

# Visual working memory representation as a topological defined perceptual object

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The question of what the basic unit is of visual working memory remains one of the most fundamental and controversial issues. In the current study, we proposed a unique perspective based on early topological perception to describe the nature of representation in visual working memory. In a series of updating change-detection tasks, the repetition-benefit effect on color memory was not affected when items in the second memory array underwent massive changes of nontopological features from the first memory array. However, when the topological properties of an item changed, the repetition-benefit effect was destroyed, suggesting that the item was perceived as a new object impairing the original memory. Hence, our results suggest that a perceptual object defined by its topological invariance might be a unique perspective

from which to describe representations of visual working memory.

## Introduction

Working memory (WM) is an online memory system in which information is maintained in the service of ongoing cognitive tasks (Baddeley, 2003, 2012). Its most salient characteristic is its capacity: The WM system has an extremely limited capacity of only a few items (Cowan, 2001, 2010). However, there has been an ongoing debate on how to best characterize the limits of WM. A classic view claims that the capacity of WM is determined by a limit on the number of discrete items

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(Luck & Vogel, 1997, 2013; Zhang & Luck, 2008). In contrast, another view proposes that capacity is a continuous resource that can be divided among large numbers of items (Bays, 2015; Ma, Husain, & Bays, 2014; Wilken & Ma, 2004). The unit of WM capacity should be consistent with the unit of WM representation. Therefore, an understanding of WM capacity requires moving beyond quantifying how many items can be remembered and instead focusing on the essence of WM representations.

Unfortunately, the fundamental unit of representations in visual working memory (VWM) remains unclear. Whether VWM operates over integrated object representations (Balaban & Luria, 2015; Luck & Vogel, 1997) or over visual features stored independent of each other (Fougnie & Alvarez, 2011; Woodman & Vogel, 2008) is controversial. Many studies have found equivalent performance between compound objects and single-dimensional features, which supports object-based VWM characterization (Shen, Tang, Wu, Shui, & Gao, 2013; Treisman & Zhang, 2006). Neuroscience data from sources such as magnetic resonance imaging, human electroencephalography, and monkey neurophysiology have also provided supportive results (Reinhart et al., 2012; Todd & Marois, 2004; Vogel & Machizawa, 2004). However, other evidence has suggested that access to VWM could be restricted to goal-relevant features only (Fougnie & Alvarez, 2011; Serences, Ester, Vogel, & Awh, 2009; Woodman & Vogel, 2008; Yu & Shim, 2017). Considering the variability of these findings, we would argue that the definition of “unit” in VWM seems to refer neither to object-based representations nor to independent feature-based representations.

In 1956, Miller proposed the term “chunk” to characterize the highly variable units in short-term memory. Miller’s chunk was defined as one single grouping unit that was bound together by principles of organization from the perceptual to the semantic level. From the perspective of perceptual organization, a chunk and a perceptual object closely resemble each other, as both address similar tasks, such as “what goes with what,” and have similar underlying concepts, such as belongingness and assignment. In this sense, the concept of a chunk has the same meaning as the concept of a perceptual object.

The definition of a perceptual object is inherited from the gestalt tradition: Like many other gestalt concepts, it is intuitive but elusive. However, Chen (1982, 2005) established a formalized theory of the perceptual object free from intuitive approaches, arguing that the core intuitive notion of a perceptual object is rooted in its holistic identity preserved over shape-changing transformations. This identity can be characterized precisely as topological invariance. Topology can be imagined as an arbitrary “rubber-sheet”

distortion, in which connectivity, the number of holes, and the inside/outside relationship remain invariable under continuous deformations, including stretching and bending. Through decades of research, the early topological-perception hypothesis has been widely explored, in the context of phenomena such as apparent motion (Zhuo, 2003), global precedence (Han, Humphreys, & Chen, 1999), multiple-object tracking (Zhou, Luo, Zhou, Zhuo, & Chen, 2010), numerosity (He, Zhou, Zhou, He, & Chen, 2015), and even pattern discrimination in insects (Chen, Zhang, & Srinivasan, 2003). These results have supported the notion that topological properties are extracted in the very beginning of visual processing to form basic constraints on object coding. The topological approach to perceptual organization provides a new definition of the global versus the local and a new perspective on viewing the formation of an object. Therefore, from the topological perspective, we proposed that the definition of a perceptual object might be integrated into VWM, which would profoundly help the understanding of representations of VWM.

Prior studies have suggested that updating in WM is based on the object-to-representation process (Balaban, Drew, & Luria, 2018; Balaban & Luria, 2015, 2017). If the item has not changed from one array to the next, then the original representation is simply reinforced by the process (Ihssen, Linden, & Shapiro, 2010). However, if the item has changed, then the updating process can replace the stored item with the new information. In 2015, Kessler and colleagues proposed an updating version of a visual change-detection paradigm, and found a repetition benefit in this paradigm—namely, better change-detection performance following a second array in which some or all items were same as in the first array. In the present study, we adapted this paradigm and examined how VWM representations were affected by perceptual objects defined by topology. We hypothesized that if the items shared the same object representation from the first to the second memory array, there would be a significant repetition-benefit effect. Once a topological property of an object changed, participants would treat that one as a new object, discard the original representation, and encode the input as a new representation, which would destroy the repetition-benefit effect.

In Experiment 1, we used the English letters E, H, and P as the stimuli and investigated the impact of topological changes on the repetition-benefit effect. To rule out the interference of letter semantics and to sufficiently contrast nontopological properties, in Experiment 2 we used as stimuli four different groups of basic geometric figures, which controlled for any differences in local features. In Experiment 3, we adapted a partial-updating paradigm and examined the

repetition-benefit effect on different types of VWM representations.

## Experiment 1

### Participants

Participants were university undergraduates who received hourly pay for their participation. Sixteen participants (18–25 years old) took part in Experiment 1. All had normal or corrected-to-normal vision, were right-handed, and were unaware of the purpose of the experiment. The study was approved by the ethics committee of the Institute of Biophysics at the Chinese Academy of Sciences, Beijing.

### Apparatus

Stimuli were displayed on a 22-in. computer monitor (Sony PVM-2541 OLED) with a resolution of  $1,024 \times 768$  pixels. The experiment was programmed and run in MATLAB (Version 2013a) with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Participants were seated in a room with dim ambient light, and their head position was stabilized using a chin and head rest.

### Stimuli and procedure

The stimuli were presented on a gray background at a viewing distance of 70 cm. A memory array contained four colored items ( $0.95^\circ \times 0.95^\circ$  each). When the four colored items appeared, each was arranged in an imaginary circle ( $7.6^\circ \times 7.6^\circ$ ) centered on the middle of the monitor. The locations of the items were fixed both within a trial and across trials. The color of each item was selected at random from a set of nine highly discriminable colors. The colors were exclusive in an array. The luminance of the colors was equal.

Participants performed an updating version of the change-detection task (Kessler et al., 2015; Luck & Vogel, 1997), as shown in Figure 1. Each trial began with a 100-ms memory array, followed by a 600-ms blank retention interval. In half of the trials, the probe screen was then presented (baseline condition). In the other half of the trials, a second memory array was presented and followed by another 600-ms retention interval and then the probe screen. An equal proportion of trials with and without a second array prevented a strategy of attending only to the second memory array.

The English letters E, H, and P were used as stimuli. They all comprised five lines of the same length. The shape of the items in the baseline and first memory array was the letter E. The second memory array consisted of three conditions. In one condition, the shape of the items in the second memory array did not change. This condition was called the *no-change condition*. In the second condition, the *nontopological-change condition*, the letter E was transformed into the letter H by moving two bars. Although phenomenologically they look quite different, E and H are topologically equivalent to each other because there is no hole in either of them. In the last condition, the *topological-change condition*, the change was created by moving one bar to transform the letter E into the letter P. Because the letter P has a hole while E does not, the transition between E and P represented a change in topology. In each condition, the colors of the second memory array were either consistent with the first array (repeated) or totally different (updated). Only one item was presented on the probe screen, and its shape was the same as in the second memory array. Participants were asked to store the most recently displayed memory array and to detect whether the color of the test item changed. They made a two-alternative forced-choice response on a response pad at the end of each trial, with no time requirement for trial completion. Each participant received 12 blocks of 48 trials.

The baseline condition included 288 trials. In the other 288 trials with the second memory array, each of the shape-change conditions was further divided into repeated or updated, with 48 trials for each. All these trials appeared randomly and unpredictably within blocks. Before the experiment, all participants completed one practice session.

### Results

The results are shown in Figure 2. Repeated-measures analysis of variance (ANOVA) was conducted on the accuracy data from the baseline ( $M \pm SD = 73.1\% \pm 5.3\%$ ) and three updated conditions. The four conditions exhibited no significant main effect,  $F(3, 45) = 0.499$ ,  $p = 0.685$ ,  $\eta_p^2 = 0.032$ . This result is similar to the finding of a previous study (Kessler et al., 2015). As expected, two memory arrays did not increase the difficulty of the task, and all participants could remember the first memory array carefully as required. In the updated trials, introducing nontopological or topological changes did not disturb the memory result. Participants processed the updated frame as a new memory array.

A 3 (shape-change condition in second memory array: no change, nontopological change, or topological change)  $\times$  2 (if-updated: updated vs. repeated) repeated-measures ANOVA showed a significant main

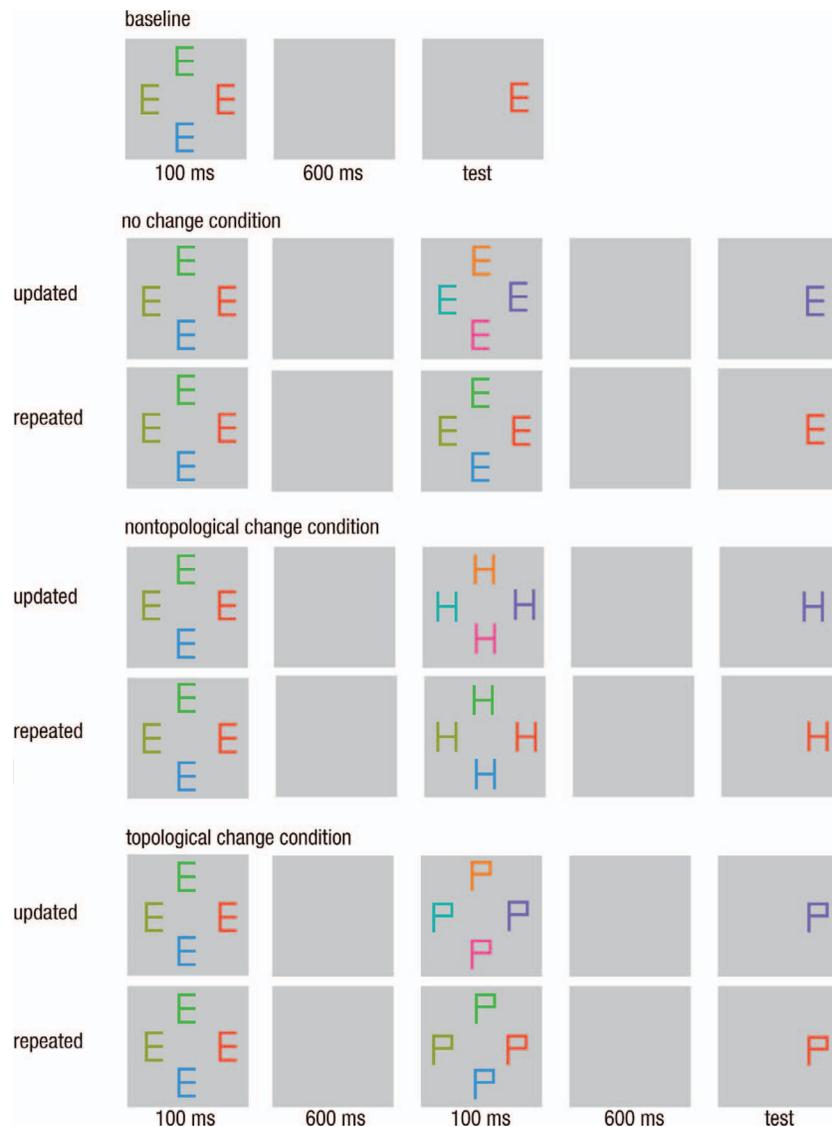


Figure 1. Experimental paradigm for Experiments 1 and 2. Half of the trials included a single frame of visual display (baseline). In the other half of the trials, a second frame of visual display was presented in three conditions: no change, nontopological change, and topological change. Participants were required to report whether the color of the probe matched the color in the last array at the same location.

effect of if-updated,  $F(1, 15) = 25.855$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.633$ , and a significant Shape-change condition  $\times$  if-updated interaction,  $F(2, 30) = 3.661$ ,  $p = 0.038$ ,  $\eta_p^2 = 0.196$ . We found no significant main effect of shape-change condition in the second memory array,  $F(2, 30) = 0.333$ ,  $p = 0.72$ ,  $\eta_p^2 = 0.022$ .

To further examine the repetition-benefit effect in three different conditions, we investigated using Bonferroni-corrected paired-samples  $t$  tests. Although our conclusions are primarily based on  $p$  values, we also analyzed the data using a Bayesian paired-samples  $t$  test. This analysis was conducted using the newly developed statistical software program JASP (Wagenmakers, Love, et al., 2017; Wagenmakers, Marsman, et al., 2017). An advantage of the Bayesian approach over

the frequentist approach is that the relative evidence favoring the null versus a specified alternative hypothesis is assessed, meaning the strength of the evidence favoring the null cannot be measured (Kruschke & Liddell, 2017; Rouder, Speckman, Sun, Morey, & Iverson, 2009). Bayes factors express the ratio between the likelihood of the data under two compared models. A Bayes factor ( $BF_{10}$ ) corresponds to the amount of evidence in favor of the alternative over the null model. A  $BF_{10}$  of 1 is equivocal evidence for the two models; if it is greater than 1, that is interpreted as greater evidence for the alternative, and when it is less than 1, that is interpreted as evidence for the null.

The data revealed that the accuracy in the no-change repeated condition ( $M \pm SD = 79.9\% \pm 6.6\%$ ) was

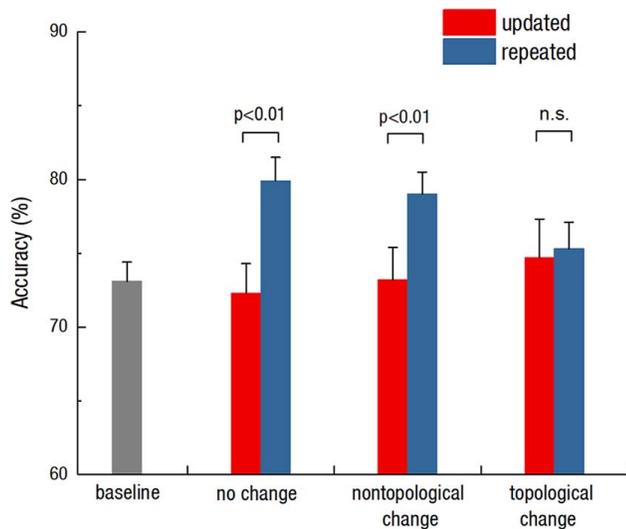


Figure 2. The results of Experiment 1. The gray bar represents the baseline. Red and blue bars represent the percent correct for updated and repeated, respectively. Error bars represent +1 standard error of the mean.

significantly higher than in the no-change updated condition ( $M \pm SD = 72.3\% \pm 8.0\%$ ),  $t(15) = 3.551$ ,  $p = 0.003$ , Cohen's  $d = 0.888$ ,  $BF_{10} = 15.39$ . Performance was also more accurate for the nontopological-change repeated condition ( $M \pm SD = 79.0\% \pm 6.2\%$ ) than for the nontopological-change updated condition ( $M \pm SD = 73.2\% \pm 9.0\%$ ),  $t(15) = 3.898$ ,  $p = 0.001$ , Cohen's  $d = 0.975$ ,  $BF_{10} = 28.195$ . In contrast, this kind of repetition benefit was not significant in the topological-change condition ( $M_{\text{repeated}} \pm SD = 75.3\% \pm 7.1\%$ ,  $M_{\text{updated}} \pm SD = 74.7\% \pm 10.2\%$ ),  $t(15) = 0.31$ ,  $p = 0.761$ , Cohen's  $d = 0.077$ ,  $BF_{10} = 0.267$ .

The results suggest that the destruction of the repetition-benefit effect was likely due to topological changes affecting the representation in VWM. When the memory items were topologically changed, participants treated the objects as new and replaced the previous information, even though the objects had the same color. On the other hand, the memory items that were topologically equivalent were treated as the same objects and did not trigger updating.

## Experiment 2

### Method

The paradigm was identical to that in Experiment 1, except for the stimuli used. To rule out the interference of semantics associated with the letters in Experiment 1, we used basic geometric figures as stimuli in Experiment 2. A major challenge to the study of topological

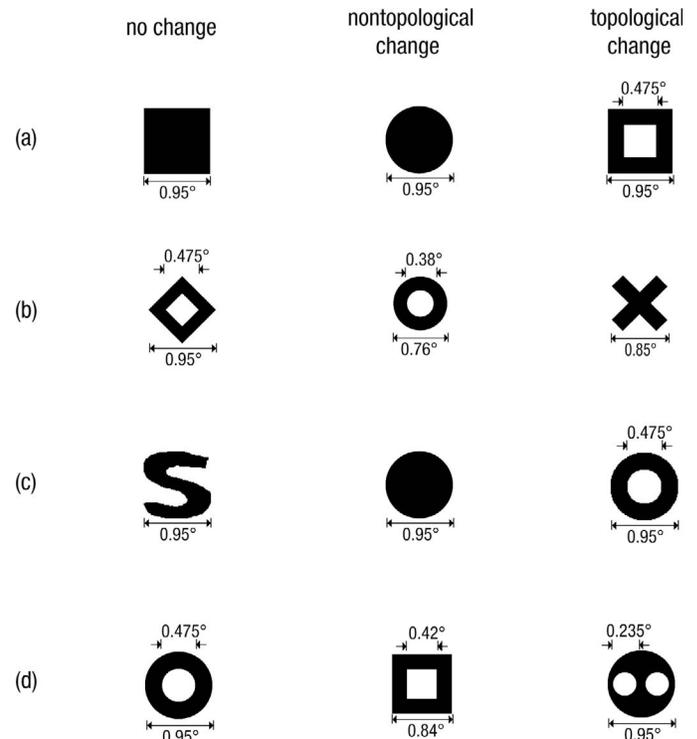


Figure 3. Schematic depiction of the stimulus groups for Experiment 2. They were designed to manipulate topological variations between stimuli while controlling for local features, such as luminous flux, spatial-frequency components, terminators, etc. In the procedure, the no-change stimulus was contained in the first display and either the no-change, the nontopological-change, or the topological-change stimulus was presented in the second display.

discrimination is that there seem to be no two geometric figures that differ only in topological properties and have no differences in local features. Thus, one cannot test for the role of topological differences in form perception in complete isolation by designing stimuli that differ only topologically, without any differences in nontopological features. To minimize this problem and rule out obvious explanations based on nontopological features, we carefully designed four groups of stimulus figures, which are described in the following. We tested the four groups of stimuli separately in four experiments. In total, 64 subjects (18–27 years old) participated in the experiment (16 with each group of experimental stimuli). All participants had normal or corrected-to-normal visual acuity and normal color vision, and they were unaware of the purpose of the experiments.

### The solid square versus the disk versus the hollow square

The shape of items in the baseline and the first memory array was a solid square (Figure 3a). In the nontopological-change condition, the solid square

turned into a disk, removing geometric similarity. Although phenomenologically they look quite different, the solid square and disk are topologically equivalent because neither has a hole. In the topological-change condition, the solid square in the first memory array turned into a hollow square containing a hole. Thus, this group of stimulus figures represented both local geometric and global topological distinctions.

### The hollow diamond versus the ring versus the crosslike symbol

The stimuli of the first memory array were hollow diamonds (Figure 3b). In the nontopological-change condition, the hollow diamonds changed to rings in the second memory array, and in the topological-change condition they changed to crosslike symbols (hereafter referred to as crosses). The ring and the hollow diamond each contain a hole, whereas the cross does not. The hollow diamond and the cross were oriented so their edges were parallel to each other, to eliminate the potential orientational cue. Meanwhile, this set of figures was also matched in terms of various nontopological factors: sloped edges and curvature (the hollow diamond and the cross were less different than the hollow diamond and the ring), spatial-frequency components, and luminous flux.

### The S-like figure versus the disk versus the ring

This group of stimuli was designed to control luminous flux, spatial-frequency components, and other possible confounds of local features (Figure 3c). The S-like figure was scaled to approximate the area of the ring, and its shape was purposely made irregular to eliminate possible effects of subjective contours and other organizational factors (such as parallelism or similarity of length). As a consequence, the S-like figure and the ring differ in holes but are quite similar in local features—such as luminous flux, spatial-frequency components, perimeter length, and averaged edge crossings—in comparison to the disk.

### One hole versus hollow square versus two holes

The preceding stimuli tested the difference between no-hole and one-hole stimuli, which was just a special case of the more general topological invariant of the number of holes. Tests of the more general case have included comparisons of differences in discriminability between shapes with one and two holes. Hence, we selected rings, hollow squares, and disks with two holes as stimulus figures (Figure 3d). The ring and the two-hole disk differ in the number of holes. The total area

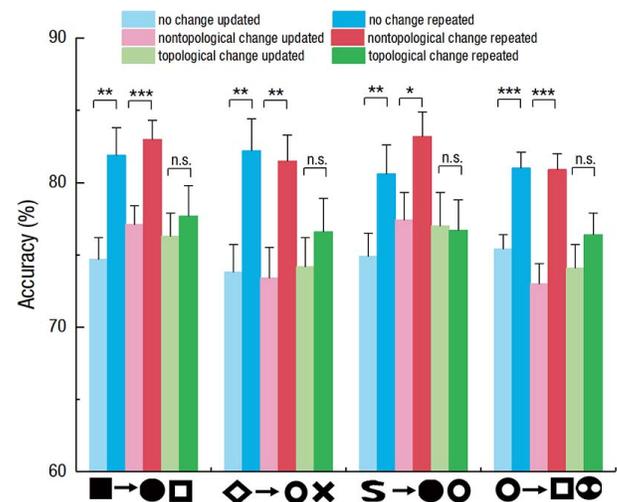


Figure 4. Comparison between updated and repeated stimuli in three conditions. Light color bars refer to updated tests, and dark color bars to repeated tests. Blue, red, and green bars represent no change, nontopological change, and topological change conditions, respectively. Error bars represent +1 standard error of the mean. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ , n.s. =  $p > 0.05$ .

of the two smaller holes in the two-hole disk was made equal to that of the larger hole in the ring, and their spatial-frequency spectrum and perimeter length were nearly equal.

## Results

For all four stimulus groups, the accuracy results are shown in Figure 4. We ran a repeated-measures ANOVA on the data from the four groups separately with two independent variables: shape-change condition and if-updated. The results all reveal a significant main effect of if-updated. The performance of repeated trials was obviously better than that of updated trials. Importantly, shape-change condition and if-updated interacted significantly. As Table 1 shows, a significant main effect of if-updated and interaction occurred, indicating that the if-updated effect was modulated by an interaction with shape-change condition. To assess whether the repetition benefit obtained significantly in different conditions, we conducted pair-wise  $t$  tests to compare the accuracy of updated and repeated conditions. The detailed statistical results are given in Table 2. All four stimulus groups consistently showed that only the no-change and nontopological-change conditions had a significant repetition-benefit effect. In the topological-change condition, the repetition-benefit effect was weakened or even disappeared.

Stimulus	Shape-change condition			If-updated			Interaction		
	$F(2, 30)$	$p$	$\eta_p^2$	$F(1, 15)$	$p$	$\eta_p^2$	$F(2, 30)$	$p$	$\eta_p^2$
	2.554	0.095	0.145	14.324	0.002	0.488	5.163	0.012	0.256
	1.160	0.327	0.072	21.499	<0.001	0.589	3.714	0.036	0.198
	3.400	0.047	0.185	17.887	<0.001	0.544	4.305	0.023	0.223
	3.307	0.05	0.181	44.646	<0.001	0.749	3.448	0.045	0.187

Table 1. Analysis-of-variance results in Experiment 2.

The results are consistent with the results of Experiment 1. When the item in the second memory array had a topological change, the repetition-benefit effect was disrupted. In this experiment, the four groups of stimuli were carefully designed to prevent the participants from using various nontopological cues. They were designed to exclude the use of orientation cues (Figure 3b), spatial-frequency components (Figure 3b–3d), luminous flux (Figure 3b–3d), perimeter length (Figure 3c and 3d), and number of edges crossed while scanning the figure (Figure 3b and 3c).

In order to make a clearer comparison, we combined the data from this experiment with the data from Experiment 1. We calculated the repetition-benefit effect under each condition separately (the accuracy of repeated trials minus the accuracy of updated trials), as shown in Figure 5. Furthermore, these data were submitted to a one-way repeated-measures ANOVA with shape-change condition as the factor of interest. There was a significant main effect,  $F(2, 158) = 19.340, p < 0.001, \eta_p^2 = 0.197$ , and post hoc pair-wise comparisons revealed that the repetition-benefit effect in the topological-change condition ( $M \pm SD = 1.3 \pm 7.0$ ) was significantly weaker than it was in the no-change condition ( $M \pm SD = 6.9 \pm 7.0, p < 0.001$ ) and the nontopological-change condition ( $M \pm SD = 6.7 \pm 6.4, p < 0.001$ ). Additionally, there was no significant difference between the no-change and nontopological-change conditions ( $p = 1.0$ ).

We also made a signal detection analysis for Experiments 1 and 2. And meanwhile, we combined

four groups of stimuli patterns in one experiment. The same results as mentioned above (see Supplementary File S1 for details).

Across all of these stimulus pairs, the topological explanation is the only one explaining all of our results in a unified manner. In contrast, nontopological features—such as orientation, luminous flux, spatial-frequency components, and size—are commonly considered in the study of vision but cannot consistently account for all of the results. Therefore, findings with different kinds of topological transitions—including the transitions from no-hole to one-hole stimuli, one-hole to no-hole stimuli, and one-hole to two-hole stimuli—consistently suggest that a perceptual object defined by topology might play an important role in the representation of VWM.

### Experiment 3

#### Method

The stimuli in this experiment were hollow diamonds, rings, and crosses, as shown in Figure 3a. The procedure was largely the same as in Experiment 1, except for the second memory array that was used. We randomly chose two items to change their colors in the second memory array, which were considered updated items, while the other two remaining items were considered repeated items. The probe could then

Stimulus	No change				Nontopological change				Topological change			
	$t(15)$	$p$	Cohen's $d$	$BF_{10}$	$t(15)$	$p$	Cohen's $d$	$BF_{10}$	$t(15)$	$p$	Cohen's $d$	$BF_{10}$
	3.843	0.002	0.961	25.610	4.271	<0.001	1.068	54.046	1.103	0.287	0.276	0.43
	3.843	0.002	0.961	25.610	5.198	<0.001	1.3	>100	1.103	0.287	0.276	0.43
	3.602	0.003	0.901	16.83	2.903	0.011	0.726	5.09	0.239	0.814	0.06	0.262
	5.805	<0.001	1.451	>100	5.083	<0.001	1.271	>100	1.304	0.212	0.326	0.524

Table 2. Results of the paired  $t$  test on the updated and repeated tests for three conditions in Experiment 2.

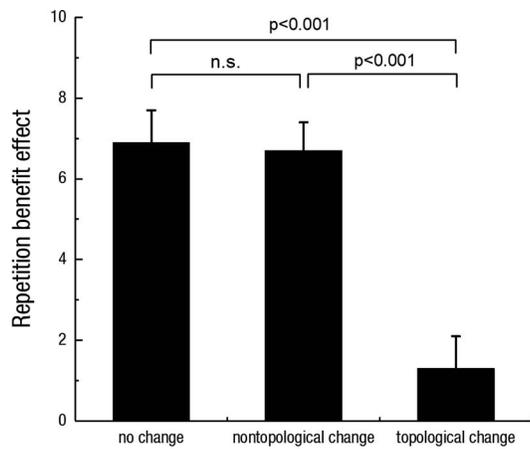


Figure 5. The repetition-benefit effect for the three shape-change conditions with the five groups of stimulus figures.

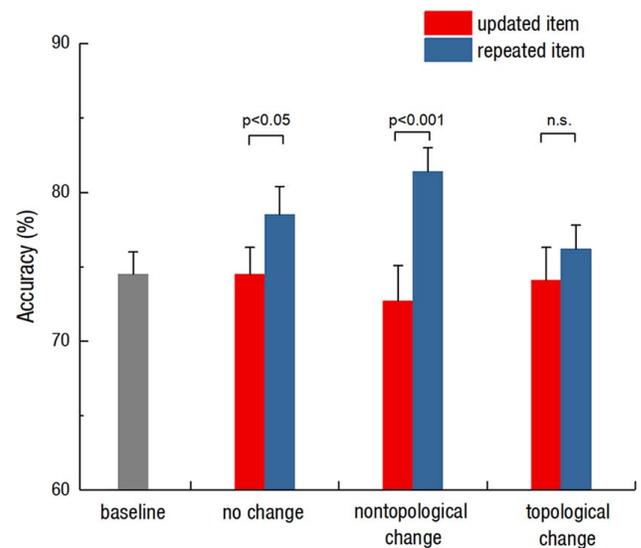


Figure 7. The results of Experiment 3. Red and blue bars are the percent correct of updated and repeated items, respectively. Error bars represent +1 standard error of the mean.

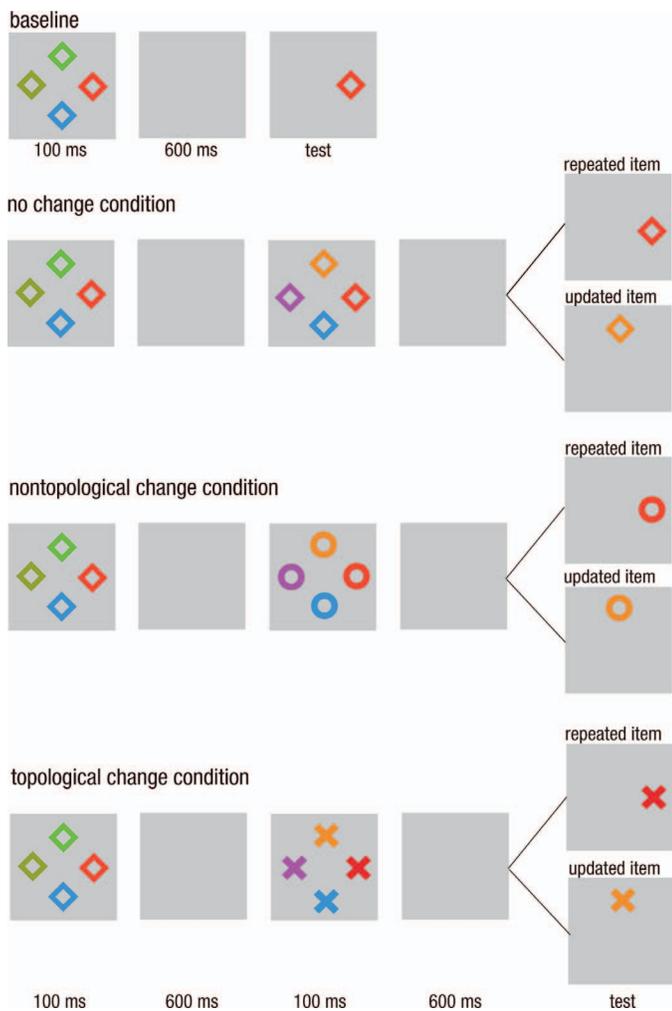


Figure 6. An overview of the paradigm in Experiment 3. Half of the trials included a single visual display (baseline). In the other half of the trials, two items in the second memory array changed colors, while the other two items remained their original colors. The probe could appear at the location of a repeated item or an updated item.

appear in the location of a repeated item or an updated item, with equal probabilities, as shown in Figure 6. The updating of stimuli in the second memory array was further categorized into three conditions: no change, nontopological change, and topological change. Sixteen subjects (19–25 years old) participated in this experiment.

## Results

A repeated-measures ANOVA was conducted on the accuracy data from the baseline and three updated conditions. The detailed results are shown in Figure 7. There was no significant main effect among the four conditions,  $F(3, 45) = 0.365, p = 0.778, \eta_p^2 = 0.024$ . Then a repeated-measures ANOVA was conducted with the shape-change condition (no change, nontopological change, or topological change) of the second memory array and the if-updated of the test item (repeated or updated). It revealed a significant main effect of test item,  $F(1, 15) = 16.834, p < 0.001, \eta_p^2 = 0.529$ , and a significant Shape-change condition  $\times$  If-updated interaction,  $F(2, 30) = 5.905, p = 0.007, \eta_p^2 = 0.282$ . There was no main effect of shape-change condition,  $F(2, 30) = 0.815, p = 0.452, \eta_p^2 = 0.052$ . To further examine the repetition benefit in the three different conditions, we used Bonferroni-corrected paired-samples  $t$  tests. The data revealed that the accuracy was significantly higher when probing repeated items than it was when probing updated items in the no-change condition,  $t(15) = 2.685, p = 0.017, \text{Cohen's } d = 0.671, \text{BF}_{10} = 3.551$ , and the nontopological-change condition,  $t(15) = 4.777, p < 0.001, \text{Cohen's } d = 1.194, \text{BF}_{10} > 100$ . However, there

was no significant repetition benefit in the topological-change condition,  $t(15) = 1.265$ ,  $p = 0.225$ , Cohen's  $d = 0.316$ ,  $BF_{10} = 0.503$ .

The partial-updating conditions engage a more complex cognitive process than whole-updating conditions. Partial updating requires updating a portion of the information while retaining the original memory. In this experiment, only a subset of the items in the second memory array were updated. The results show that the repetition benefit was item specific. The ability to recognize a matched probe depended only on whether that item was repeated or updated, regardless of what happened with the other items in WM. This finding is in line with previous studies (Kessler et al., 2015). Along with Experiments 1 and 2, our results demonstrate that changes in topological properties affected the representation in VWM, indicated by a weakened repetition-benefit effect. In other words, the topological properties might play a fundamental role in the unit of representations in VWM.

## Discussion

The goal of our study was to investigate the unit of VWM representations. We provided evidence that perceptual objects defined by topological properties, as indicated by the repetition-benefit effect, are important for VWM representation. Across three experiments, we found that in both whole-updating and partial-updating tasks, the repetition-benefit effect on color memory was not affected when items in the second memory array underwent modest feature changes in shape from the first memory array. However, when the topological properties of the item were changed, such as the number of holes, the repetition-benefit effect was eliminated or weakened. Taken together, these results are in general agreement with our expectation: Topological change interfered with the continuity of an object and caused the stimulus to be perceived as a new object. Even if the colors of two consecutive objects were identical, participants still needed to update their memories because of the appearance of new objects. The new object replaced the original object, and this replacement caused the repetition-benefit effect to become weaker. In contrast, object continuity survived a broad spectrum of nontopological changes, including massive deformations of shape. A significant repetition-benefit effect did not occur when two consecutive objects were perceived to be one object. This finding is in line with the multiple-object tracking experiment of Zhou et al. (2010), which revealed that topological change could disrupt the continuity of an object and impair subjects' tracking performance. Therefore, the extraction of topological properties was not only the starting point for the

formation of object representation but also the origin of the unit in VWM representation.

It is worth noting that the current findings are congruent with the recently proposed resetting theory of VWM (Balaban et al., 2018; Balaban & Luria, 2017). In a resetting process, VWM discards the original representation and encodes the novel input as a new representation. Balaban and colleagues found that when a black uniform polygon separated into two independent halves, a sharp drop occurred in the amplitude of contralateral delay activity, as did a behavioral cost to detect salient changes, indicating a loss of VWM contents. This was due to object separation, which disrupted the correspondence between the object and its VWM representation. When the object separation occurred, a new object was generated, which was not the same object as the original representation. In such a case, VWM was reset by encoding the object in its novel status as a new representation. Based on the definition of perceptual objects, object separation essentially was a kind of change in topological properties.

Previously, some studies have provided similar evidence that topological properties play an essential role in VWM representations. For instance, Kibbe and Leslie (2016) found that topological class information can be stored in 6-month-old infants' WM by showing infants two topologically distinct objects separately and revealing one of the objects to test. The results showed that infants could remember the topological class of the last-hidden of the two objects. However, they failed to recall both the topology and the existence of the first-hidden object. However, those researchers' previous work showed that infants could remember the existence of two objects when the objects were from the same topological class (Kibbe & Leslie, 2011). These results are in line with our conclusion. Compared to discrepancies in surface features such as color or shape, when objects differ topologically the VWM representation might be more costly to maintain. In addition, the topological class interacted with object individuation in a way that surface features do not. That is, the topological properties would inevitably be represented whenever an object appeared, even if they were a task-irrelevant feature in our studies.

In addition, there is a considerable amount of research demonstrating that the gestalt grouping principles (connectedness, common region, color similarity, and spatial proximity) facilitate VWM performance (Gao, Gao, Tang, Shui, & Shen, 2016; Peterson & Berryhill, 2013; Quinlan & Cohen, 2012; Woodman, Vecera, & Luck, 2003; Xu, 2006). To some extent, improvements in performance can be attributed to the fact that a low-level perceptual grouping treats multiple individual items as a single unit in memory. From the perspective of global topological theory, these percep-

tual grouping principles could essentially be defined by topological properties. Therefore, the inclusion of topological cues would foster the representations of separate objects to be chunked.

The current study provides further evidence regarding two aspects of VWM mechanisms. First, Miller (1956) gave an intuitive description of the essence of chunks: integrality. Massive information at the more local level (e.g., letters) was bound into chunks at the more global level (e.g., words). However, he did not give a mathematical definition of the decisive factors of the integrality, including the grouping, the belongingness, and “what goes with what.” Topology could not only explain various phenomena in perceptual organization but also provide a promising mathematical tool to define chunks. Hence, we propose that the integrality of chunks might be described with global topological properties, including tolerance connectivity and the number of tolerance holes. In addition, our study adds new evidence supporting the perception-alike hypothesis. Several studies have consistently demonstrated the many similarities between visual perception and VWM (Ester, Serences, & Awh, 2009; Gao, Bentin, & Shen, 2015; Gao et al., 2016; Serences et al., 2009). For instance, VWM and perception follow similar gestalt principles. The paradoxical question “what is the unit being represented?” is also embodied in the study of visual perception. The application of the theory of topology successfully addresses this fundamental question. In this study, we found that the perceptual object defined by topological similarity was the unit of VWM representation. From this perspective, the theory of topology could unify the accounts of VWM and visual perception very well. In general, the topological approach to perceptual organization provides a unique perspective for understanding representations in VWM.

*Keywords:* visual working memory (VWM), chunk, topological invariance, repetition-benefit effect

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