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Interactions between Visual Working Memory Representations in Grouping Contexts*

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Studies have shown that stimulus representations interact in visual working memory (VWM). Using Gestalt grouping cues, we investigated how VWM representations of individual stimuli interact in grouping contexts. Two closely located colored circles (proximity) were connected or separated by a line (connectedness). These pairs were shown in memory and test arrays. Participants performed color change detection tasks in which they were asked not only to detect changes but also to locate the changed items. Color change was made to one (Experiment 1) or two (Experiment 2) item(s) in each test array. In Experiment 1, individual items grouped by both proximity and connectedness showed lower detection performance than those only by proximity. In Experiment 2, the colors of two stimuli changed in the same group (intragroup) or across different groups (intergroup). As in Experiment 1, the same grouping effect was observed in the intragroup-change condition. In addition, the change detections were better in the intragroup- than intergroup-change condition. This effect was reversed when data obtained from correctly detected (not necessarily located) trials were analyzed. Collectively, change detections of individual items differed depending on grouping strength, group membership status, and levels of data analysis, suggesting that items represented in VWM affect one another in a hierarchical structure.

Keywords: stimulus representation, visual working memory, proximity, connectedness, hierarchical structure

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Over the past two decades, a large body of research on visual working memory (VWM) has extensively focused on its capacity (e.g., Alvarez & Cavanagh, 2004; Luck & Vogel, 1997; Zhang & Luck, 2008) along with the development of two different views (Bays & Husain, 2008; Zhang & Luck, 2008). These views differ on the organization of object storage (discrete, fixed slots vs. a resource-dependent flexible store) but share the idea that visual stimuli are independently stored. Thus, quantifying the number of individual items one can store from a visual scene has been the central part of this research. In fact, various measures to estimate VWM capacity have been developed in behavioral (Cowan, 2001; Pashler, 1988; Rouder, Morey, Morey, & Cowan, 2011; Zhang & Luck, 2008) and electrophysiological (Jolicœur, Brisson, & Robitaille, 2008; Vogel & Machizawa, 2004)

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studies. This line of research has contributed greatly to elucidating the limits of the VWM system. Yet, the assumption of items' independence needs some scrutiny as a number of studies have reported that visual stimuli interact and are not independently stored (e.g., Bae & Luck, 2017; Brady & Alvarez, 2011; Jiang, Olson, & Chun, 2000; Shin, Fabiani, & Gabriele, 2006).

Gestalt grouping cues (e.g., proximity, connectedness) can generate a situation in which stimuli interact (Wagemans et al., 2012). Individual stimuli and their relationships with one another both exist in a grouping context. Previous studies have investigated how perceptual organization principles (Wagemans et al., 2012) influence the storage of items in VWM (e.g., Balaban & Luria, 2016b; Luria & Vogel, 2014; Peterson & Berryhill, 2013; Peterson, Gözenman, Arciniega, & Berryhill, 2015; Woodman, Vecera, & Luck, 2003; Xu, 2006). They used change detection tasks in which grouped and ungrouped items were shown in memory and test arrays, and found that grouped items yielded better memory performance than ungrouped ones in varying degrees (Peterson & Berryhill, 2013; Woodman et al., 2003; Xu, 2006). This grouping benefit was also accompanied by neural efficiency (Peterson et al., 2015; Xu & Chun, 2007). Presumably, grouped items were integrated into an object-like representation (Xu, 2006), which can be explained by some studies suggesting that object-based representations are units of information processing in VWM (Luck & Vogel, 1997; Luria & Vogel, 2011; but also see Fougnie, Cormiea & Alvarez, 2013; Shin & Ma, 2017).

As perceptual grouping creates wholeness from the sum of its parts, we began by asking how parts making up a whole are represented in VWM. Literature on visual perception provides reasonable expectations about this question. According to studies on face perception (e.g., Farah, Wilson, Drain, & Tanaka, 1998), faces are represented as a whole. When we perceive a face, we perceive it as a whole in which relationships between individual parts of the face (e.g., eye, nose, or mouth) are represented. For this reason, correct face recognition is difficult when we have to rely on part-based analysis, for example, with inverted faces or randomly positioned parts within a face presented (Tanaka & Farah, 1993; Farah, Tanaka, & Drain, 1995). Whether face recognition is special or not (Farah, 1996; Farah et al., 1998; Gauthier & Logothetis, 2000), we can infer that when we perceive the whole, we may not accurately perceive its parts or vice versa (Farah et al., 1995; Farah et al., 1998; Poljac, de-Wit, & Wagemans, 2012).

Analogous to this relationship, when perceptually grouped items are represented as a whole, the individual items may not be faithfully represented. An electrophysiological study (Shin, Fabiani, & Gratton, 2013) reported that two identical alphabet letters encoded in one hemifield resulted in a different size of encoding-related lateralization (Fabiani, Stadler, & Wessel, 2000; Fabiani, Ho, Stinard, & Gratton, 2003; Gratton, 1998; Shin et al., 2006) as a function of the distance between the letters (proximity). The encoding-related lateralization reflects the quality of stimulus representation activated during individual probing, and its size increases as the representational quality of the probed stimulus goes higher (Shin et al., 2006, 2013). In this study, it significantly rose for the letters that were encoded apart (a weak grouping condition) but not for those close to each other (a strong grouping condition). This suggests that the extent to which perceptual grouping occurs is inversely related to the representation quality of each item that participates in the grouping.

Previous studies (Brady & Alvarez, 2011; Jiang et al., 2000; Shin et al., 2006, 2013) have noted that when multiple items are stored in VWM, hierarchical relations among them are also represented. For example, Brady and Alvarez (2011) used color similarity as a grouping cue, and investigated how the size of an individual item within a group of same-colored items was remembered. They found that the memory of the item size was biased toward the mean size of the same-colored items, suggesting that information about groups is represented in addition to that of items. How an individual item is represented in VWM must be determined by its status (e.g., group membership) in a given context as well as by its feature. For this reason, memory representations should be understood at both an individual and a group level.

The current study is based on the fact that grouped stimuli can form an object-like representation. If items that make up a group are represented as an object, these member items should be stored as parts making up the whole and also be marked as ingroup members as opposed to outgroup members. Using color change detection tasks, we investigated how items were interactively represented in grouping contexts. Pairs of items were presented in memory and test arrays in which two items forming a pair were closely located (proximity) and were physically connected or separated (connectedness), as shown in Figure 1. With these forms of grouping maintained, we conducted two experiments using slightly different change detection tasks. If we encode the ways in which items form relations with each other, these relations can be formed within a pair as intragroup members and between pairs as intergroup members. Experiment 1 investigated within-a-pair relations by manipulating grouping strength during encoding, influencing the quality of item representation. Experiment 2 investigated both within-a-pair and between-pairs relations. Specifically, it investigated how these two types of relations were represented. To this end, two items selected from the same group or across different groups were changed, and these changes had to be located.

Because we focused on individual items in a group rather than on groups per se, we asked participants to use a mouse and point to changed items. This item-probing method allowed us not only to examine how precisely they were represented in VWM but also to test if individual items making up a group in fact interacted with each other within the group and across different groups. In this sense, the current study is different from many previous studies in which grouping benefits were examined with a binary decision of change or no-change in change detection tasks (e.g., Gao, Gao, Tang, Shui, & Shen, 2015; Woodman et al., 2003; Xu, 2008).

Experiment 1

Experiment 1 investigated how a member item of a pair was represented in VWM. When closely located items are connected or separated, the connected items should induce stronger pairing than the separated ones, forming an object-like representation. Using a single-item probing, we compared change detection performance for a member item in a pair between the connected and separated conditions. If the detection performance is poorer for the connected than separated items, it should indicate that the connected items were not represented as faithfully as the separated ones and, further, that the

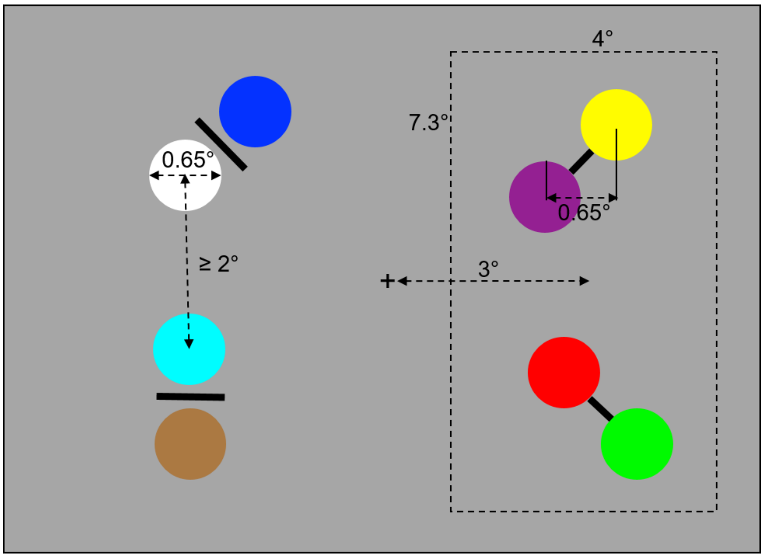

Figure 1. Stimuli and their groupings.

connected items were represented as parts of the pair more strongly than the separated ones.

Methods

Participants Seventeen university students participated in this experiment. This sample size was predetermined based on previous studies on effects of grouping on VWM (Woodman et al., 2003; Xu, 2006: 6 - 22 participants). We estimated a necessary sample size based on the set-size 4 results of Experiment 1 in Woodman et al. (2003) which tested proximity effects in a change detection task. When Anderson, Kelly, and Maxwell's (2017) procedure was used with the desired level of statistical power and of assurance for correcting publication bias and uncertainty, all set to 0.8, it recommended eight participants. Given this sample size, we considered the additions (i.e., set sizes, grouping cues, detection precision) that we had compared to Woodman et al. (2003) and raised the figure to 17, about a twofold increase in sample size. All participants reported normal or corrected-to-normal visual acuity and normal color vision. Upon the completion of the experiment, participants received course credit for their participation.

The experimental protocol was approved by the Institutional Review Board of Yonsei University, and signed informed consent was obtained from all participants before their participation.

Stimuli and Design The stimuli were highly discernable colored circles (0.65° in diameter). The colors were red (9.5 cd/m^2), yellow (56.9 cd/m^2), green (29.9 cd/m^2), blue (5.4 cd/m^2), violet (6.7 cd/m^2), white (56 cd/m^2), and brown (4.8 cd/m^2), similar to those used in the study by Vogel and Machizawa (2004). Different degrees of luminance across the colors were used to equate subjective color intensity. As shown in Figure 1, these stimuli were presented on a gray background (12.7 cd/m^2) within two 4° × 7.3° rectangular regions whose centers were distanced 3° to the left and right of a central fixation cross. A set of 4, 6, 8, or 12 circles was presented on a computer screen. Half of the items in each set were shown to the left and right sides of the fixation cross, resulting in two, three, four, or six circles being placed in each visual field. This divided-field paradigm was used because we aimed to expand the current study to an electrophysiological study in the future. Thus, our stimuli and design were similar to

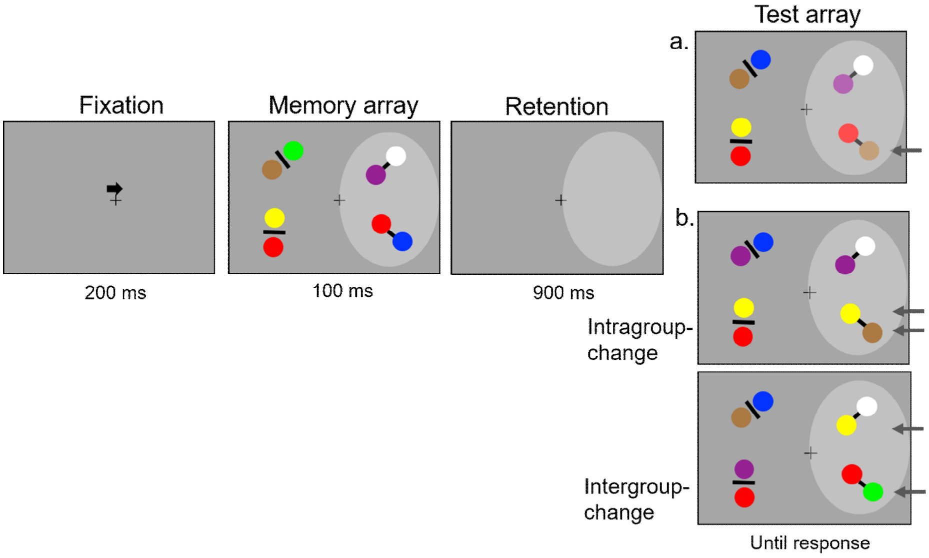

Figure 2. The color change detection tasks used in Experiments 1 and 2 are illustrated in a and b, respectively. In b, the upper and lower panels illustrate the intragroup-change and intergroup-change conditions, respectively. The white shaded areas indicate the areas to which attention should be directed. The dark gray arrows shown in the test arrays indicate changed circles. These shades and arrows are shown here for expository purposes and did not appear during the experiments.

those in Vogel and Machizawa (2004) which used event-related potentials. The numbers of the circles within the visual field (two, three, four, and six) are referred to as set-size conditions throughout this paper. On each side, two closely located circles were either connected or separated by a thick black bar. If the bar connected circles in one visual field, it separated stimuli in the other visual field. The circles forming a pair were distanced 0.65° from their centers, but different pairs were separated by at least 2° between the centers of the two closest circles (see Figure 1). When three circles were presented in the visual field, a pair of two circles and one single circle were presented together. The colors of stimuli were randomly selected with the constraint that no color was identical within the same visual field.

Figure 2 illustrates the experimental paradigm used in both Experiments 1 and 2. A fixation cross was presented in the center of the screen at the outset of the experiment. It remained in the same location throughout the experiment to encourage participants to fixate their eyes on the center of the screen. Each trial began with a central arrow pointing to the left or right side of the fixation cross. It was shown above the cross for 200 ms and indicated the side to which participants should attend. After intervals of 100 – 200 ms, a memory array was presented for 100 ms followed by a 900-ms retention interval. A test array was then presented and remained until response was made. Stimuli in the memory and test arrays could be identical or different by the color(s) of one stimulus (Experiment 1) or two stimuli (Experiment 2). When the color was changed, it was made on both the cued and uncued sides. In addition, the changed color was randomly selected from unused colors within the visual field. Participants were instructed to detect a color change on the cued side. The ratio of change to no-change trials was 50:50 for each set-size. Because participants always made same/different judgments on the cued side, cue validity was 100%.

Procedure Using a mouse, participants indicated a change or no change in the test array. The mouse had three buttons (i.e., left, central wheel, and right). Participants initiated each trial by pressing the central wheel on the mouse. A left-click indicated a change, and a right-click no change. To indicate a change, participants put the cursor on the changed location and clicked the left mouse button. Sound feedback was provided whenever an incorrect response was made. Under these response rules, change detection failed in the following cases: (a) no report of change despite presence of change, (b) report of change at an incorrect location, and (c) report of change despite no change. Case (a) was observed when participants erroneously clicked the right button, representing a “miss” trial. Both cases (b) and (c) were observed when participants clicked the left button incorrectly. In case (b), they clicked it on an incorrect location, which was also treated as a “miss” trial in data analysis. In case (c), they clicked the left button when they should have clicked the right button, treated as a “false alarm” trial in data analysis.

Thirty-two practice trials preceded the experimental trials at the beginning of the experiment. If accuracy was below 0.65, participants performed additional 32 trials prior to the experimental trials. If it was above 0.65, they moved on to the experimental trials and performed 10 blocks of 32 trials, resulting in a total of 320 trials. Participants were instructed to fixate their eyes on the central cross at all times.

Results and Discussion

We computed sensitivity (d') to assess participant's performance using a following formula.

$$d' = Z\left[\frac{\text{Hit}}{\text{Hit} + \text{Miss}}\right] - Z\left[\frac{\text{False alarm}}{\text{False alarm} + \text{Correct rejection}}\right],$$

where trials in which participants correctly indicated changed circles were considered hits, and those in which they correctly indicated no changes correct rejections. Miss and false alarm trials were explained in the previous section. These sensitivity values were submitted to a 4 (set-size: 2, 3, 4, 6) × 2 (pairing mode: connected, separated) repeated measures analysis of variance

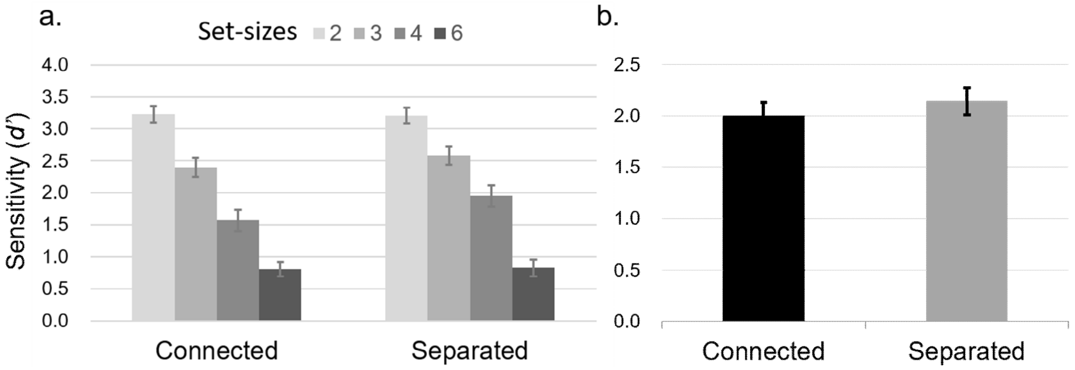

Figure 3. Experiment 1 results across the different set-sizes (a) and between the two pairing conditions (b). The error bars represent standard errors of the means.

(ANOVA). As expected, participants detected changes better for the smaller than larger set-sizes, $F(3, 48) = 100.09$, $p < .001$, $\eta_p^2 = .86$ (see Figure 3a). No significant interaction between pairing mode and set-size was found, $F(3, 48) = 1.41$, $p = .251$, $\eta_p^2 = .08$, but the pairing mode itself yielded a significant difference, $F(1, 16) = 6.39$, $p = .022$, $\eta_p^2 = .29$, with the separated pairs ($M = 2.14$) showing higher sensitivity than the connected ones ($M = 2.00$, see Figure 3b). This effect was most visible for set-sizes 3 and 4. Additional tests revealed that the set-size 4, but not the set-size 3, resulted in a significant difference between the connected and separated pairs, $F(1, 16) = 8.74$, $p = .009$, $\eta_p^2 = .35$, indicating that participants showed better performance when the circles were separated than connected, particularly for the set-size 4.

We also calculated response bias and performed an ANOVA as done with the sensitivity values. Results showed that the bias significantly increased with the set-sizes, $F(3, 48) = 28.43$, $p < .001$, $\eta_p^2 = .59$, suggesting that participants became more conservative in making positive responses as the set-sizes grew. Neither the main effect of the pairing mode nor an interaction between set-size and pairing mode was significant, $F(1, 16) = 0.27$, $p = .608$, $\eta_p^2 = .02$; $F(3, 48) = 0.44$, $p = .729$, $\eta_p^2 = .03$, respectively. Thus, it appears that the sensitivity effect found in the mode of pairing was not affected by response bias.

To delve into the sensitivity effects, we further analyzed hit trials in which participants accurately indicated changed circles in the change condition. Proportions of hit trials were calculated across participants and submitted to a 4 (set-size: 2, 3, 4, 6) × 2 (pairing mode: connected, separated) repeated measures ANOVA. As shown in Table 1, the hit rate significantly dropped with the increasing set-sizes, $F(3, 48) = 146.97$, $p < .001$, $\eta_p^2 = .90$, but did not significantly differ between the two pairing modes, $F(1, 16) = .974$, $p = .338$, $\eta_p^2 = .06$, albeit higher in the separated than connected condition in the set-sizes 3, 4, and 6. An interaction was not significant between set-size and pairing mode, $F(3, 48) = .380$, $p = .768$, $\eta_p^2 = .02$.

In relation to the grouping effect on item representations, these results suggest that (a) the pairing mode affected how participants represented member items, (b) representations of physically connected circles

Table 1. Proportions of hit trials in the connected and separated conditions across the four set-sizes.

	Set-size 2	Set-size 3	Set-size 4	Set-size 6
Connected	0.932 (0.015)	0.824 (0.019)	0.591 (0.037)	0.388 (0.041)
Separated	0.921 (0.016)	0.844 (0.026)	0.626 (0.037)	0.397 (0.036)

Note. Standard errors of the means are in parentheses.

may have been compromised, and (c) this compromise was best revealed when the VWM load approached its capacity limit (Cowan, 2001; Vogel & Machizawa, 2004).

In this experiment, two closely located circles were connected or separated by a line. As the two grouping cues (i.e., proximity and connectedness) influenced the connected circles, they were more strongly grouped than the separated ones influenced by only one cue (i.e., proximity). This difference led to greater difficulty in locating changes in the connected than separated items. This stronger grouping with the connected circles may have induced an object-like representation, in turn, suggesting that the individual circles were represented as parts of an object, not as independent circles. For the separated pairs, however, this close interaction between the circle members may have been weak.

Experiment 1 showed that stimuli affected by stronger grouping cues interacted with each other and were not independently represented in VWM. In Experiment 2, we attempted to replicate Experiment 1 and further investigated impacts of a group membership on item representations. If we encode relations of items in a grouping context, items that belong to the same or different groups should also be differently encoded.

Experiment 2

Unlike Experiment 1, we made color changes to two test items. These changes could be made to two items forming a single pair (i.e., intragroup changes) or selected from two different pairs (i.e., intergroup changes). For this reason, participants had to sequentially indicate two changed items for each test array. This two-item probing allowed us to investigate how group membership status (intra- or intergroup) influences the representations of the individual items. The Experiment 1 result suggests that the representation of an item was more precise in the separated than connected conditions, leading to the prediction that change detection performance should be better for the separated than connected pairs in the intragroup-change condition. Further, if pairs of items are encoded as objects (albeit in different strength), the intragroup changes are considered changes occurring in the whole object, but the intergroup changes partial changes in two separate objects. In this case, the object-based benefits (e.g., Xu, 2002, 2006), often evidenced by grouped stimuli (relative to ungrouped stimuli) showing higher accuracy and sensitivity (Peterson & Berryhill, 2013; Woodman et al., 2003; Xu, 2006), predict that change detection should be better for the intragroup than intergroup changes. This prediction is also supported by the notion of hierarchical VWM stimulus representations (Brady & Alvarez, 2011; Shin et al., 2006) that postulates a level in which individual stimuli are associated with others based on their features, locations, and so forth. Thus, the individual items forming the same group or different groups should be differently represented, and it should be reflected in differences between the intragroup- and intergroup-change conditions.

Methods

Participants Ten university students participated in the study. This sample size falls between the size of Experiment 1 (sharing many similarities to Experiment 2) and that recommended by Anderson et al. (2017). All participants reported normal or corrected-to-normal vision and no color blindness. Upon the completion of the experiment, they received course credit for their participation. The experimental protocol was approved by the Institutional Review Board of Yonsei University, and signed informed consent was obtained from all participants before their participation.

Stimuli and Design Many aspects were identical to those in Experiment 1 except that (a) the color cyan (48.5 cd/m^2) was added to the previous color list (red, yellow, green, blue, violet, white, and brown), (b) only set-sizes 4 and 6 were used, and (c) for the color-change trials, colors of two circles were changed in each visual field. As shown in Figure 2b, these changes were made within a pair (intragroup changes) or between pairs (intergroup changes). Both the cued and uncued sides showed the same type of change (either intra- or intergroup), keeping all conditions the same in the two sides. As in Experiment 1, changed colors were randomly selected from unused colors within the visual field. The ratio of change to no-change trials was 50:50. For the color-change trials, half of the trials were assigned to the intragroup changes, and the other half to the intergroup changes. Thus, no-change, intra-change and inter-change trials accounted for 50, 25, and 25% of all trials.

Procedure This experiment only differed from Experiment 1 in the following ways. As two colors were changed in the test array, participants indicated changed locations by clicking the left mouse button twice. Sound feedback was provided for each click when the response was incorrect. Thirty-two practice trials preceded the experimental trials at the beginning of the experiment. Participants performed 20 blocks of 32 trials, resulting in a total of 640 trials.

Results and Discussion

Figure 4 shows hit rates in different conditions. Unlike in Experiment 1 hit rates were analyzed, because we were interested in comparing the trials in which changes actually happened and it was difficult to define misses and false alarms for each trial. For their analysis, we included the trials in which participants correctly responded to both of the changed circles and performed a 2 (set-size: 4, 6) × 2 (pairing mode: connected, separated) × 2 (color-change unit: intragroup, intergroup) repeated measures ANOVA. As shown in Figure 4a, the hit rate was significantly higher for the set-size 4 than set-size 6 trials, $F(1, 9) = 79.49$, $p < .001$, $\eta_p^2 = .90$, and there was a significant main effect of the color-change unit, $F(1, 9) = 65.47$, $p < .001$, $\eta_p^2 = .88$. Specifically, the hit rate in the intragroup-change condition ($M = 0.61$) was almost twice as high in the intergroup-change condition ($M = 0.31$), indicative of the object benefit. Change detection in change trials must

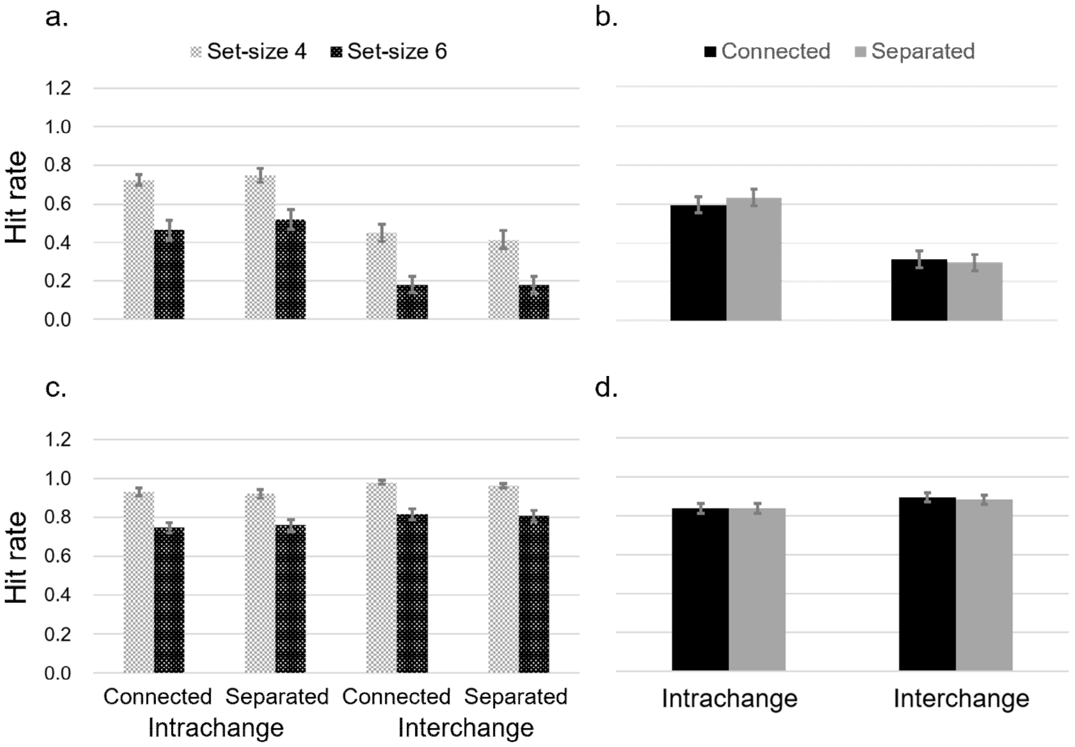

Figure 4. Hit rates obtained in Experiment 2. a and b were obtained from the trials in which participants correctly located two changed circles in each test array. c and d were obtained from the trials in which participants correctly detected changes regardless of accuracy of the reported locations. For this reason, the hit rates were higher in c and d than a and b. The abscissas of a and b are identical to those of c and d. The error bars represent standard errors of the means.

have been easier when the changes were made to the entire single pair than to two pairs in part (see Figure 4b). This is consistent with the idea that unit of change detection is an object (i.e., a pair in this study). Moreover, it confirms a group level of representation in which stimuli sharing visual features are associated with each other and form a hierarchical structure.

Furthermore, this color-change unit effect significantly interacted with the pairing mode, $F(1, 9) = 6.59$, $p = .030$, $\eta_p^2 = .42$ (Figure 4b). Therefore, separate ANOVAs were performed to examine this interaction more closely. For the intragroup change, the hit rate was significantly lower in the connected ($M = 0.60$) than separated ($M = 0.63$) condition, $F(1, 9) = 6.23$, $p = .034$, $\eta_p^2 = .41$, consistent with the grouping effect found in Experiment 1 with the significant sensitivity difference and an overall pattern of the hit rate. For the intergroup change, the two pairing mode conditions did not significantly differ, $F(1, 9) = 0.73$, $p = .414$, $\eta_p^2 = .08$. Given the very low hit rate in the intergroup change condition, it appears that locating changed items across different pairs was equally difficult in both the separated and connected conditions. Although participants sensed some changes across different pairs, accessing the exact representations of the items might have been challenging.

For this reason, we included the trials in which participants correctly indicated that changes occurred whether the indicated changes were accurately located or not. Please note that this analysis is similar to the analysis typically done using conventional change detection tasks (e.g., Luck & Vogel, 1997). In these trials, participants may not have accessed precise information about individual items (e.g., locations, features) but were at least aware of some changes in the test arrays. The same 2 (set-size: 4, 6) × 2 (pairing mode: connected, separated) × 2 (color-change unit: intragroup, intergroup) ANOVA was performed. As expected, the hit rate was significantly higher for the set-size 4 than set-size 6 trials, $F(1, 9) = 112.54$, $p < .001$, $\eta_p^2 = 0.93$ (Figure 4c). The intergroup-change condition ($M = 0.89$) showed a significantly higher hit rate than the intragroup-change condition ($M = 0.84$), $F(1, 9) = 8.40$, $p = .018$, $\eta_p^2 = .48$ (Figure 4d), indicating that correct change awareness was higher when two pairs contained the changes than when a single pair did. As we see the forest before trees (e.g., Navon, 1977), there seems to be a global level of memory access during which changes are coarsely detected. During this access, it may have been easier to notice the intergroup changes occurring globally than the intragroup changes. None of the other effects were significant, $Fs < 0.45$, $ps > .522$, $\eta_p^2s < .05$.

The sequential detections of two-color changes in the test array yielded the following results. First, as the set-sizes became larger, the hit rate decreased. Second, the change detections were better for the intragroup than intergroup changes. Third, the detections were better for the separated than connected pairs when the changes occurred within a pair. Fourth, change awareness was better when changes occurred across pairs than within a pair. Collectively, change detection performance differed depending on the item's grouping strength and group membership status, suggesting that stimulus representations are affected by the roles they are playing as group's building blocks and members of an ingroup or outgroup in a given visual scene, which, in turn, underscores the idea that stimuli are interactively represented in VWM. In addition, depending on levels of detection precision we seem to access different types of representations, reflecting a hierarchical structure of VWM (Brady & Alvarez, 2011; Jiang et al., 2000; Shin et al., 2006).

General Discussion

Previous studies suggest that the representations of VWM are more than the collection of individual items in the memory due to interactions between the items (e.g., Bae & Luck, 2017; Brady & Alvarez, 2011; Jiang et al., 2000; Shin et al., 2006). As Gestalt grouping cues (Wagemans et al., 2012) induce interactions between items, the current study sought to investigate how individual stimuli held in VWM interact with others in grouping contexts using an item-probing method and to provide evidence that VWM representations interact.

Based on the finding that strongly grouped stimuli form an object-like representation (Xu, 2006), we carried out two experiments in which two closely located circles (proximity) were either connected or separated by a line (connectedness), inducing different strengths of grouping effects. In this grouping context, participants performed color change detection tasks in which they judged whether changes occurred or not and further located the changed items (if any) using a mouse.

In Experiment 1, we investigated how individual items were represented as members of a group. We reasoned that two circles paired by both proximity and connectedness would be more strongly grouped and, hence, more likely to be represented as an object-like unit than those paired by proximity but separation. If the storage of visual stimuli is object-based, one of the connected circles should be represented less faithfully than one of the separated circles. The sensitivity values revealed that participants performed less well in the connected than separated condition, and the hit rates also showed a similar pattern of the grouping effect. This result was replicated in the intragroup change condition in Experiment 2, in which two items were probed for each test array. In this experiment, we found again that changed items were harder to locate in the connected (associated with strong grouping) than separated group (associated with weak grouping), consistently suggesting that the representation qualities of individual items differed depending on grouping strength and that the individual items within the connected pair were represented as parts of a whole, not as standalone items.

Despite the significant grouping effect with the sensitivity, the hit rate did not show a significant difference between the two pairing modes in Experiment 1 unlike in the intrachange condition of Experiment 2. This difference might have stemmed from the ease with which changed items were detected. The set-size of Experiment 1 increased as many as that of Experiment 2, but the items to rule out for a correct change detection in Experiment 1 were greater than in Experiment 2, causing the hit rate to fall rapidly with the set-size increase and resulting in a lower average of the set-sizes 4 and 6 (M = 0.501 in Experiment 1, M = 0.614 in Experiment 2). The task performance hovering around and even below chance would have made the difference between the two pairing modes be difficult to reach significance.

Whether grouping cues lead to an object-like representation in VWM may depend on a number of factors (Balaban & Luria, 2016a, 2016b)—for example, grouping strength, task type and context, and object history. Previously, Gestalt grouping cues such as a combination of proximity and connectedness (Xu, 2006) or of similarity and proximity (Peterson & Berryhill, 2013), connectedness (Woodman et al., 2003; Xu, 2006, 2008), and common region (Xu & Chun, 2007) yielded object benefits such as higher accuracy and sensitivity. These benefits were not observed in our results. We rather observed better performance as grouping strength became weak. This discrepancy may have come from the specific ways of reporting changes. Whereas many previous studies (e.g., Jiang et al., 2000; Vogel & Machizawa, 2004; Xu, 2006) simply asked participants to detect changes or no changes, the current study asked them to locate changed items in the event of change detection, emphasizing precision of item (rather than group) representations. Thus, it is possible that this task context could have led to better performance for weekly grouped items. Nevertheless, this specific way of reporting allowed us to *probe* how single items making up a group were stored and represented.

Given the superior detection of the separated to connected items, Experiment 2 was designed to replicate this effect in addition to investigating how group membership status influenced item representations. These goals were achieved by making changes to two intragroup or intergroup items and asking participants to locate the two changes. We found that the intragroup-change condition showed more accurate detections than the intergroup-change condition, indicating that full changes occurring in one group led to significantly accurate detections of them compared to partial changes made across two groups. Presumably, the grouping cues induced object-like representations, and these representations resulted in object-based benefits in the change detection performance. In addition, it confirms the notion of the hierarchical structure of VWM representations in which group information of each item is also included.

Interestingly, when detection precision was lowered to detecting changes without specifying changed locations, change awareness was higher for the intergroup than intragroup changes. This coarse change detection benefited from the larger number of changed groups (two over one). Jiang and colleagues (2000) found that participants performed significantly better when the spatial configuration of memory items was maintained between memory and test arrays. This could mean that if this global level of memory representations does not match between the memory and test arrays, detecting changes correctly becomes harder. From this analysis, we learned that depending on the level of access a given task requires, the representations uncovered by the task could be different.

Stimuli on visual arrays presented in a controlled experiment are far from similar to the visual environment surrounding us in real life. Still, with this simplified version of a visual environment, we were able to show interactions between items in VWM by probing individual items situated in different grouping contexts as we moved beyond conventional change detection tasks. This interaction should be stronger and more complicated when it comes to real visual scenes, where depth and distance between objects exist, things are moving, a number of Gestalt grouping principles are applied, statistical regularities are extracted, and so on. For this reason, it is necessary to continue doing a variety of research to uncover how visual stimuli interact and shed light on the organization of VWM.

Previous studies (Peterson & Berryhill, 2013; Woodman et al., 2003; Xu, 2006) have used perceptual grouping cues to show the advantages of grouped stimuli over ungrouped stimuli in measures of accuracy and sensitivity. We used perceptual grouping cues in order to investigate how individual items forming a group were represented in the structure of VWM. We found that representations of individual items could show not only grouping costs depending on grouping strength, but also grouping benefits as a function of group membership status. We also found that changes could be detected better across groups than within a group when getting access to precise representations is not required. These results indicate that VWM is organized in a hierarchical fashion, from individual items, groups they form, perhaps to their global configurations, and further suggest that item representations should be understood in relation to others because of their interactive nature.

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집단화 맥락에서 본 시각 작업 기억 표상 간의 상호작용

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시각작업기억의 자극들이 상호작용한다는 연구가 잇따르고 있는 가운데, 본 연구는 게슈탈트 집단화 단서들을 이용하여 시각작업기억 속의 개별 자극들이 어떻게 상호작용하는지에 대해서 연구하였다. 집단화를 위해 서로 다른 색깔의 원 모양 자극 둘이서 '근접성'을 이루며 한 쌍을 형성하는 동시에 선으로 연결하거나 분리해서(연결성) 그 강도를 조정하였다. 이러한 쌍들이 매 시행마다 기억 화면과 검사 화면에 제시되었고, 참가자는 검사 화면이 제시될 때 자극의 색에 변화가 있는지, 있다면 어느 자극인지를 마우스로 가리키는 과제를 수행하였다. 실험 1에서는 한 자극의 색에, 실험 2에서는 두 자극의 색에 변화가 있었다. 여기서 두 자극이 변한 방식은 한 쌍을 이루는 두 자극이 변하거나(집단 내 변화), 두 쌍에 걸쳐 한 자극씩 변하는(집단 간 변화) 방식이었다. 결과는 다음과 같다. 실험 1에서는 색 변화 탐지가 분리된 조건보다 연결된 조건에서 더 저조한 것으로 나타났다. 이 결과는 실험 2 집단 내 변화 조건에서도 같은 방식으로 나타났다. 집단 내 변화와 집단 간 변화는 변화 자극을 정확히 특정했던 자료를 분석할 경우 집단 내 변화가 더 우수한 수행을 보였으나, 변화 유무만을 정확히 탐지했던 자료 분석의 경우에는 집단 간 변화가 더 우수한 수행을 보였다. 결과를 종합해 본다면, 개별 자극에 대한 변화 탐지가 집단화의 강도, 집단 구성의 여부, 자료의 분석 수준에 따라 달랐고, 이것은 시각작업기억의 위계 구조 내에서 표상되는 자극들이 서로 영향을 주고 받는다는 것을 시사한다.

주제어: 자극표상, 시각작업기억, 근접성, 연결성, 위계구조