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Separate Capacities for Storing Different Features in Visual Working Memory

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Recent empirical and theoretical work suggests that visual features such as color and orientation can be stored or retrieved independently in visual working memory (VWM), even in cases when they belong to the same object. Yet it remains unclear whether different feature dimensions have their own capacity limits, or whether they compete for shared but limited resources in VWM. In 3 experiments, participants memorized arrays of dual-feature objects, for which the number of feature values was fixed on one feature dimension and was varied on the other feature dimension. The results show that memory performance on the fixed dimension was not affected by the number of to-be-stored feature values on the other. These findings provide converging evidence that visual features can be encoded and stored separately in VWM if the task requires it, with each having its own capacity limit and little cross-dimensional interference.

Keywords: visual working memory, independent stores, feature, object

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Working memory is crucial for complex cognitive tasks, such as learning and reasoning (Baddeley, 1992, 2003, 2012). In the 1970s, Baddeley and Hitch (1974) proposed the concept of a multicomponent working memory in which visual and verbal information is stored separately in different subsystems, controlled by a central executive mechanism (see Baddeley, 2012, for a review). The separation of the visual and verbal subsystems has so far gained support from behavioral, lesion, and brain-imaging studies (for reviews, see Gathercole, 1994; Jonides et al., 2008; Smith & Jonides, 1997). The visual subsystem is now frequently referred to as visual working memory (VWM). The current study is an investigation of the possibility that VWM itself may be further carved up into separate storage modules for different visual features.

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Using a number of different tasks, researchers have shown that the capacity limit of VWM puts a severe constraint on human performance (Bays & Husain, 2008; Cowan, 2001; Fougnie, Asplund, & Marois, 2010; Luck & Vogel, 1997; Ma, Husain, & Bays, 2014; Pashler, 1988; Phillips, 1974; Prinzmetal, Amiri, Allen, & Edwards, 1998; Vogel & Machizawa, 2004; Zhang & Luck, 2008). It has been argued that the brain can counteract such constraints by binding small perceptual units (i.e., features) into integrated objects (Cowan, 2001; Delvenne & Bruyer, 2004; Hollingworth & Rasmussen, 2010; Lee & Chun, 2001; Luck & Vogel, 1997; Miller, 1956; Rensink, 2000; Scholl, 2001; Vogel, Woodman, & Luck, 2001; Zhang & Luck, 2008). In an influential demonstration, Luck and Vogel (1997) showed that memory performance in a change-detection task was virtually the same regardless of whether participants were required to memorize all features, or just one feature of each object, from an array of multiple-feature objects (see also Delvenne & Bruyer, 2004; Vogel et al., 2001). Although this finding has been taken as evidence that features are stored as integrated objects in VWM, it is also consistent with the idea that different features are stored separately, with each feature dimension having its own storage capacity. To rule out this possibility, Luck and Vogel (1997, see also Vogel et al., 2001) repeated the experiment with objects constructed with two feature values from the same feature dimension (color), and again found no deterioration in memory performance when both colors belonging to an item had to be remembered. Several follow-up studies, however, failed to replicate this important additional finding (Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu, 2002). Instead, these studies consistently showed that features from the same dimension interfere with each other and hamper memory performance, leaving open the possibility that "individual feature dimensions may be

stored in parallel feature-specific memory stores" (Wheeler & Treisman, 2002, p. 50).

The debate about whether VWM stores integrated objects continues (Awh, Barton, & Vogel, 2007; Fougnie et al., 2010; Fougnie, Cormiea, & Alvarez, 2013; Xu, 2002), but here it is important to acknowledge that feature- and object-based stores are not necessarily mutually exclusive. Depending on the task at hand, the human brain may flexibly draw on either feature- or object-based representations in VWM. Several recent studies have shown that the successful recall of one feature does not hinge on the successful recall of other features contained in the same visual item (Bays, Wu, & Husain, 2011; Fougnie & Alvarez, 2011; Fougnie et al., 2013), suggesting some independence between feature dimensions during either encoding or maintenance. Furthering this line of work, in the present study we sought to answer the question whether observers *can* draw on separate feature stores, by examining whether different feature dimensions compete for shared resources in VWM.

We conducted three experiments using the classic change-detection task (Luck & Vogel, 1997; see Figure 1). This task requires the participant to first memorize an array of briefly presented visual items (the sample display). Then, after a short retention interval, a test display is presented and the participant indicates whether any of the items differs from those presented in the sample display. In all experiments, the memory items were defined by color and orientation. In Experiment 1, the number of feature values was held constant at the value of two for one feature dimension (e.g., there were two different colors in the display), whereas the number of feature values systematically varied with item-set size on the other feature dimension between two and six (e.g., when there were six items, there were six different orientations). Note that typical estimates of VWM capacity are around three to four items (Cowan, 2001). If the two different feature dimensions compete for shared VWM resources, increasing the number of feature values to six on one of them should be detrimental to the other dimension as well. However, the results showed that memory performance for the constant feature dimension (with two feature values) was unaffected by the increase of feature values on the other dimension. Experiment 2 served to test whether observers would simply adopt the strategy of assigning all shared resources to the dimension of which there were only a few values at the expense of the variable dimension. We repeated the procedure, but we varied the number of feature values between two, four, and six on one dimension, and the number of feature values was kept fixed at six (rather than two) on the other dimension. Again, memory failures on the dimension with the fixed number of feature values did not vary with the number of feature values on the other dimension. Experiment 3 replicated the findings of Experiments 1–2 with a mixed design to exclude other potential strategic contributions. These findings, though they cannot settle the object versus feature debate in the literature, do provide clear evidence that the visual subsystem of working memory (Baddeley & Hitch, 1974) can draw upon separate modules for basic visual features.

Experiment 1

To test whether different feature dimensions have independent stores that do not interfere with each other, in Experiment 1, the number of feature values on one dimension was held constant at two, whereas the number of feature values on the other dimension was varied between two and six. In other words, we tested the effect that variation in set size within one dimension had on memory for the other dimension. Participants were asked to memorize the entirety of all objects, and changes could occur on any of the two object-defining feature dimensions. Typical estimates of VWM capacity are around three to four items (Cowan, 2001). If different feature dimensions compete for shared VWM resources, increasing the number of feature values to six in one dimension should lead to a degradation in memory performance for the other dimension.

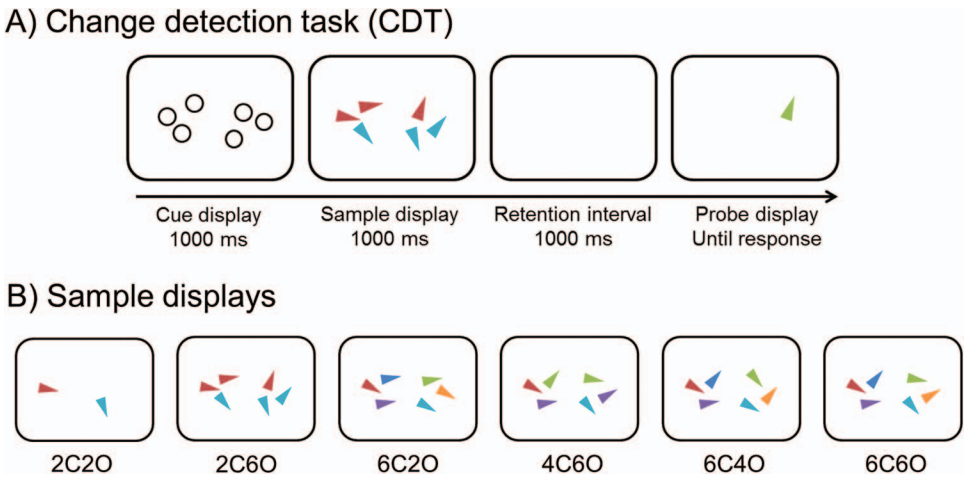


Figure 1. (A) A schematic illustration of the change-detection task. (B) The stimuli used in the present experiments. Letters "C" and "O" denote color and orientation, respectively; the numbers before these letters denote the number of colors and orientations, respectively. For instance, the condition labeled "2C2O" had two colors and two orientations in the sample display. See the online article for the color version of this figure.

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Method

The research protocol reported here was approved by the institutional review board of Center for Cognition and Brain Disorders at Hangzhou Normal University.

Participants. Nine participants (two women, mean age = 25.6 years) were recruited from the local community. They all provided written informed consent and they reported normal color vision, and normal or corrected-to-normal visual acuity. They were paid 40 yuan/hr for their participation.

Apparatus. The experiments were conducted in a dimly lit laboratory. Visual stimuli were presented against a gray background (red–green–blue: 128, 128, 128) on a 21-inch cathode ray tube monitor, at a viewing distance of 71 cm. Stimulus presentation and response registration were controlled by scripts written in Python (www.python.org).

Stimuli, procedure, and design. In Experiment 1, to-be-memorized visual items were colored triangles (see Figure 1B). The color of these triangles was randomly selected from eight colors, evenly distributed along a circle in the International Commission on Illumination (CIE) $L^*a^*b^*$ color space (centered at L = 70, a = 5, b = 0, with a radius of 40). The orientation of these triangles was randomly selected from eight values (10–325°, in 45° steps). These visual items could appear at any of eight locations, evenly distributed along the circumference of two invisible circles (radius: 4°) centered on the horizontal meridian, 9° from the center of the display. To prevent adaptation, each location was randomly jittered by 0.5° in both horizontal and vertical directions on each trial.

The sequence of events in the change-detection task is illustrated in Figure 1A. To promote fast encoding, each trial began with the presentation of an array of cues for 1000 ms, signaling the locations of the to-be-memorized objects in the sample display. Then, the sample display was presented for 1000 ms, followed by a retention interval (1000 ms) and a test display. Only one item (probe) was presented in the test display and the participant indicated whether this item was the same as the one presented at the same location in the sample display, by pressing the "Z" (no) or "/" (yes) key on a standard "QWERTY" keyboard. All experiments in the present study used single-probe test displays to minimize the effect of decision factors on the assessment VWM (Awh et al., 2007; Palmer, 1990). After an intertrial interval (ITI) of 500 ms, the next trial began.

Every to-be-memorized visual item was defined by both its color and orientation. The set sizes tested were two and six. When the set size was two, two colors and two orientations were contained in the sample display. When the set size was six, one feature dimension (orientation or color) had six values and the other feature dimension had only two values, which were always equally distributed across the items. Thus, one feature dimension always had the same number of values as the set size, whereas the other feature dimension had only two values regardless of set size. For convenience, we will refer to these two feature dimensions as variable and fixed dimensions, respectively. Within a block, no change occurred on a random one third of the trials; on the remaining trials, changes occurred equal probably to either feature dimension (color or orientation).

Each participant completed three blocks of 180 trials: (a) two items with two colors and two orientations (2C2O), (b) six items with six colors and two orientations (6C2O), and (c) six items with two colors and six orientations (2C6O). These three blocks were counterbalanced across participants.

Results

The results of Experiment 1 are presented in Figure 2. Repeated-measures ANOVA on overall change-detection accuracies showed that there were significant differences between the 2C2O, 6C2O, and 2C6O conditions, $F(2, 16) = 63.43$, $p < .001$, partial $\eta^2 = 0.89$. Replicating previous findings (e.g., Luck & Vogel, 1997), the overall change-detection accuracy was much lower when the set size was six than when the set size was two, for both the 2C6O condition, $t(8) = 12.51$, $p < .001$, and 6C2O condition, $t(8) = 13.15$, $p < .001$ (Figure 2A, left panel).

The overall false-alarm rates were 6% (±2%) in the 2C2O condition, 29% (±3%) in the 6C2O condition, and 29% (±5%) in the 2C6O condition. Note that with the current design, a false-alarm response meant that the participant either assumed a color or an orientation change, but there was no objective way to determine which of the two it was, so we could neither determine false-alarm rates nor overall percent correct separately for each feature dimension (see Xu, 2002 for similar reasoning). Instead, we focused our analysis on the hit rate (i.e., the proportion of trials in which participants responded "no, not the same" when a change had actually occurred), which can be computed separately for color and orientation. Repeated-measures ANOVA on hit rates showed that there were significant differences between conditions, $F(2, 16) = 17.08$, $p < .001$, partial $\eta^2 = 0.68$. Moreover, the hit rate was much lower when the set size was six, for both the 2C6O condition, $t(8) = 7.87$, $p < .001$, and 6C2O condition, $t(8) = 5.74$, $p < .001$ (see Figure 2A, right panel). To reveal whether different feature dimensions competed for shared VWM resources, it is important to determine whether the memory performance on the fixed dimension was affected by the number of feature values on the variable dimension. Two separate ANOVAs were performed for color-fixed conditions (2C2O and 2C6O) and orientation-fixed conditions (2C2O and 6C2O), with factors Variable Set Size (two vs. six) and Change Type (color vs. orientation change).

Analysis of color-fixed conditions. The results for the color-fixed conditions are presented in Figure 2B. Significant main effects were found for Variable Set Size, $F(1, 8) = 32.92$, $p < .001$, partial $\eta^2 = 0.8$, and Change Type, $F(1, 8) = 32.53$, $p < .001$, partial $\eta^2 = 0.8$. A significant interaction between Variable Set Size and Change Type was also observed, $F(1, 8) = 36$, $p < .001$, partial $\eta^2 = 0.82$, which is critical. The two-way interaction occurred because the hit rate for orientation changes decreased with set size, $t(8) = 6.13$, $p < .001$, whereas that for color changes did not, $t(8) = 1.07$, $p = .314$. The slope of the decline was much steeper for orientation change (−8.7%/item) than for color change (0.46%/item), $t(8) = 6.0$, $p < .001$.

Analysis of orientation-fixed conditions. The results for the orientation-fixed conditions are presented in Figure 2C. Significant main effects were observed for Variable Set Size, $F(1, 8) = 61.88$, $p < .001$, partial $\eta^2 = 0.89$, and Change Type, $F(1, 8) = 28.83$, $p < .01$, partial $\eta^2 = 0.78$. Again, a significant interaction between Variable Set Size and Change Type was observed, $F(1, 8) = 33.51$, $p < .001$, partial $\eta^2 = 0.8$. The hit rates for color changes, $t(8) = 9.27$, $p < .001$, and orientation changes,

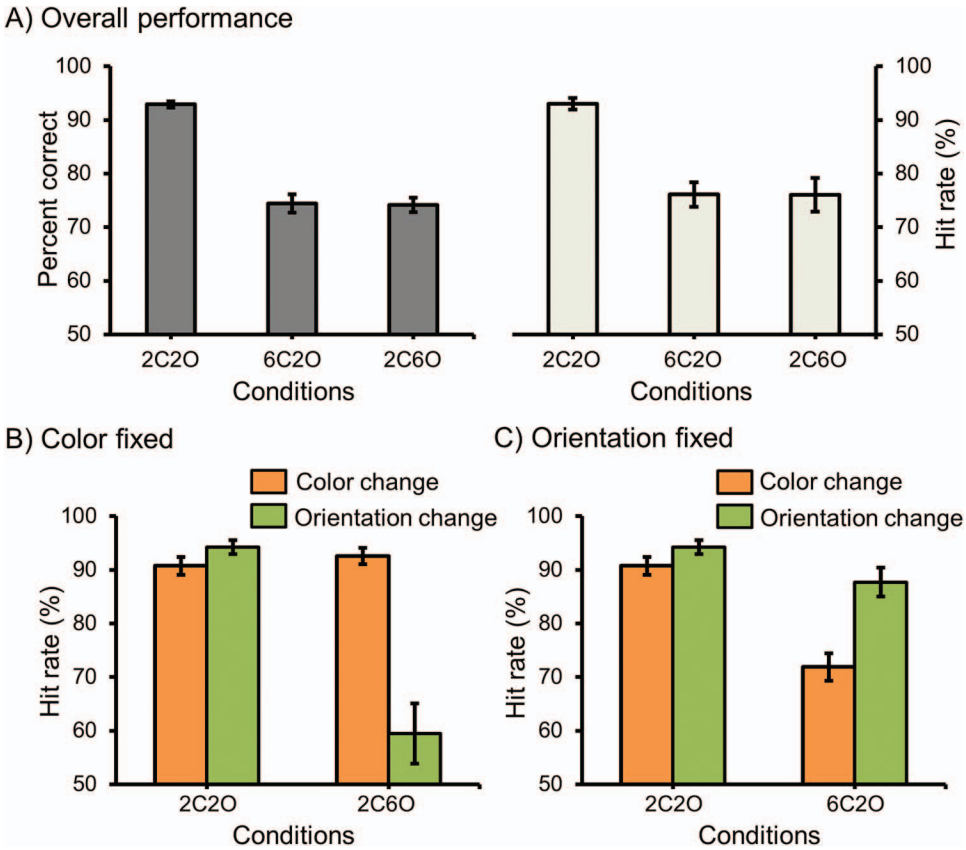


Figure 2. The results of Experiment 1. (A) Overall change-detection accuracies and hit rates; (B–C) hit rates for color and orientation changes in the color-fixed and orientation-fixed conditions. Error bars denote ± SEM. See the online article for the color version of this figure.

$t(8) = 3.93$, $p = .004$, both decreased with set size. The two-way interaction occurred because the slope of the decline was much steeper for color change (−5.93%/item) than for orientation change (−2.27%/item), $t(8) = 5.79$, $p < .001$.

Discussion

As is clear from Figure 2, the variation in the overall change-detection accuracy was mainly the result of failures to detect changes on the variable-feature dimension. Regardless of which dimension was varied, and which was fixed, the decline in hit rate, as a function of set size, was much steeper for the variable-feature dimension than for the fixed-feature dimension, indicative of a feature-based dissociation. This pattern of results is largely consistent with the idea of independent feature stores.

One might argue that the decline in hit rate reflected a more conservative response criterion rather than a decline in memory. For example, when observers see more orientations or more colors, they might be more careful in reporting a change. However, we consider this to be less likely because the decline was dimension-specific (i.e., strongest for the variable dimension). Moreover, the pattern for the overall percent correct, which included the correct rejections, followed that for the hit rate (see Figure 2A), which would not have been the case if participants simply became more conservative.

Note that the argument for independence hinges on performance on the fixed dimension as a function of set size in the variable dimension. If feature dimensions compete for shared VWM resources, a decrease in memory performance on the fixed dimension should be observed as the memory load increases on the variable dimension. For the color-fixed analysis, this did not happen; consistent with independent storage, color memory did not suffer from an increase in to-be-remembered orientations. For the orientation-fixed analysis, however, a small (3.5%) but statistically significant decline in hit rate for orientation was observed, as the color set size increased from two to six. This suggests some dependence, though the cross-dimensional interference was considerably weaker than the effect on orientation memory itself. Note that one design feature of Experiment 1 was that the total set size varied across conditions (i.e., the number of items varied together with the number of different features on the variable dimension). The increase in number of items per se may have contributed to decreased memory performance in the fixed-color condition. To control for this, the total number of items in Experiment 2 was kept constant, whereas only the number of features varied (on one feature dimension).

Furthermore, one may argue that performance on the fixed-feature dimension did not change much with set size because observers strategically gave priority to this dimension. Note that

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the total number of feature values (two) on this dimension was well within the typical estimation of VWM capacity of three to four items, whereas the other dimension often exceeded the capacity limit (containing up to six feature values). Observers may have decided to take the easy route to encode and maintain the fixed-feature dimension first, and to allocate whatever capacity was left to the other, variable-feature dimension. Such a strategy would, for example, allow for grouping on the basis of similarity, a higher success rate in guessing, or a higher rehearsal rate for the fixed-feature dimension. To rule out this possibility, in Experiment 2, the fixed-feature dimension was set to have six rather than two values, whereas the variable-feature dimension varied between two, four, and six values. If observers prefer the easy route, they should prioritize the variable dimension and whatever shared capacity is left over should go to the fixed dimension. Consequently, as the number of feature values increases in the variable-feature dimension, a systematic decline in performance on the fixed-feature dimension should be observed.

Experiment 2

In this experiment, the total set size was kept constant at six. Furthermore, the number of to-be-memorized feature values was now fixed at six on one dimension (whether color or orientation), whereas it was varied between two, four, and six on the other dimension. In case of shared resources, increasing the number of values on one dimension should go at the expense of the fixed dimension, especially if people prioritize the dimension with fewer values, on average.

Method

Participants. In Experiment 2, 10 participants were tested (six women, mean age = 22.3 years).

Stimuli and design. In Experiment 2, the stimuli and task procedures were identical to those of Experiment 1, except for the following. The set size was fixed at six in all conditions. One feature dimension had six values and the other feature dimension had two, four, or six values. For convenience, we refer to these two feature dimensions as fixed (i.e., the number of feature values was the same as the set size) and variable, respectively.

Each participant completed five blocks, with the sample display containing six colors and two orientations (6C2O), six colors and four orientations (6C4O), two colors and six orientations (2C6O), four colors and six orientations (4C6O), or six colors and six orientations (6C6O). These five blocks were counterbalanced across participants, with each tested for 180 trials.

Results

The results of Experiment 2 are presented in Figure 3. As in Experiment 1, analyses were performed to see if the increase of feature values on one dimension affects the hit rate on the other dimension. Note that this time, the number of feature values on the fixed-feature dimension was constant, but the numbers on the variable-feature dimension changed across condition. The overall change-detection accuracy decreased as the number of feature values on the variable-feature dimension increased from two to six, in both the color-fixed conditions (see Figure 3A, left panel), $F(2, 18) = 12.85$, $p < .001$, partial $\eta^2 = 0.59$, and the orientation-fixed conditions (see Figure 3B, left panel), $F(2, 18) = 15.45$, $p < .001$, partial $\eta^2 = 0.63$.

The overall false-alarm rates were 49% (±5%) in the 6C6O condition, 32% (±3%) in the 2C6O condition, 45% (±4%) in the 4C6O condition, 43% (±5%) in the 6C2O condition, and 50% (±3%) in the 6C4O condition. The hit rate, as expected, also decreased as the number of feature values on the variable-feature dimension increased, in both the color-fixed conditions (Figure 3A, right panel), $F(2, 18) = 12.18$, $p < .001$, partial $\eta^2 = 0.58$, and the orientation-fixed conditions (Figure 3B, right panel), $F(2, 18) = 6.97$, $p = .006$, partial $\eta^2 = 0.44$.

As in Experiment 1, separate ANOVAs were performed on the hit rates of the color-fixed conditions (6C2O, 6C4O, and 6C6O) and orientation-fixed conditions (2C6O, 4C6O, and 6C6O), with Number of Feature Values (two, four, and six) on the variable-feature dimension and Change Type (color vs. orientation change) as factors.

Analysis of color-fixed conditions. The results for the color-fixed conditions are presented in Figure 3C. Significant main effects were observed for Number of Orientations, $F(2, 18) = 6.99$, $p = .006$, partial $\eta^2 = 0.43$, and Change Type, $F(1, 9) = 39.34$, $p < .001$, partial $\eta^2 = 0.81$. Critically, a significant interaction between Number of Orientations and Change Type was also observed, $F(2, 18) = 3.9$, $p = .039$, partial $\eta^2 = 0.3$. This interaction occurred because the hit rate decreased with the increase of the number of orientations for orientation changes (slope = −4.33%/value), $F(2, 27) = 11.58$, $p = .001$, partial $\eta^2 = 0.56$, but not for color changes (slope = 0%/value), $F(2, 27) = 0.06$, $p = .942$, partial $\eta^2 < 0.01$.

Analysis of orientation-fixed conditions. The results for the orientation-fixed conditions are presented in Figure 3D. Significant main effects were found for Number of Colors, $F(2, 18) = 12.18$, $p < .001$, partial $\eta^2 = 0.58$, and Change Type, $F(1, 9) = 7.61$, $p = .022$, partial $\eta^2 = 0.46$. Again, a significant interaction between Number of Colors and Change Type was also observed, $F(2, 18) = 17.57$, $p < .001$, partial $\eta^2 = 0.66$. This latter two-way interaction occurred because the hit rate decreased with the increase of the number of colors for color changes (slope = −2.21%/value), $F(2, 27) = 19.73$, $p < .001$, partial $\eta^2 = 0.69$, but not for orientation changes (slope = −0.21%/value), $F(2, 27) = 0.05$, $p = .955$, partial $\eta^2 < 0.01$.

Discussion

The results of Experiment 2 were clear-cut: Change-detection accuracy was, by and large, determined by memory performance on the dimension of which the number of features varied, and performance on the other dimension was not affected by the number of feature values on the variable dimension. These findings replicate those of Experiment 1, while controlling for additional factors (total number of objects, and whether or not the fixed set size was small or large), and further support the claim that different features have separate VWM capacities, in that they do not compete with each other for shared VWM resources.

One potential alternative explanation for the fact that performance for the fixed dimension remained constant across variations in the variable dimension here is that observers simply ignored the fixed dimension. Given that whichever feature was fixed was blocked, such a strategy might have been further promoted. The data nevertheless suggest that this is not likely the case because the hit rates remained

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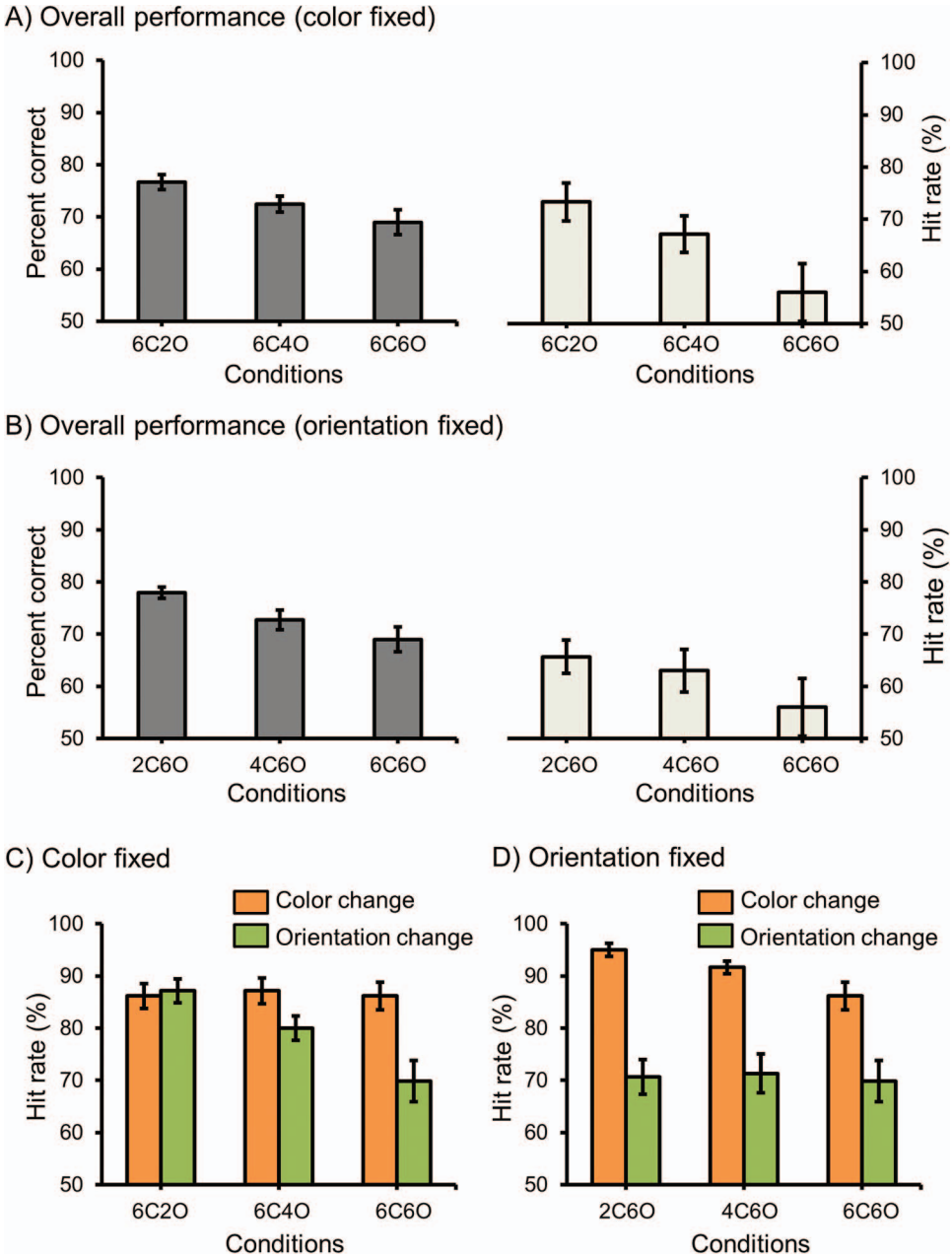


Figure 3. The results of Experiment 2. (A–B) Overall change-detection accuracies and hit rates in the color-fixed and orientation-fixed conditions; (C–D) hit rates for color and orientation changes in the color-fixed and orientation-fixed conditions. Same notations as Figure 2. Error bars denote ± SEM. See the online article for the color version of this figure.

well above chance for the fixed dimension (87% and 70%; see Figures 3C–D). This notwithstanding, we thought it prudent to replicate the results of Experiments 1 and 2 using a fully mixed design, rather than a blocked design, to see whether the results would hold, regardless of whatever strategy blocking might facilitate.

Experiment 3

Experiment 3 was carried out to control for potential contribution of strategies or attentional sets induced by blocking the variable- and fixed-feature dimensions, by testing the crucial conditions again with a mixed and fully balanced design.

Method

Participants. Experiment 3 had 12 participants (10 women, mean age = 19.8 years).

Stimuli and design. In Experiment 3, the stimuli and task procedures were identical to those of Experiments 1 and 2, except for the following. Four conditions (2C2O, 6C2O, 2C6O,

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and 6C6O) were mixed within blocks of trials. So, in each trial, whether two or six colors, or two or six orientations would be presented was totally unpredictable. As in Experiments 1 and 2, in a single block, no change occurred on one third of the trials; on the remaining trials, changes occurred with equal probability for both feature dimensions. All participants completed a total of four blocks of 180 trials over 2 successive days.

Results

Replicating the findings of Experiments 1–2, the overall change-detection accuracy decreased as the set size and the total number of feature values increased (see Figure 4A, left panel), $F(3, 33) = 106.02$, $p < .001$, partial $\eta^2 = 0.91$. The hit rate, on the other hand, decreased with set size and the total number of feature values to memorize (see Figure 4A, right panel), $F(3, 33) = 8.65$, $p < .001$, partial $\eta^2 = 0.44$. The overall false-alarm rates were 11% (±2%) in the 2C2O condition, 17% (±2%) in the 2C6O condition, 9% (±2%) in the 6C2O condition, 52% (±5%) in the 6C6O condition.

The primary purpose of Experiment 3 was to assess if the results of Experiments 1–2 were effectuated by the use of a blocked design. To this end, two sets of analyses were per-

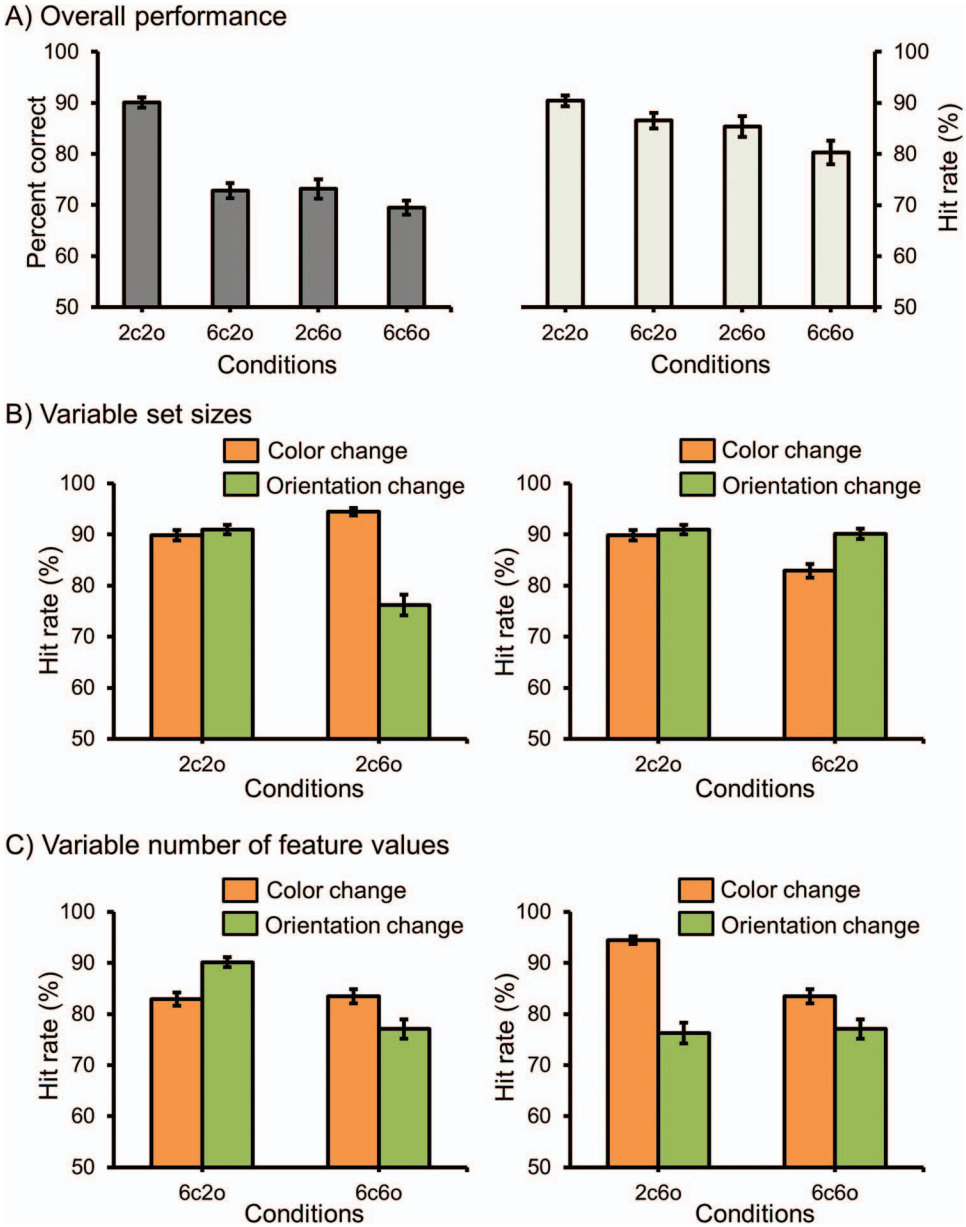


Figure 4. The results of Experiment 3. (A) Overall change-detection accuracies and hit rates; (B–C) hit rates for color and orientation changes in conditions included in the variable set sizes and variable number of feature-values analyses. Same notation as Figures 2 and 3. Error bars denote ± SEM. See the online article for the color version of this figure.

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formed: one with variable set sizes (2C2O vs. 2C6O, and 2C2O vs. 6C2O, as in Experiment 1) and one with variable number of feature values (2C6O vs. 6C6O, and 6C2O vs. 6C6O, as in Experiment 2).

Variable Set Sizes (Replication of Experiment 1)

For easy comparison with Experiment 1, ANOVAs were separately performed for color-fixed conditions (2C2O and 2C6O) and orientation-fixed conditions (2C2O and 6C2O).

Analysis of color-fixed conditions. The results for the color-fixed conditions are presented in Figure 4B (left panel). A significant main effect was found for Change Type, $F(1, 11) = 4.34$, $p = .061$, partial $\eta^2 = 0.28$. The main effect of Variable Set Size was marginally significant, $F(1, 11) = 4.34$, $p = .061$, partial $\eta^2 = 0.28$. Again, a significant interaction between Variable Set Size and Change Type was observed, $F(1, 11) = 37.93$, $p < .001$, partial $\eta^2 = 0.78$. The hit rate for orientation changes decreased with Set Size (slope = −2.21%/item), $t(11) = 4.22$, $p = .001$, whereas that for color changes actually increased with Set Size (slope = 0.69%/item), $t(11) = 2.14$, $p = .056$.

Analysis of orientation-fixed conditions. The results for the orientation-fixed conditions are presented in Figure 4B (right panel). A significant main effect was observed for Variable Set Size, $F(1, 11) = 5.65$, $p = .037$, partial $\eta^2 = 0.34$. The main effect of Change Type reached marginal significance, $F(1, 11) = 4.62$, $p = .055$, partial $\eta^2 = 0.3$. As in Experiment 1, a significant interaction between Variable Set Size and Change Type was observed, $F(1, 11) = 5.98$, $p = .032$, partial $\eta^2 = 0.35$, which is critical. This interaction occurred because the hit rate for color changes decreased with Set Size (slope = −1.04%/item), $t(11) = 3.37$, $p = .006$, whereas that for orientation changes did not change (slope = −0.13%/item), $t(11) = 0.41$, $p = .693$.

Variable Number of Feature Values (Replication of Experiment 2)

For easy comparison with Experiment 2, ANOVAs were also performed separately for color-fixed conditions (6C2O and 6C6O) and orientation-fixed conditions (2C6O and 6C6O), with Number of Feature Values (two vs. six) and Change Type as factors.

Analysis of color-fixed conditions. The results for the color-fixed conditions are presented in Figure 4C (left panel). A significant main effect was observed for Number of Orientations, $F(1, 11) = 13.78$, $p = .003$, partial $\eta^2 = 0.56$, but not for Change Type, $F(1, 11) = 0.04$, $p = .84$, partial $\eta^2 = 0.01$. A significant interaction between Number of Orientations and Change Type was observed, $F(1, 11) = 17.55$, $p = .002$, partial $\eta^2 = 0.62$, which is critical. This interaction occurred because as the number of orientations increased, the hit rate for orientation changes decreased (slope = −1.96%/value), $t(11) = 5.34$, $p < .001$, but did not for color changes (slope = 0.08%/value), $t(11) = 0.25$, $p = .808$.

Analysis of orientation-fixed conditions. The results for the orientation-fixed conditions are presented in Figure 4C (right panel). Significant main effects were found for Number of Colors, $F(1, 11) = 8.5$, $p = .014$, partial $\eta^2 = 0.44$, and Change Type, $F(1, 11) = 24.92$, $p < .001$, partial $\eta^2 = 0.69$. As in Experiment 2, the two-way interaction between Number of Colors and Change Type reached significance, $F(1, 11) = 15.16$, $p = .003$, partial $\eta^2 = 0.58$. As the number of colors increased, the hit rate for color changes decreased (slope = −1.65%/value), $t(11) = 6.28$, $p < .001$, but did not for orientation changes (slope = 0.13%/value), $t(11) = 0.3$, $p = .768$.

Discussion

Experiment 3 produced two important findings. First and foremost, in replicating the results of Experiments 1 and 2, feature-based dissociations in memory performance were observed, even with a mixed design. Consistent with the idea of independent feature stores, memory failures on each feature dimension are mainly determined by the number of feature values on the same dimension, rather than the total number of items to be memorized. Second, the important finding that feature dimensions do not interfere with each other was also replicated. Together, these findings show that memory performance on one feature dimension does not load on the other feature dimension, indicating that different feature dimensions do not compete for shared VWM resources.

General Discussion

Recent work has suggested that multiple features of the same object are not necessarily encoded or stored as an integrated representation in VWM, such that the chance of successfully encoding or retrieving one feature is independent of encoding or retrieving the other (Bays et al., 2011; Fougnie & Alvarez, 2011; Fougnie et al., 2013). The primary purpose of the present study was to directly test whether different feature dimensions had separate capacities, or competed for shared VWM resources.

In Experiment 1, the number of feature values was fixed at two for one feature dimension, whereas it varied with set size for the other feature dimension. Memory performance (hit rates) on the fixed-feature dimension were largely unaffected by the number of feature values on the other, variable-feature dimension, suggesting that little or no cross dimensional interference exists in VWM. This conjecture was further confirmed by Experiment 2, in which the number of feature values was fixed at six, rather than two, for one feature dimension, whereas the other feature dimension varied. In a final experiment, we ruled out the possibility that these observations were caused by potential strategies evoked by the blocked designs.

Taken together, the present findings favor the proposition that features can be stored independently in VWM (Heathcote, Walker, & Hitch, 1994; Isenberg, Nissen, & Marchak, 1990; Stefurak & Boynton, 1986; Wheeler & Treisman, 2002; Wolfs, Friedman-Hill, & Bilsky, 1994). Specifically, the observation that the memory load on one dimension does not affect the memory performance on the other dimension suggests that, rather than competing for shared VWM resources, different feature dimensions may recruit separate VWM modules, with

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each having its own capacity limit. Interference may also be suggested as an alternative explanation of the current results. That is, as the number of feature values on one feature dimension increases, the interference within this dimension increases because people are required to memorize a larger set of less discriminable features. Because interference is what happens when representations have to share the same resources, such an interference account is fully compatible with our conclusion on separate feature capacities.

It is a well-established fact that visual features, such as color, orientation, and spatial frequency, are processed by separate brain modules (Conway, 2009; Issa, Trepel, & Stryker, 2000; Kourtzi & Kanwisher, 2000; Paik & Ringach, 2011; Zeki et al., 1991). Other studies have demonstrated that the same brain regions that encode separate features can also maintain information across a relatively long period of time (Pasternak & Greenlee, 2005; Serences, Ester, Vogel, & Awh, 2009). Thus, the idea of independent feature stores in VWM not only is backed by behavioral findings, but is also neurally plausible. This is not to say that the brain does not represent and store objects, too; the activation of the intraparietal sulcus and the lateral occipital complex—regions believed to represent objects—is known to correlate with the number of objects held in VWM (Todd & Marois, 2004; Xu & Chun, 2006). As we argue next, feature- and object-based stores are not necessarily mutually exclusive.

Implications for the Object-Based Theory of VWM

Partly fueled by the widely held assumption that visual features need to be bound into unitary objects (Kahneman, Treisman, & Gibbs, 1992; Treisman, 1996) and the canonical view that "chunking" is an efficient strategy to circumvent the capacity limit of short-term memory (Miller, 1956), the theory that VWM stores integrated objects has gained a strong foothold in the field (Delvenne & Bruyer, 2004; Hollingworth & Rasmussen, 2010; Luck & Vogel, 1997; Rensink, 2000; Scholl, 2001; Vogel et al., 2001; Zhang & Luck, 2008). The present study was not set out to refute this idea. Nevertheless, we believe the results may have some implications for such theories. If integrated objects are *the* storage unit in VWM, the driving factor for VWM performance should only be the number of objects. However, our experiments revealed that when participants were instructed to memorize visual items defined by two feature dimensions, performance on each dimension was determined by the number of feature values on that dimension, rather than by the total number of visual objects in the display. This important finding puts new constraints on the object-based theory of VWM.

The present findings do not rule out the possibility that VWM can also store integrated objects, but they do pose a challenge to the object-based theory of VWM. It is likely that VWM is hierarchically organized, with storage spaces for both features and objects. In this hierarchical store, depending on the requirements of the task at hand, attention flexibly selects which VWM store to tap into. In change-detection tasks that only require the participant to detect a feature change, as in the present experiments, the feature stores rather than the object stores might be recruited; for change-detection tasks that involve comparing complex objects (e.g., Awh et al., 2007), the object store might be recruited instead. Furthermore, in contrast to the rather ad hoc conjunctions of features used in the current and many VWM experiments, everyday objects may be more likely to tap into the integrated object store, because the familiarity of these objects may make it difficult to perceptually decompose them into the separate features of which they consist (e.g., Melcher, 2001; Rensink, 2000). Moreover, differences in working memory capacity and processing times between everyday objects and ad hoc feature conjunctions also suggest differences in representation (Alvarez & Cavanagh, 2004; Brady, Konkle, Oliva, & Alvarez, 2009; Chun & Potter, 1995; Luck & Vogel, 1997; Melcher, 2001, 2006; Perez, Vogel, Luck, & Kappenman, 2012; Potter, 1976; Vogel, Woodman, & Luck, 2006).

Conclusion

The present study demonstrated that memory performance on one feature dimension does not vary with the number of feature values on other object-defining feature dimensions. We conclude that different feature dimensions can recruit separate VWM modules, with each having its own capacity limit and little cross-dimensional interference.

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