Topological change induces an interference effect in visual working memory

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The "irrelevant-change distracting effect" refers to the effect of changes in irrelevant features on the performance of the target feature, which has frequently been used to study information processing in visual working memory (VWM). In the current study, we reported a novel interference effect in VWM: the topological-change interference effect (TCIE). In a series of six experiments, we examined the influence of topological and nontopological changes as irrelevant features on VWM using a color change detection paradigm. The results revealed that only topological changes, although task irrelevant, could produce a significant interference effect. In contrast, nontopological changes did not produce any evident interference effect. Moreover, the TCIE was a stable and lasting effect, regardless of changes in locations, reporting methods, particular stimulus figures, the other salient feature dimensions and delay interval times. Therefore, our results support the notion that topological invariance that defines perceptual objects plays an essential role in maintaining representations in VWM.

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Introduction

Visual working memory (VWM) is a system of storing, manipulating, and using a limited amount of visual information (Baddeley, 2012). It is fundamental to almost all high-level cognitive processes. A large number of studies conducted over the past decades have revealed various properties of VWM, such as its capacity (Alvarez & Cavanagh, 2004; Cowan, 2010; Luck & Vogel, 1997), the different stages (Vogel, Woodman, & Luck, 2006), and the neural mechanisms underlying this system (Todd & Marois, 2004; Vogel & Machizawa, 2004). However, the fundamental unit of VWM representations remains unclear. Whether VWM operates over integrated object representations (Balaban, Drew, & Luria, 2018; Luck & Vogel, 1997) or over visual features stored independently from each other (Fougnie & Alvarez, 2011; Woodman & Vogel, 2008) is controversial.

In fact, this paradoxical question, “What is the unit being represented?” is also embodied in the study of visual perception. In 1982, Chen proposed a seminal theory of early topological perception to answer this fundamental question (L. Chen, 1982). This topology theory claims that topological properties are primitives of visual representation and that topological properties play a major role in the operational definition of a perceptual object. The core intuitive notion of a perceptual object is rooted in its holistic identity preserved over shape-changing transformations (L. Chen, 1982, 2005). This identity can be precisely characterized as topological invariance, including properties such as connectedness, continuity, and boundary, which are preserved 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 et al., 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 (L. Chen, Zhang, & Srinivasan, 2003). These results support the notion that topological properties are extracted at the very beginning of visual processing to form basic constraints on object coding. The topological definition of perceptual object has been successfully applied in so many cognitive fields. Therefore, we hypothesize that topological invariance may be suitable for defining the basic unit of VWM, which would profoundly facilitate the understanding of the representational maintenance of VWM.

Some previous studies have provided evidence to support the notion that topological properties play an essential role in maintaining VWM representations. For instance, Kibbe found that topological class information can be stored in the working memory of 6-month-old infants. When objects differ topologically, the VWM representation may be more costly to maintain than when they differ in surface features such as color or shape. In addition, the topological class interacts with object individuation in a way that surface features do not (Kibbe & Leslie, 2011, 2016). Furthermore, Balaban found that when a black uniform polygon was separated into two independent halves, the contralateral delay activity (CDA) amplitude sharply decreased, indicating a loss of VWM content. This decrease was due to object separation, which disrupted the correspondence between the object and its VWM representation. Based on the definition of perceptual objects, object separation is a type of change in topological properties (Balaban et al., 2018; Balaban & Luria, 2017).

Another, and the most direct, piece of evidence came from our previous research (Wei, Zhou, Zhang, Zhuo, & Chen, 2019). Participants were presented with either a single memory array or two successive memory arrays. They were asked to store the items’ colors from the most recent memory array and to report whether the color of the test item changed. The colors of the second array were either consistent with those of the first array (repetition) or completely different (updating). There were three conditions: the no shape-change condition, the shape-change condition (the items’ shapes, which were task irrelevant in the second array, were different from those in the first memory array, e.g., a solid square changed to a solid disk), and the topological change condition (the items’ topological properties changed, e.g., a solid square changed to a hollow square). A series of experiments showed that a repetition benefit effect was found when the items in the second array were the same as those in the first array. In addition, this effect was not altered when items underwent modest feature changes in the second memory array. However, when the topological properties of the item were changed, such as the number of holes, the repetition benefit effect was eliminated. The reason was that once a topological property of an object changed, participants would treat that object as a new object, discard the original representation, and encode the input as a new representation. Therefore, the disappearance of this repetition benefit effect suggests that defining perceptual objects by their topological properties is essential for VWM representations.

There are three main stages involved in VWM: encoding, consolidation, and retrieval. In our repetition benefit effect study, we manipulated the memory items at the encoding stage. If the topological properties of the items were changed at that stage, the memory items would need to be reencoded. However, there are two problems with this paradigm. First, the repetition benefit effect was destroyed when the topological properties of the item changed, which was represented as null results in the data. The effect of topology on memory representation could not be assessed. Second, the paradigm was too complicated, and the influence of other factors (such as the number of items, interval times, and spatial locations) could not be examined conveniently.

The "irrelevant change distracting effect" has been frequently used in many studies to assess whether representations in VWM are based on objects or features. To test this hypothesis, researchers have predominantly used multiple-featured objects (e.g., colored shapes) as the stimuli of interest and required participants to remember one feature dimension (e.g., color) while ignoring the others (e.g., shape). If an item's recognition was disrupted by task-irrelevant changes, the researchers could infer that the irrelevant feature was presented in memory representation. Adopting this type of manipulation, many previous VWM studies found that irrelevant feature changes in the test array dramatically influenced the behavioral performance for the target feature. They assumed that, once selected, all features of an object are then obligatorily stored in VWM regardless of their behavioral relevance (Treisman & Zhang, 2006). However, some studies were unable to replicate this effect (Serences, Ester, Vogel, & Awh, 2009; Yu & Shim, 2017). The participants could perfectly restrict their selection of the task-relevant information while filtering out the task-irrelevant information. These findings demonstrated natural strategies for efficiently using limited memory resources. Other studies supported object-based theory but relied on some restrictions. For example, Xu found that object-based task-irrelevant shape processing was present at low color-encoding loads. It was attenuated or even suppressed at high color-encoding loads (Xu, 2010). Likewise, Ecker presented a series of experiments strongly suggesting that irrelevant intrinsic but not extrinsic object-irrelevant information was obligatorily stored, affecting performance in VWM task-relevant feature recognition (Ecker, Maybery, & Zimmer, 2013). The essence of the irrelevant feature interference effect was destroyed by the stored object representation. One possible reason for the discrepancies in these results may be that the definition of objects across these studies was not unified.

Given this background, the present study was conducted by probing the "irrelevant change distracting effect," a simpler and more straightforward method for verifying the importance of perceptual objects defined by topological properties for VWM representation. Based on our hypothesis that a perceptual object is defined by its topological properties, we predicted that the distracting effect would be observed when topological properties changed in the test array as a task-irrelevant feature; otherwise, there should be no distracting effect. We name this "irrelevant-change distracting effect" caused by changes in topology the "topological-change interference effect" (TCIE).

This hypothesis was explored in six different experiments. First, we assessed whether interference effects occurred when the topological properties changed. If the TCIE existed, we further clarified whether it was stable, regardless of changes in location, reporting methods, particular stimulus figures, the other salient feature dimensions and delay interval times.

Experiment 1: Measure the TCIE in VWM

We first examined the influence of topological and nontopological properties as irrelevant features under different VWM loads in a color change detection paradigm. If a change in the task-irrelevant feature in the test array dramatically influenced the behavioral performance related to the target feature, the irrelevant feature would have been stored and processed in VWM.

Method

Participants

The sample size was comparable to that in our previous study (Wei et al., 2019). A power analysis conducted with G*Power revealed that to detect a relatively large effect, $f(U) = 0.58$, of interaction between shape-change conditions with a power of 95% and an alpha of 0.05, a sample of only 12 participants would be required. We further increased our sample to $N = 15$ to ensure sufficient statistical power in our analyses for each experiment.

The participants were university undergraduates who received hourly pay for their participation. There were 15 participants (8 males; age, 19–23 years) in Experiment 1. All participants had normal or corrected-to-normal vision and were right-handed, and they were all naive to the purpose of the experiments. The study was approved by the ethics committee of the Institute of Biophysics at the Chinese Academy of Sciences, Beijing.

Apparatus and stimuli

Stimuli were displayed on a 19-in. CRT monitor (refresh rate 100 Hz) with a resolution of 1,024 × 768 pixels. The experiment was programmed and run in MATLAB 2013a with 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.

All stimuli were presented within a 9.8° × 7.3° region on a gray background at a viewing distance of 70 cm. Each item was randomly placed within

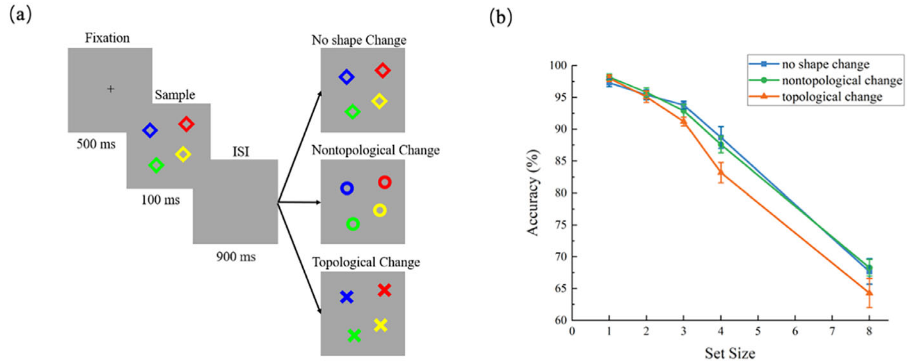

Figure 1. (a) Schematic description of a no-change trial from Experiment 1. (b) Accuracy in Experiment 1; error bars represent ± 1 *SEM*.

this region with the constraint that the items in a given array were separated from each other by at least 2° (center-to-center). The color of each square was randomly selected from a set of seven highly discriminable colors: white, red, blue, green, black, yellow, and purple. Note that for both the memory array and the test array, each color appeared no more than twice. When a color changed between the memory and test arrays, the new value was randomly selected from all other possible feature values. Each stimulus subtended a visual angle of 0.95° × 0.95°. Three stimulus patterns were used in the experiment: hollow diamonds, rings, and x-like symbols (hereafter referred to as crosses).

Procedure

The experimental paradigm is shown in Figure 1a. Each trial began with a 500-ms fixation to warn the participants of the start of a trial. Then, a 100-ms sample display containing one, two, three, four, or eight colored items was presented, followed by a 900-ms blank interval. Finally, a test array was presented on the screen until a response was made. Three conditions were imposed on the stimulus shapes in the test array. In the no shape-change condition, the shapes presented in the memory and test arrays were identical hollow diamonds. In the nontopological-change condition, the hollow diamonds changed to rings in the test array. Different from the hollow diamond, the ring was composed of curves instead of directional line segments. There was a hole in the middle of a hollow diamond and a ring, so their topological properties were identical. In the topological-change condition, the shapes changed to crosses. Compared with the hollow diamond, the cross was also composed of four line segments. The ring and the hollow diamond each contained a hole, whereas the cross did not. This set of figures was matched in terms of various nontopological factors: sloped edges and curvature (there was less difference between the hollow diamond and the cross than the hollow diamond and the ring), spatial-frequency components, and luminous flux.

Using a whole-probe report method, the test array was identical to the sample array in 50% of trials and differed in the color of one item in the remaining 50% of trials. The participants were explicitly instructed to detect whether a color changed between the memory and test array while ignoring the shape, which would impair their performance if they attended to it. The participants were encouraged to respond accurately using two-alternative forced-choice responses on a response pad at the end of each trial, and their response accuracy and capacity under different conditions were analyzed.

A 3 (shape change in test array: no change, nontopological change, or topological change) by 5 (set size: 1, 2, 3, 4, or 8) within-participant design was used. There were 56 trials in each condition, resulting in a total of 840 trials per participant. These trials appeared randomly and unpredictably within 12 blocks. Before the experiment, all participants performed 60 trials (4 trials per combination of shape-change and set-size conditions).

Results and discussion

The percentage of correct responses is shown in Figure 1b. To determine whether there were differences in accuracy across the different experimental conditions, we performed 3 × 5 repeated-measures analysis of variance (ANOVA). Greenhouse–Geisser corrections were applied when sphericity assumptions were violated, although these corrections did not change any inferences. This analysis yielded significant main effects of shape-change conditions, $F(2, 28) = 8.84$, $p = 0.001$, $\eta_p^2 = 0.39$. Further Bonferroni post hoc tests showed that the mean accuracy in the topological-change condition was significantly lower than those in the no-change condition and in the nontopological-change condition ($p_{bonf} = 0.016$, $p_{bonf} = 0.005$). There was no difference between the no-change condition and the nontopological-change condition ($p_{bonf} = 1$). The effect of set size was also significant, $F(2.25, 31.43) = 300.72$, $p < 0.001$, $\eta_p^2 = 0.96$. The accuracy decreased as the set size increased. The interaction effect of the shape-change condition with set size was not significant, $F(3.20, 44.81) = 1.99$, $p = 0.126$, $\eta_p^2 = 0.12$.

These findings were consistent with our expectations: The interference effect was found only in the topological-change condition, and no interference effects were found in the nontopological-change condition. The reason may be that the topological change interfered with the continuity of an object and caused the stimulus to be perceived as the emergence of a new object. In other words, the memory items that were topologically equivalent, such as a diamond and a ring, were treated as the same objects. However, when the items were topologically different, such as a diamond and a cross, participants would treat the object in the test array as a new object. This result implies that the topological change would produce a novel interference effect and destroy the original VWM representation.

Experiment 2: Assess the influence of item locations

The entire pattern (interitem relationships) of memory items plays an important role in VWM. A previous study implied that participants seemed to remember the entire pattern or spatial configuration of an array rather than the individual items (Jeong & Xu, 2013; Jiang, Olson, & Chun, 2000). Scrambling the locations led to impairments in change-detection performance (Hollingworth & Rasmussen, 2010; Jiang et al., 2000). In the following experiment, we considered the impact of the entire pattern on TCIE by scrambling the location consistency between the test array and memory array. Theoretically, the TCIE was produced by changes in an individual item's representation, and we suspected that this effect would not be altered by differences in spatial configuration.

Method

The display and procedure were the same as those in Experiment 1, except that the number of items in the sample array was two, four, six, or eight. Thirty university undergraduates volunteered to participate in this experiment, which was divided into two parts. Fifteen (6 males; age, 17–24 years) subjects participated in the same location experiment, in which the test items occupied the same locations as the sample display. Another 15 (8 males; age, 18–27 years) subjects participated in different location experiments, in which the test items were presented in new locations. The participants were required to ignore the variations in position and to detect whether there was a color change between the sample and test arrays.

All participants had normal or corrected-to-normal visual acuity and normal color vision, and they were naive to the purpose of the experiments. There were 84 trials for each condition, resulting in 1,008 total trials per participant presented randomly in 14 blocks. Before the experiment, all participants performed 72 trials (6 trials per combination of shape-change and set-size conditions).

Results and discussion

Participant accuracy in the same location experiment is shown in Figure 2b. A 3 (shape change) × 4 (set size) repeated-measures ANOVA showed a significant main effect of set size, $F(3, 42) = 264.62$, $p < 0.001$, $\eta_p^2 = 0.95$. No significant main effect of shape-change condition was found, $F(2, 28) = 2.12$, $p = 0.139$, $\eta_p^2 = 0.13$. Importantly, the interaction effect between shape-change condition and set size was significant, $F(6, 84) = 2.47$, $p = 0.030$, $\eta_p^2 = 0.15$. We further analyzed the effect of the shape-change condition under different set sizes. A significant TCIE was revealed with a set size of 4, $F(2, 28) = 6.08$, $p = 0.006$, $\eta_p^2 = 0.30$. The accuracy was significantly worse in the topological-change condition (mean = 81.6 ± 6.0) than in the no-change condition (mean = 86.0 ± 7.9, $p_{bonf} = 0.046$) and nontopological-change condition (mean = 85.9 ± 5.1, $p_{bonf} = 0.015$). The difference between the no-change condition and the nontopological-change condition was not significant ($p_{bonf} = 1$). No significant TCIE was found for set sizes 2, 6, and 8 ($p = 0.711$, $p = 0.995$, $p = 0.142$).

Figure 2c shows the mean accuracy of the location change experiment. A 3 (shape change) × 4 (set size) repeated-measures ANOVA was performed. The main effect of set size was significant, $F(3, 42) = 436.16$, $p < 0.001$, $\eta_p^2 = 0.97$. Again, there was no main effect of conditions, $F(2, 28) = 2.37$, $p = 0.112$, $\eta_p^2 = 0.15$. The interaction effect between set size and shape-change condition was marginally significant, $F(6, 84) = 1.99$, $p = 0.076$, $\eta_p^2 = 0.13$. We also found that there was a significant TCIE only when participants remembered four items, $F(2, 28) = 15.07$, $p < 0.001$, $\eta_p^2 = 0.52$. When the test items involved a topological change, the memory performance (mean = 79.1 ± 6.7) was significantly lower than that in the

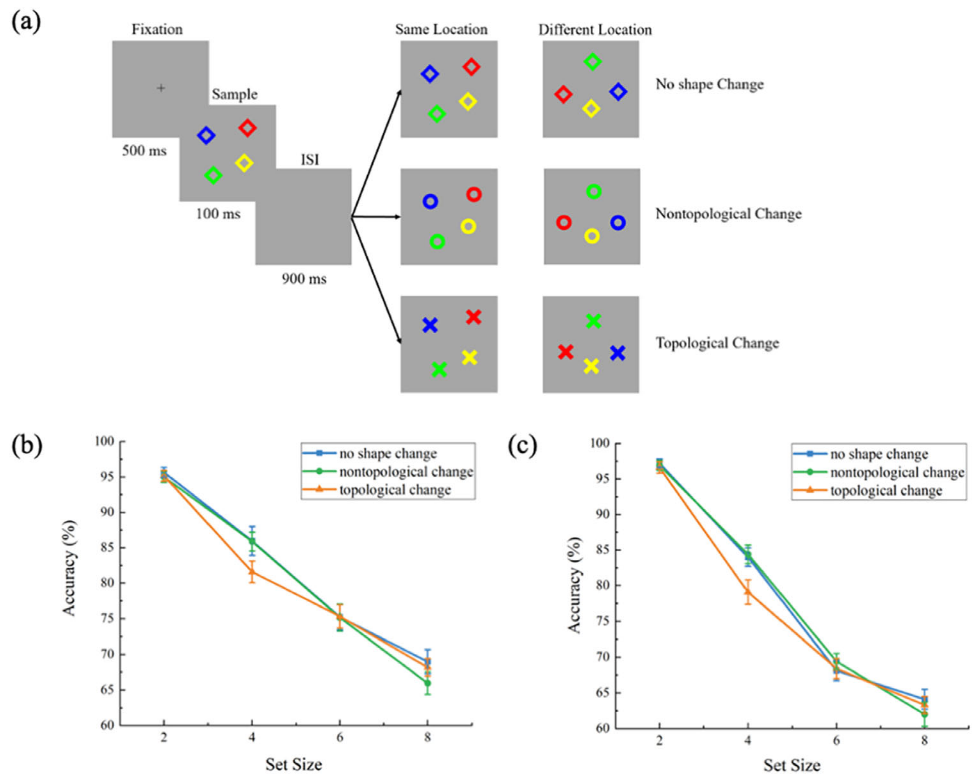

Figure 2. (a) Schematic description of Experiment 2. (b, c) Results for the same location and different locations, respectively.

nontopological-change condition (mean = 84.4 ± 5.1, $p_{bonf} < 0.001$) and no-change condition (mean = 84.0 ± 5.0, $p_{bonf} = 0.003$). Again, we did not find a significant TCIE for set sizes 2, 6, and 8 ($p = 0.646$, $p = 0.785$, $p = 0.619$).

Cross-experiment analysis

To investigate the effect of location cues on TCIE, we analyzed the data from the same location experiment together with the data from the different location experiment. A 2 (location: same, different) × 3 (shape change: no shape change, nontopological change, topological change) × 4 (set size: 2, 4, 6, 8) mixed ANOVA showed a significant main effect of location, $F(1, 28) = 5.24$, $p = 0.03$, $\eta_p^2 = 0.16$. The participants performed better in the same-location experiment than in the different-location experiment. This finding was consistent with previous studies showing that scrambling the locations led to impairments in change-detection performance (Hollingworth & Rasmussen, 2010; Jiang et al., 2000). The entire pattern (interitem relationships) of memory items plays an important role in VWM. The main effects of shape condition, $F(2, 56) = 4.08$, $p = 0.022$, $\eta_p^2 = 0.13$, and set size, $F(3, 84) = 686.92$, $p < 0.001$, $\eta_p^2 = 0.96$, were significant. The performance in the topological-change condition was significantly lower than that in the no-change condition ($p_{bonf} = 0.037$). More important, there was no significant interaction effect between shape change and location change, $F(2, 56) = 0.43$, $p = 0.651$, $\eta_p^2 = 0.00$. These results implied that the TCIE was stable, regardless of any changes in location. When a sample array is memorized, both the properties of the items and the pattern of the sample array are processed by working memory. The pattern could help with the task of extracting the memory. Therefore, the changed pattern of objects with scrambled locations could impair memory. However, this interference effect was not similar to that of TCIE, which was generated by the representation of the individual item itself and was not due to a change in the entire pattern. We supposed that the representation of VWM is hierarchical and that the representation of the memory item defined by topology was relatively abstract and not tightly bound to locations.

Experiment 3: Probing method did not erase TCIE

Both Experiments 1 and 2 used a whole-probe method, in which all the test stimuli could be

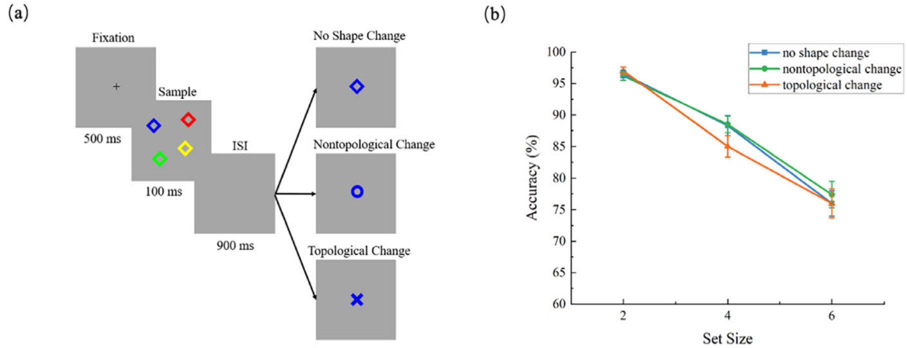

Figure 3. Paradigm and results of Experiment 3, which presented only a single probe.

represented in a global configuration. It is possible that this testing method primed the participants to process the memorized stimuli in a global manner, which constrained the study of the representation of the individual memory items themselves. Moreover, more items changed their shapes in the whole display test, which may have increased the total conflict. To rule out these alternatives, we used a single-probe method in Experiment 3, in which only one item was presented at the center of the screen for judgment. The goal of this experiment was to study whether the TCIE was affected by the reporting methods.

Method

Fifteen (8 males; age, 19–25 years) university undergraduates volunteered to participate in this experiment. The display and procedure were the same as in Experiment 1, except that at testing, a single probe item was presented in the center of screen. The number of items in the sample array was two, four, or six. The seven different colors appeared only once in one trial. The task was to detect whether this probe's color had been presented in the sample array or was a novel color. There were 84 trials in each condition, resulting in 756 total trials per participant.

Results and discussion

The mean accuracy in each condition is shown in Figure3b. A 3 (shape change) × 3 (set size) repeated-measures ANOVA was conducted. Performance was better when participants needed to remember fewer memory items with small set sizes, $F(2, 28) = 96.08$, $p < 0.001$, $\eta_p^2 = 0.87$. There was no main effect of shape-change condition, $F(2, 28) = 1.71$, $p = 0.199$, $\eta_p^2 = 0.11$. Importantly, there was a significant interaction effect between shape-change condition and set size on accuracy, $F(4, 56) = 3.34$, $p = 0.016$, $\eta_p^2 = 0.19$. Closer analysis of the interference effects across set sizes revealed a significant TCIE only with a set size of 4, $F(2, 28) = 10.57$, $p < 0.001$, $\eta_p^2 = 0.43$. The performance in the topological-change condition (mean = 85.0 ± 6.4) was significantly worse than that in the no-change condition (mean = 88.3 ± 6.3, $p_{bonf} = 0.003$) and in the nontopological-change condition (mean = 88.5 ± 4.9, $p_{bonf} = 0.008$). The shape-change effect was not significant for set size 2, $F(2, 28) = 0.59$, $p = 0.561$, $\eta_p^2 = 0.04$, and set size 6, $F(2, 28) = 0.55$, $p = 0.583$, $\eta_p^2 = 0.04$.

Performance is usually worse for the single-probe method than for the whole-probe method (Jiang et al., 2000). However, the single-probe method had two possible advantages in our experiments. First, only one item must be checked, reducing the decision load relative to the whole-probe display. The second potential advantage of the single-probe condition was that interference from multiple items in the probe was eliminated. Using the single-probe method, we replicated the main finding from Experiments 1 and 2, confirming that the TCIE was significant. Therefore, regardless of the probing methods, the TCIE persisted.

Experiment 4: TCIE observed with different stimuli

In Experiments 1, 2, and 3, we used only one group stimulus graphic as the sample stimulus. A major challenge in the study of topological discrimination is that no two geometric figures appear to differ only in their topological properties while demonstrating no differences in local features. Thus, one cannot assess the role of topological differences in form perception in complete isolation by designing stimuli

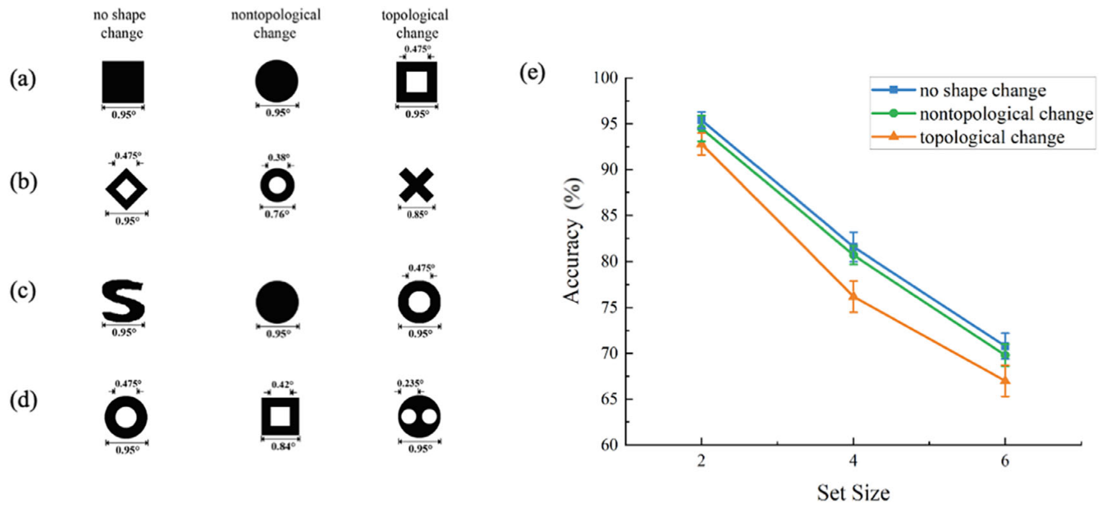

Figure 4. (a–d) Schematic depiction of the stimulus groups used in Experiment 4. They were designed to manipulate topological variations between stimuli while controlling for local features, such as luminous flux, spatial-frequency components, and terminators. (e) Results of Experiment 4.

that differ only topologically without any differences in nontopological features. To solve this problem and rule out explanations based on nontopological features, we carefully designed four groups of stimulus figures in Experiment 4.

Method

Fifteen (8 males; age, 18–27 years) university undergraduates volunteered to participate in this experiment.

The paradigm was identical to that in Experiment 1 except for the stimuli and the set size. Four different groups of patterns of stimuli were used, as shown in Figure 4a, adapted from our previous studies (Wei et al., 2019). The topology was generalized to different types of topological transitions, including the transition from no hole to one hole (Figure 4a,c), from one hole to no hole (Figure 4b), and from one hole to two holes (Figure 4d). Additionally, we carefully controlled for nontopological features, such as the color area, luminous flux, spatial-frequency components, perimeter length, sloped edges and curvature, and other possible confounding local features. The nontopological changes included massive shape deformations involved in various local feature changes. Although phenomenally they looked quite different, these stimulus figures were topologically equivalent to each other.

The number of memory items was two, four, or six, and the seven different colors appeared only once in one trial. Twenty-eight trials for each condition with every stimulus resulted in a total of 1,008 trials per participant, appearing randomly within 14 blocks.

Results and discussion

The results of the experiment are shown in Figure 4e. A 3 (shape-change condition) × 3 (set size) × 4 (stimulus figures) repeated-measures ANOVA showed a significant effect of the shape-change condition, $F(2, 28) = 21.20$, $p < 0.001$, $\eta_p^2 = 0.60$. Further Bonferroni post hoc tests showed that the accuracy in the topological-change condition was significantly lower than that in the no-change condition and nontopological-change condition ($p_{\text{bonf}} < 0.001$, $p_{\text{bonf}} = 0.003$). There was no difference between the no-change condition and the nontopological-change condition ($p_{\text{bonf}} = 0.072$). There was also a significant effect of set size, $F(2, 28) = 329.97$, $p < 0.001$, $\eta_p^2 = 0.96$. However, the interaction of the shape-change condition with set size was not significant, $F(4, 56) = 1.06$, $p = 0.392$, $\eta_p^2 = 0.07$. The main effect of four stimulus sets was not significant, $F(3, 42) = 1.87$, $p = 0.149$, $\eta_p^2 = 0.12$. The interaction of stimulus and conditions was also not significant, $F(6, 84) = 49.66$, $p = 0.474$, $\eta_p^2 = 0.06$.

In this experiment, more stimulus graphics were used than in the prior experiments. The four groups of stimuli were carefully designed to prevent the participants from using various nontopological cues. Meanwhile, the participant's expectation of the stimulus pattern was eliminated. The results supported that the variations of different stimulus figures do not change the TCIE. We further analyzed the performance separately for each of the four stimulus groups, as shown in the supplementary material.

Experiment 5: Rule out the salience account and other possible confounds of local feature

Perceptually, topological changes are always considered more salient than nontopological changes. Obviously, this is exactly the intrinsic performance of “topology first.” But experimentally, in order to provide a “fair” comparison, it needs to be determined whether the topology is essentially different from other salient but nontopological changes. Next, we individually tested the stimulus group that included S-like figure, disk, and ring. The test item of nontopological changes, the solid disk, is maximally dissimilar to the memory item (S-like figure).

Method

Fifteen (5 males; age, 20–31 years) university undergraduates volunteered to participate in this experiment. The experimental paradigm is shown in Figure 5a. The display and procedure were the same as in Experiment 4 except for the stimulus patterns. In the no shape-change condition, the shapes presented in the memory and test arrays were identical S-like figures. In the nontopological-change condition, the S-like figures changed to disks in the test array, and in the topological-change condition, the shapes changed to rings. 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 in comparison to the disk. The number of items in the sample array was two, four, or six. There were 56 trials in each condition, resulting in 504 total trials per participant.

Results and discussion

The results for each condition are shown in Figure 5b. Repeated-measures ANOVA revealed a significant effect of shape-change conditions, $F(2, 28) = 8.15$, $p = 0.002$, $\eta_p^2 = 0.37$. The effect of set size was also significant, $F(2, 28) = 93.99$, $p < 0.001$, $\eta_p^2 = 0.87$. Furthermore, a nearly significant interaction effect of shape-change condition with set size was revealed, $F(4, 56) = 2.43$, $p = 0.058$, $\eta_p^2 = 0.15$. We further analyzed the effect of the shape-change condition under different set sizes. The results revealed a significant TCIE with a set size of 4, $F(2, 28) = 9.78$, $p < 0.001$, $\eta_p^2 = 0.41$. Further Bonferroni post hoc tests showed that the mean accuracy in the topological-change condition (mean = 79.6 ± 9.9) was significantly lower than that in the no-change condition (mean = 87.4 ± 6.1, $p_{bonf} = 0.002$) and in the nontopological condition (mean = 84.8 ± 8.7, $p_{bonf} = 0.016$). By contrast, there was no significant difference between the no-change condition and nontopological change condition ($p_{bonf} = 0.191$). For set sizes of 2 and 6, the TCIE was not significant ($p = 0.309$, $p = 0.131$). This set of stimuli showed that with a sufficient number of trials, the TCIE was stable when the set size was 4. This result will be further discussed across all experiments in the general discussion section.

Experiment 6: TCIE at different interstimulus intervals

A previous study showed that randomizing location as a task-irrelevant feature was more disruptive than randomizing other features, but its interference effect disappeared after a 1,500-ms delay interval and was not

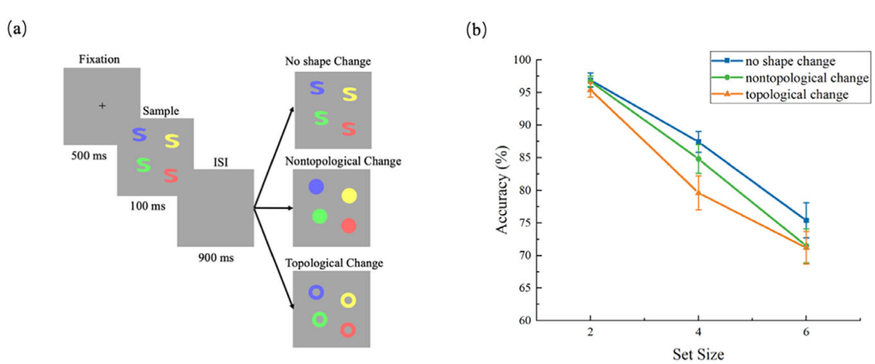

Figure 5. The paradigm and results of size change. Error bars represent ± 1 *SEM*.

persistent (Logie, Brockmole, & Jaswal, 2011). As we hypothesized that TCIE is derived from memory item representation, it should not be affected by longer delay intervals. In the present experiment, we investigated the TCIE with different delay intervals with a set size of 4, which was the most sensitive to the TCIE, to assess whether TCIE was maintained over longer delays. Furthermore, we investigated whether TCIE would be affected when the participants could not predict delay intervals.

Method

Fifteen (8 males; age, 18–27 years) university undergraduates volunteered to participate in this experiment. The procedure was the same as that in Experiment 1 with the following exceptions: There were four different delay intervals between the initial display and the probe: 1 s, 2 s, 3 s, and 8 s. The four delays were randomly presented within the blocks. The number of items in the memory set size was four. There were 56 trials in each condition, resulting in 672 total trials per participant.

Results and discussion

The accuracy results from this experiment are shown in Figure 6. A 3 (shape-change condition: no change, nontopological change, topological change) × 4 (study-test interval: 1 s, 2 s, 3 s, 8 s) ANOVA was conducted to analyze the accuracy of the memory of the test array. Violations of sphericity were Greenhouse–Geisser corrected throughout. The analysis of the accuracy showed a significant main effect of the study-test interval, $F(1.53, 22.16) = 28.08$, $p < 0.001$, $\eta_p^2 = 0.67$, indicating that the accuracy decreased as the interstimulus interval (ISI) increased. A significant main effect of shape-change condition was observed, $F(2, 28) = 27.12$, $p < 0.001$, $\eta_p^2 = 0.66$. Post hoc pairwise comparisons revealed that the accuracy in the topological-change condition (mean = 80.7 ± 6.4) was significantly lower than the accuracy in the no-change condition (mean = 84.3 ± 6.8, $p_{bonf} < 0.001$) and the nontopological-change condition (mean = 83.0 ± 7.0, $p_{bonf} < 0.001$), and there was no significant interaction between these variables, $F(6, 84) = 1.38$, $p = 0.232$, $\eta_p^2 = 0.09$. We also analyzed each ISI separately. The detailed statistical results are presented in Table 1. These results consistently showed that only the topological-change condition showed a significant interference effect, indicating that regardless of the ISI duration, the TCIE was always stable.

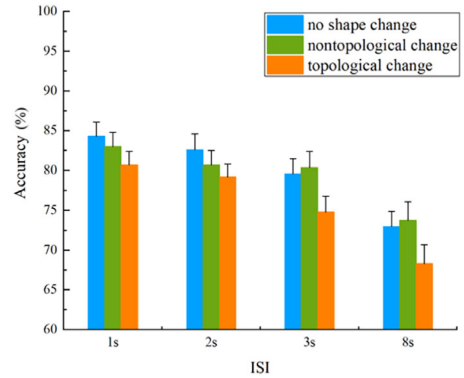

Figure 6. Accuracy in Experiment 6 across different ISIs. Error bars represent ± 1 *SEM*.

There is one difference between our results and those of previous studies. Although an interference effect caused by irrelevant information was also found in several studies (Logie et al., 2011; Xu, 2010), their interference effects vanished as the interval increased. However, according to our results, the TCIE persisted even when the interval was as long as 8 s. It did not decay as the storage time was prolonged. This result indicates that topological properties are inherent to the items being represented in VWM.

Discussion

The goal of the current study was to investigate the role of perceptual objects defined by topological properties in VWM representations. We first examined the effect of topological change and nontopological change under different VWM loads using a whole-probe

ISI	ANOVA	No change vs. nontopological	No change vs. topological	Nontopological vs. topological
1 s	$F(1.44, 20.20) = 7.04$, $p = 0.009$, $\eta^2 = 0.36$	$p_{bonf} = 0.823$	$p_{bonf} = 0.011$	$p_{bonf} = 0.008$
2 s	$F(2, 28) = 4.00$, $p = 0.030$, $\eta^2 = 0.22$	$p_{bonf} = 0.439$	$p_{bonf} = 0.078$	$p_{bonf} = 0.448$
3 s	$F(2, 28) = 9.42$, $p < 0.001$, $\eta^2 = 0.40$	$p_{bonf} = 1$	$p_{bonf} = 0.005$	$p_{bonf} = 0.005$
8 s	$F(2, 28) = 8.03$, $p = 0.002$, $\eta^2 = 0.37$	$p_{bonf} = 1$	$p_{bonf} = 0.007$	$p_{bonf} = 0.020$

Table 1. Results of ANOVA and paired *t* tests for each ISI.

method, in which the topological and nontopological properties were designed to be irrelevant to the task. We found that a change in topology (i.e., a change in the number of holes) reliably impaired WM performance: The memory accuracy was significantly lower than that in the no-change condition and in the nontopological-change condition. In Experiment 2, we deconstructed the configural properties (interitem relationships) by randomizing the locations of items in the test array. In Experiment 3, only one item was presented and assessed in the test phase, reducing the decision load relative to the whole display and eliminating interference from multiple items in the probe. Regardless of the change in location or the method of reporting, the TCIE was always evident. In Experiment 4, four different types of topological transitions were tested. To rule out the possibility that the TCIE was caused by surprise or salience, similar perceptual changes were used in the topological and nontopological methods in Experiment 5. In both these experiments, the TCIE was again found. In Experiment 6, although the memory performance gradually decreased as the ISI increased from 1 s to 8 s, the TCIE could be detected with little decrement.

Through a series of experiments, interference effects were found only in those conditions in which the topological properties of the test items changed. No interference was observed in conditions where nontopological properties changed. This finding is in accordance with Zhou's multiple-objects tracking experiment (Zhou et al., 2010). He found that performance was not disrupted when moving items underwent significant feature changes. However, performance was significantly impaired when the topological properties of items (the number of holes) changed. Based on the “early topological perception” theory (L. Chen, 2005), when the test item undergoes a topological change, manifested in the form of holes, the topological change interferes with the continuity of an object and causes it to be perceived as a new object. In other words, the item in the test array is no longer the same object as the originally stored item. This change makes it quite difficult for participants to match the new object with the original memory. Hence, an interference effect occurs, resulting in a dramatic change in the behavioral performance for the target feature. In contrast, object continuity survives a broad spectrum of nontopological changes, including massive deformations in the shape of the object. The item in the test array is still perceived as the object in memory. Combined with the previous study on the repetitive benefit effect, the topological changes occur while encoding the sample array. We found that regardless of the encoding or retrieval stage, the topological properties were inevitably represented whenever an object appeared, even if the topological properties were task irrelevant.

In addition, a growing number of studies have found that the representation in VWM is hierarchical. Different levels of information representation in the hierarchical structure jointly determine the capability and quality of VWM representation. Importantly, the various features are influenced by feedback from global-level object representation (Timm & Papenmeier, 2019). A considerable amount of research has demonstrated that the Gestalt grouping principles (connectedness, closure, color similarity, and spatial proximity) facilitate VWM performance (S. Chen, Kocsis, Liesefeld, Muller, & Conci, 2021; Peterson & Berryhill, 2013; Quinlan & Cohen, 2012; Woodman, Vecera, & Luck, 2003). Perceptual grouping provides an efficient way to combine multiple elements into global-level units (Brady & Alvarez, 2011; Nie, Muller, & Conci, 2017; Papenmeier & Timm, 2021). From the perspective of global topological theory, these perceptual grouping principles could essentially be defined by topological properties. Compared with the Gestalt principle, the topological framework provides a formal analysis of concepts and the process of perceptual origination as a promising mathematical tool. It could be general enough to address various phenomena in perceptual organization, such as “what goes with what,” grouping, and belongingness. Therefore, we proposed that the topological property as a global-level structure could be automatically integrated into the representation of VWM.

It is worth noting that color and shape, so-called separable dimensions, were used in this study. A "separable" feature is a feature, such as color or shape, that shows no Garner interference in selective attention tasks, similar to those pioneered by Garner. These features similarly show no redundancy gains, indicating that they can be processed independently (Algom & Fitousi, 2016). However, we found an apparent failure of selective attention when shape changes were topological. In other words, in cases where shape changes are topological, color changes cannot be processed independently from shape changes. A previous study showed that topological perception modulates object-level masking and influences the ongoing visual processing of features that are at a lower and local level (Huang et al., 2018). This finding implies that topological properties dominate in the perception of objects, breaking through the filters that normally keep shape information from entering memory. These topological properties are inherent to the object and cannot be filtered. Therefore, regardless of low-level visual perceptual or high-level cognitive processing, the global topological property of an object is extracted at the very beginning of visual processing to form basic constraints on object coding and maintenance. A similar information extraction mechanism is shared between visual perception, which selects objects from the outside scene, and VWM, which extracts information from a perceptual object. In future studies, the perceptual object defined by topological similarity could help us better understand the relationship between perception and VWM.

It should be noted that there were some limitations in this study. One limitation was the discrepancy in the results between the current study and some previous studies. Other studies found that irrelevant feature changes in the test array influenced the behavioral performance of the target feature (Gao, Gao, Li, Sun, & Shen, 2011; Shen, Tang, Wu, Shui, & Gao, 2013; Treisman & Zhang, 2006). However, there are differences in the experimental details between our experiments and their experiments. First, most supportive evidence was presented with reaction times (RTs) (Gao et al., 2011; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Shen et al., 2013; Yin et al., 2012). Participants needed more time to respond when an irrelevant dimension change was present than when it was absent. In fact, similar results were observed in a study of perceptual comparisons (Hyun et al., 2009). We considered accuracy may be a better indicator of working memory in the study, as accuracy could directly reflect whether the items were remembered. In contrast, RT is influenced by many complicated factors and cannot directly reflect the characteristics of memory. Second, a small number of studies have shown the interference effect to be caused by irrelevant features with d′ measures or accuracy. However, the results were not stable across all experiments, as in Yin et al. (2012), which showed a difference in d′ only with the whole-probe method but not with the partial-probe method. In our study, the TCIE was not affected by the reporting methods. In addition, the topological properties of the stimuli were not normalized in these studies (Yin et al., 2012). We cannot rule out the possibility that the distracting effect was caused by topological changes. Third, even if the nontopological interference effect was present, it would not be maintained for as long as TCIE (Xu, 2010). As mentioned above, location played a unique role as a task-irrelevant feature. However, its interference effect only lasted for 1,500 ms. Based on all this evidence, the TCIE in the current study is indeed different from the irrelevant-change distracting effect induced by other features. The TCIE is a significant and lasting effect because topological change destroys the representation of the memorized items.

Another limitation was that the TCIE seems to be restricted to an intermediate set size of 4. According to our theory, the TCIE is caused by changes in the representation of items and should be effective regardless of set size. In Experiments 1 and 4, we also found that the TCIE was also present for other set sizes. Taking all the data together, we do not think that a set size of 4 has specific psychological implications for the TCIE. The absence of the TCIE could be explained by its sensitivity to task difficulty, reaching its peak for tasks of moderate difficulty. Therefore, whether the task difficulty is increased or decreased, the TCIE will be reduced. The task load made it easier to observe interference caused by topological changes with a set size of 4. Another possibility is that 4 is a relatively special number that is close to the capacity of VWM and that TCIE may have some relationship with memory capacity. However, this hypothesis needs to be investigated in a more systematic study that examines the relationship between TCIE and capacity in a larger population.

In conclusion, across six experiments, we presented consistent evidence demonstrating that topological changes could produce a significant distracting effect, regardless of changes in locations, reporting methods, particular stimulus figures, and delay interval times. Therefore, our results suggest that the definition of a perceptual object by its topological invariance may be a unique perspective from which to describe representations in VWM.

Keywords: visual working memory (VWM), topological invariance, irrelevant-change interference effect

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Appendix

We performed the experimental procedure and data on Mendeley Data (ning, wei (2021), "topological-change interference effect on visual working memory," doi: 10.17632/wnh7wcwf4j.2).