired, the presence of semantic representations led to the deactivation of their basic features. Since animals and body poses share similar basic features, the same features were deactivated by the two categories. This resulted in greater deactivation than when each category was mixed with colors. Being mixed with colors resulted in each item deactivating its own features, and due to the perceptual difference between the two categories, no overlap in deactivation occurred. Our model cannot directly explain the observed asymmetry between two semantic categories, but note that the model can rely on previous accounts that address asymmetric performance between semantic categories (Avital-Cohen & Gronau, 2021, Cohen et al., 2014).

It is important to note that our interpretation focuses on addressing a specific aspect of the mixed-category asymmetric pattern, specifically at the level of basic features. In contrast, other theories primarily interpret this pattern in terms of high-level interactions between categories. These theories commonly employ semantic categories (e.g., faces, bodies, objects) with no control of their basic features, making it challenging to directly link the results to our proposed mechanism. Nevertheless, there are relevant connections to previous arguments and findings. One can be seen in the Jiang et al.'s (2016) asymmetric advantages in Experiment 4, where both faces and body parts showed greater benefits when paired with objects compared to being paired with each other. However, to determine whether similarities in basic features influence this asymmetry, it is necessary to control for low-level similarities, which was not the primary objective of previous studies.

Hence, it's worth noting that our model was designed to account for the applications of low-level similarities between categories on mixed-category asymmetry. The model does not rule out any previously proposed mechanism for the basic cross-category asymmetry, rather, it adds a set of processes that can account for the effect of low-level similarities in the mixed-category phenomenon and provides clear predictions that can be tested by future research.

Figure 6
The Basic-Feature Deactivation Mechanism



Note. The suggested mechanism illustrates the deactivation of basic features of semantic stimuli in VWM. In a mixed-category condition where polygons and animals are paired, both items activate low-level encoding features like color and shape orientations. (A) Semantic representation emerges for the elephant, but not for the polygon. Both the semantic representation of the elephant and the basic features of both stimuli are stored in VWM. (B) The semantic representation of the elephant deactivates the shared low-level features for both the elephant and the polygon. As a result, the VWM representation of the polygon significantly decreases since it is mostly represented by basic features. VWM = visual working memory.

Our interpretation of the mixed-category asymmetry effect is premised on the idea that VWM involves deactivation processes when the encoded items are represented at higher levels. Future studies can test our proposed mechanism in different conditions, such as by mixing novel categories that share basic features. Our model predicts that memory performance in the mixed conditions will be similar to the novel stimuli same-category condition because we argue that deactivation is triggered by the semantic level of the category such that there should not be any basic-feature deactivation among novel stimuli. Furthermore, a potential direction for further investigation could involve varying the extent to which the two categories are similar in their basic features. (e.g., by pairing bodies with black silhouettes of animals and varying the scale of similarity in orientations).

Constraints of Generality

In order to generalize effectively, it is important to consider participants within the appropriate age range for visual perception. While future studies may choose to use different stimuli, it is crucial to maintain the timing of the VWM mechanism.

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(*Appendix follows*)

Appendix

The Analysis of the Set Size Effect in the Same-Category Conditions for the Categories in All Experiments

Experiment 1

A Category (Colors/Animals/Poses) × Set Size (1–3) repeated-measures ANOVA performed on the accuracy revealed a significant main effect of category, $F(2, 26) = 32.7$, $p < .001$, $\eta_p^2 = .56$. Stimming that colors category gained higher accuracy as compared to both animals, $t(52) = 5.67$, Cohen's $d = 0.947$, $p < .001$, and poses, $t(52) = 7.37$, Cohen's $d = 1.05$, $p < .001$. A significant main effect was additionally obtained to set size, $F(2, 26) = 160.26$, $p < .001$, $\eta_p^2 = .86$. Stimming significant differences between the set sizes across categories, set size 1 compared to set size 2, $t(52) = 7.05$, Cohen's $d = 0.621$, $p < .001$; set size 1 compared to set size 3, $t(52) = 15.43$, Cohen's $d = 1.93$, $p < .001$ and, set size 2 compared to set size 3, $t(52) = 11.5$, Cohen's $d = 1.3$, $p < .001$. Moreover, a significant interaction between category and set size was emerged, $F(1, 19) = 12.17$, $p < .001$, $\eta_p^2 = .32$. Reflecting that the set size effect is larger for animals and poses categories as compared to colors category (set size 1 for colors compared to animals and poses, $t(135.65) = 2.59$, Cohen's $d = 0.89$, $p = .01$, set size 1 for animals compared poses, $t(135.65) = 0.43$, $p = .66$, set size 3 for colors compared to set size 3 for animals and poses, $t(135.65) = 10.43$, Cohen's $d = 2.34$, $p < .001$, set size 3 for animals compared to set size 3 for poses, $t(135.65) = 0.87$, Cohen's $d = 0.25$, $p = .38$, see Figure A1 for plotted results).

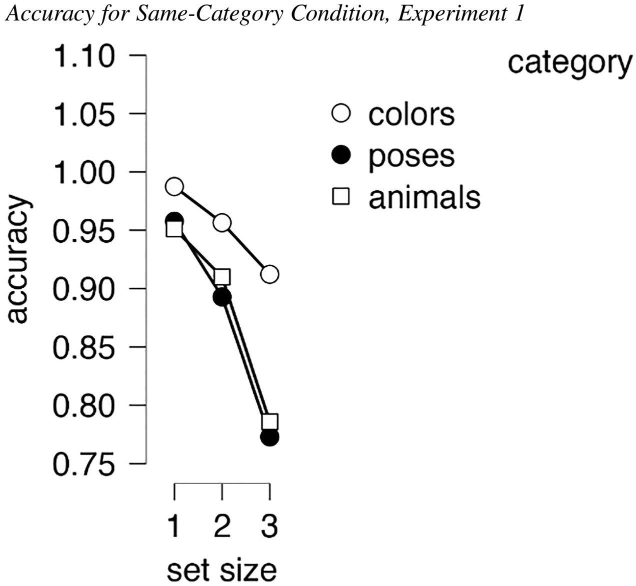
Experiment 2

A Category (Colors/Animals/Polygons) × Set Size (1–3) repeated-measures ANOVA performed on the accuracy revealed a significant main effect of category, $F(2, 26) = 118.38$, $p < .001$, $\eta_p^2 = .82$. Stimming that colors category gained higher accuracy as compared to both animals, $t(52) = 6.14$, Cohen's $d = 0.9$, $p < .001$, and polygons, $t(52) = 15.28$, Cohen's $d = 2.24$, $p < .001$; and higher accuracy for animals compared to polygons category, $t(52) = 9.14$, Cohen's $d = 1.34$, $p < .001$. A significant main effect was additionally obtained to set size, $F(2, 26) = 112.97$, $p < .001$, $\eta_p^2 = .81$. Stimming significant differences between the set sizes across categories, set size 1 compared to set size 2, $t(52) = 6.48$, Cohen's $d = 0.96$, $p < .001$; set size 1 compared to set size 3, $t(52) = 14.93$, Cohen's $d = 2.22$, $p < .001$ and, set size 2 compared to set size 3, $t(52) = 8.45$, Cohen's $d = 1.26$, $p < .001$. Moreover, a significant interaction between category and set size was emerged, $F(1, 19) = 25.88$, $p < .001$, $\eta_p^2 = .50$. Reflecting that the set size effect is larger for animals and polygons categories as compared to colors category (set size 1 for colors compared to animals and polygons, $t(149.68) = 2.17$, Cohen's $d = 0.61$, $p = .032$, set size 1 for animals compared polygons, $t(149.68) = 1.7$, Cohen's $d = 0.33$, $p = .09$, set size 3 for colors compared to set size 3 for animals and polygons, $t(149.68) = 13.06$, Cohen's $d = 3.1$, $p < .001$, set size 3 for animals compared to set size 3 for poses, $t(149.68) = 8.23$, Cohen's $d = 1.8$, $p < .001$, see Figure A2 for plotted results).

Experiment 3

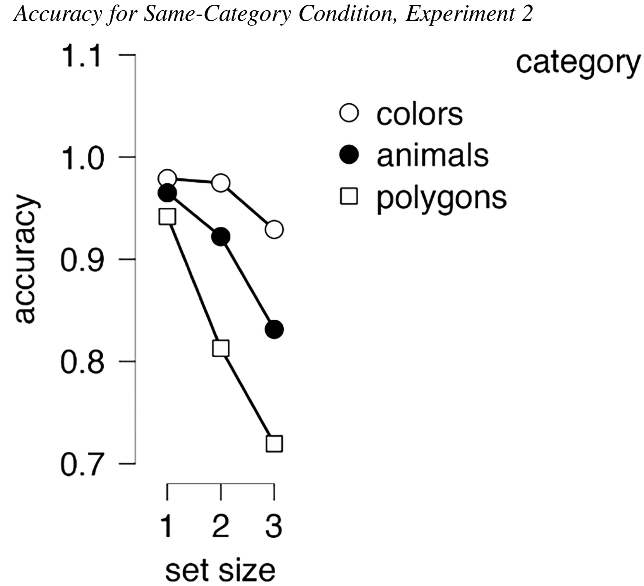
A Category (Colors/Animals/Polygons) × Set Size (1–3) repeated-measures ANOVA performed on the accuracy revealed a significant main effect of category, $F(2, 28) = 42.11$, $p < .001$, $\eta_p^2 = .61$. Stimming that colors category gained higher accuracy as compared to both animals, $t(56) = 3.63$, Cohen's $d = 0.46$, $p = .002$, and polygons, $t(56) = 9.11$, Cohen's $d = 1.16$, $p < .001$;

Figure A1
Accuracy for Same-Category Condition, Experiment 1



Note. Accuracy for colors, poses, and animal categories across set size 1–3 in the same-category condition in Experiment 1.

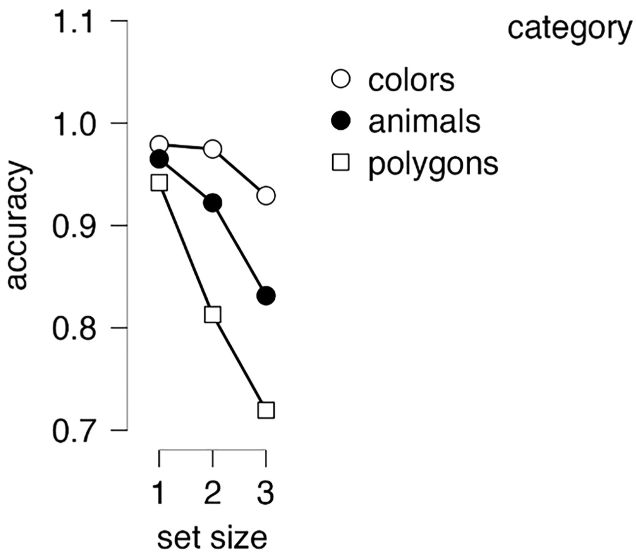
Figure A2
Accuracy for Same-Category Condition, Experiment 2



Note. Accuracy for colors, polygons, and animal categories across set size 1–3 in the same-category condition in Experiment 2

Figure A3

Accuracy for Same-Category Condition, Experiment 3



Note. Accuracy for colors, polygons, and animal categories across set size 1–3 in the same-category condition in Experiment 3.

and higher accuracy for animals compared to polygons category, $t(56) = 5.48$, Cohen's $d = 0.69$, $p < .001$. A significant main effect was additionally obtained to set size, $F(2, 28) = 106.77$, $p < .001$, $\eta_p^2 = .79$. Stimming significant differences between the set sizes across categories, set size 1 compared to set size 2, $t(56) = 5.1$, Cohen's $d = 0.51$, $p < .001$; set size 1 compared to set size 3, $t(56) = 14.41$, Cohen's $d = 1.46$, $p < .001$ and, set size 2 compared to set size 3, $t(56) = 9.3$, Cohen's $d = 0.94$, $p < .001$. Moreover, a significant interaction between category and set size was emerged, $F(1, 19) = 18.54$, $p < .001$, $\eta_p^2 = .38$. Reflecting that the set size effect is larger for animals and polygons categories as compared to colors category (set size 1 for colors compared to animals and polygons, $t(134.07) = 1.43$, Cohen's $d = 0.25$, $p = .155$, set size 1 for animals compared polygons, $t(134.07) = 1.48$, Cohen's $d = 0.29$, $p = .14$, set size 3 for colors compared to set size 3 for animals and polygons, $t(134.07) = 10.02$, Cohen's $d = 2.1$, $p < .001$, set size 3 for animals compared to set size 3 for poses, $t(134.07) = 5.58$, Cohen's $d = 0.98$, $p < .001$, see Figure A3 for plotted results).

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