What determines the object-level visual masking: The bottom-up role of topological change

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Object substitution masking (OSM) is said to occur on an object level without a close spatiotemporal proximity of target and mask. An influential account for OSM is "object updating," which espouses that OSM occurs when the target is updated by the mask as they share a single object representation. However, it is unclear what attribute determines whether the mask shares the same object representation as the target. We hypothesize that topological property determines whether a new object representation is built, and hence topological perception modulates object-level masking. We systematically manipulated the similarity between the target and the mask by changing a topological property (number of holes), color, shape, and orientation. We found that the topological change between the target and the mask reduced masking effects of all the other properties. Changing color, shape, or orientation, however, did not affect the masking effect of any other property. The global effect of the topological change remained across a variety of temporal and spatial distances between the target and the mask and was not limited to masking paradigms. Thus, our results suggest that the object representation, constrained by its topological properties, serves as a higher and global level of OSM, influencing the ongoing visual processing of features that are at a lower and local level.

Introduction

Visual masking refers to such a phenomenon that a briefly presented stimulus (target) that is clearly visible when shown alone is rendered less visible or invisible by another stimulus (mask) with spatiotemporal proximity. Masking is not only a powerful tool to regulate the visibility of a target, but also itself is a useful way for studying basic visual processes (B. Breitmeyer & Öğmen, 2006; see review by Ansorge, Francis, Herzog, & Öğmen, 2007). Yet consensus regarding the underlying causes of masking is lacking despite decades of research. Previous studies have focused mainly on spatiotemporal aspects of masking, suggesting that the effect of masking depends critically on spatial distance and the time interval between target and mask (e.g., B. Breitmeyer & Öğmen, 2006; Polat, Sterkin, & Yehezkel, 2007). In the recent two decades, object substitution masking (OSM), which is a special type of masking, has been reported to disobey strict spatiotemporal relationships, and OSM has, therefore, been considered to reflect an object-level masking (Enns & Di Lollo, 1997, 2000; Goodhew, Pratt, Dux, & Ferber, 2013). Two common forms of OSM are four-dot masking and common-onset masking. Four-dot masking is designed with a backward paradigm in which a target is followed by four dots surrounding the target and has a relatively large contour distance (Enns & Di Lollo, 1997). Common-onset masking is when the target and the mask come into view simultaneously, but the mask continues to be displayed after the target disappears (Jannati, Spalek, & Di Lollo, 2013). These two forms of OSM are often combined (Enns & Di Lollo, 2000; Gellatly, Pilling, Cole, & Skarratt, 2006). OSM masking effects are considered to occur at a higher level, i.e., the level of object representation, rather than at a lower level, such as the local contour interactions. There are two major accounts of OSM: object substitution and object updating. The object-substitution theory suggests that masking occurs when a separate mask representation replaces the target whereas the object-updating theory proposes that masking comes from the updating of the target by a mask within a single object representation (see review by Goodhew, 2017). The object-updating theory, however, is supported by overwhelming evidence (Goodhew, 2017). Within the frames of the object-updating theory, an object representation (the target) is initially established and, later, updated by a new input (the mask) if the mask is perceived as the same object as the target (Enns, Lleras, & Moore, 2009; Harrison, Rajsic, & Wilson, 2016; Lleras & Enns, 2004; Moore & Lleras, 2005). If the mask, however, is treated as a different object, the updating process for the target ceases, and the initial target information remains unchanged, i.e., survives from object-level masking. Hence, an underlying question is what stimulus attributes determine if the target and the mask share their object representation in the object-updating theory. Gellatly et al. (2006) tried to answer this question by separating different object-level components of OSM and studying which dimensions of target–mask similarity impact object-level masking. However, they could not find any dimensions of target–mask similarity significantly impacting the masking of the whole target. Instead their study showed that OSM can operate at the level of independent features. Specifically, target–mask similarity on a particular dimension, e.g., the color, only affects reporting of that dimension, and as pointed out by Gellatly et al., it is a major challenge to empirically distinguish between object-level and feature-level OSM effects.

In the present study, we demonstrate an object-level effect in OSM, i.e., the similarity in topological attribute between the target and the mask. We reason that, from the perspective of perceptual organization, the basic constraint on objecthood abstracted from everyday objects should tolerate a certain degree of smooth shape-changing transformations (such as bending, twisting, and stretching but disallowing tearing it apart or gluing parts together). Imagine an object flying toward you with its shape constantly changing. Initially, it may resemble a bird, then an airplane as it comes closer, and finally it turns out to be Superman. Nonetheless, your impression of the approaching object is likely to retain the identity of a single connected entity throughout the process despite the changes in object features (e.g., location, size, and shape) and your different object interpretation. In this example, connectivity is a topological property, i.e., a holistic identity that remains constant across various smooth shape-changing transformations. For instance, the number of holes remains unchanged in this kind of distortion and hence is a topological property. Chen (1982, see reviews by Chen, 2005; Pomerantz, 2003) put forward the "early topological perception" hypothesis, claiming that topological properties are extracted at the very beginning of visual processing to form basic constraints on object coding. This topological account is consistently supported by evidence from human and even insect research (e.g., Chen, Zhang, & Srinivasan, 2003; Han, Humphreys, & Chen, 1999; Huang, Zhou, & Chen, 2011; Todd & Kuzmova, 2011; Wang, Zhou, Zhuo, & Chen, 2007; Zhou, Luo, Zhou, Zhuo, & Chen, 2010; Zhuo et al., 2003). To understand the mechanism of masking in the OSM model, we propose, from this topological perspective, that topological similarity between the target and the mask determines whether the two stimuli are treated as the same object, and the early topology-constrained object representation will affect ongoing processes of stimulus features but not vice versa. Specifically, the target–mask similarity based on topological properties would affect the masking of the whole target across a variety of features (e.g., color, orientation, and shape) whereas the similarity on feature dimensions affects masking of that dimension only.

We employed common-onset masking and backward masking to investigate the similarity effects of different attributes on object-level masking. Hence, we avoided potential low-level effects from spatial interaction. In Experiment 1, we investigated similarity effects of various properties in different discrimination tasks. We manipulated the similarity between the target and the four-item mask in three pairs: color and orientation (1A), number of holes (henceforth referred to as hole) and orientation (1B), and hole and color (1C). First, we examined whether topological similarity can affect masking of the other attributes of the target under the common-onset paradigm in which the masking effect is considered to come from the trailing mask. In the other four experiments, we continued to investigate similarity effects using the backward masking paradigm with the "one-item" mask as used by Lleras and Moore (2003), who demonstrated that OSM is obtained even when the mask is just a single dot. The mask located on the peripheral side of the target and the distance between the mask and target being equal to or larger than 0.6° (0.77° for Experiments 2 and 3, 1° for Experiment 4, and 0.6° to 3.6° for Experiment 5). It is worth noting that the target–mask distances used in these five experiments are larger than what is usually used in metacontrast masking, e.g., 0.1°. In Experiments 2 and 3, we made similar contrasts in the backward masking but controlled stimuli for differences in luminance/flux deriving from the topological difference between the target and the mask. In Experiment 3, we tested the topological effects with another form of topological difference, i.e., two holes versus one hole, and contrasted especially with the nontopological shape effects. In Experiment 4, we investigated if the topological similarity effects on masking depend on the time interval between the target and the mask. Finally, in Experiment 5, we examined the influence of the spatiotemporal separation between target and mask stimuli on the topological similarity effects.

General methods

Participants

Eighty-four volunteers (12 in each experiment, i.e., Experiments 1A, 1B, 1C, 2, 3, 4, and 5; 18–32 years old, mean age = 23; 39 males and 45 females) participated after providing their verbal consent. All participants had normal or corrected-to-normal visual acuity, normal color vision, and were naïve to the purpose of the experiments. For Experiments 1A through C, sample sizes were set to include all 12 participants. The study was approved by the ethics committee of the Institute of Biophysics at Chinese Academy of Sciences, Beijing.

Stimuli

Stimuli were presented within a $10.55° \times 8.97°$ region in the center of a 19-in. CRT monitor (100 Hz refresh) that was viewed from a distance of 57 cm in a dimly lit room. The target–mask pairs appeared at one of four corners in the central region (upper left, upper right, lower left, and lower right). The mask stimuli in Experiment 1 consisted of four identical items surrounding the target (Figure 1a) and were one item locating to the peripheral side of the target in the other four experiments. In Experiment 1A (see Figure 1a), the target and the mask had one of two possible colors, red or yellow, and one of two possible orientations, horizontal or vertical, yielding the four target–mask similarity conditions: congruent color/congruent orientation, incongruent colors/congruent orientation, congruent color/incongruent orientations, and incongruent colors/incongruent orientations. Participants were required to report the color or the orientation of the target in two separate blocks.

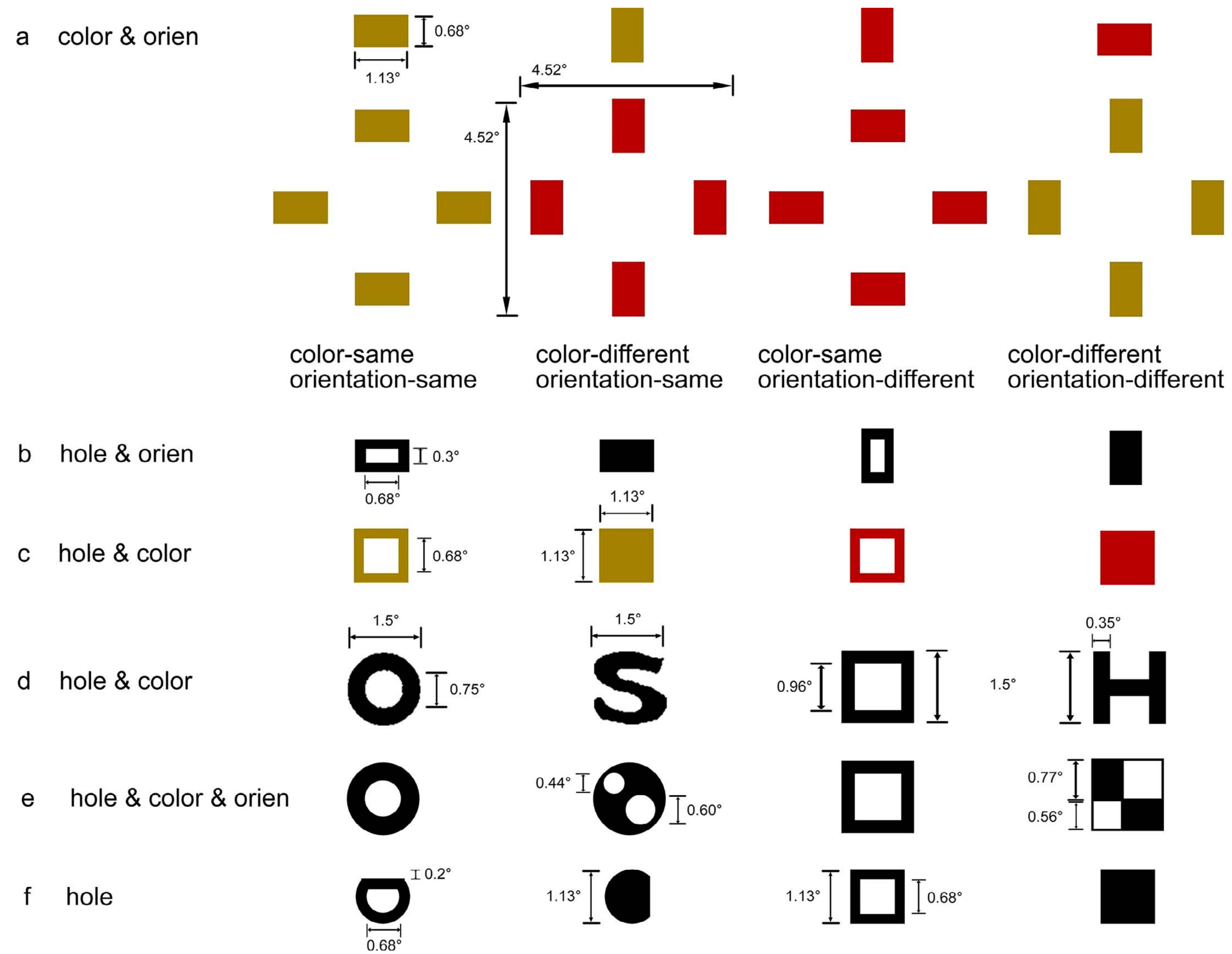

Figure 1. Example stimuli for all experiments. Four of the 16 possible combinations of the target (upper) and the four-item mask (lower) used in (a) Experiment 1A, illustrating examples of four possible similarity conditions. The target and the mask could have one of two possible colors, red or yellow, and one of two possible orientations, horizontal or vertical. Samples of the target and mask stimuli in (b) Experiment 1B: hole (one hole, no hole) × orientation (horizontal, vertical). Samples of the targets and mask stimuli in (c) Experiment 1C: hole (one hole, no hole) × color (red, yellow). Illustration of the four area-matched shapes for targets used in (d) Experiment 2. The masks (2.26° × 2.26°) were bigger replicas of these stimuli. The target and mask could be one of the eight stimuli: 4 shapes × 2 colors (red, yellow). O and □ are topologically different from S and H because O and □ have one hole and S and H have none. Illustration of the four area-matched shapes for targets used in (e) Experiment 3. The target and mask could be one of the eight stimuli: 4 shapes (one hole–circle, two hole–circle, one hole–square, two hole–square) × 2 colors. Samples of the D-shaped targets and square masks in (f) Experiment 4. The target and mask could have one hole or no hole. The orientation of the truncated flat of the target could be up, down, left, or right.

Similarly, in Experiment 1B, the target–mask similarities were designed as the four combinations of hole (one hole/no hole) and orientation (horizontal/vertical; Figure 1b), and participants reported the number of holes and the orientation. In Experiment 1C, stimuli were four types of combinations of hole (one hole/no hole) and color (red/yellow; Figure 1c), and the task was to report the number of holes and the color. In Experiment 2 (Figure 1d), the stimuli were matched for area across different conditions: O-like, S-like, a square frame, and H-like figures (hereafter referred to as O, S, □, and H, respectively), which were adapted from our previous study (Huang et al., 2011). Targets and masks were chosen randomly from these stimuli: 4 shapes × 2 colors (red/yellow). The target and the mask were presented at 3.74° and 6.39° from screen center, respectively. Again, participants were asked to report about the

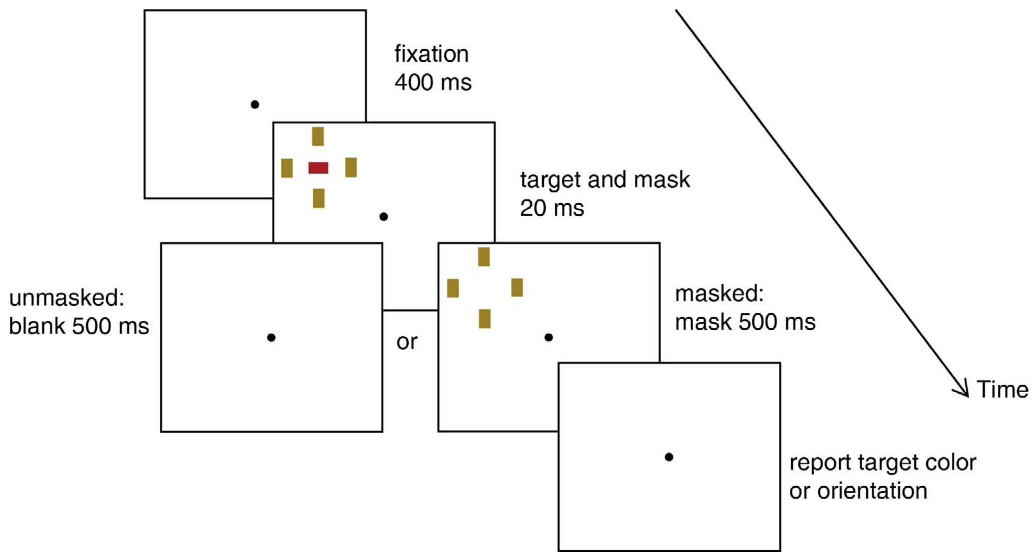

Figure 2. Stimulus sequence for Experiment 1. Mask stimulus was either turned off simultaneously (unmasked condition) or delayed by 500 ms (masked condition). Masking effect is computed from the accuracy difference (percentage) between unmasked and masked trials. The target–mask pairing here illustrates the condition in which both stimuli are different in color and orientation in Experiment 1A.

hole (i.e., whether there is a hole in the target regardless of its shape) or the color in separate blocks. In Experiment 3 (Figure 1e), stimuli were chosen from the four figures: one hole–circle, two hole–circle, one hole–square, and two hole–square. Targets and masks could be one of these eight stimuli: 2 hole (one hole/two hole) × 2 shape (circle/square) × 2 color (red/yellow). Participants were asked to report about the hole, the shape, and the color in three separate blocks. In Experiment 4 (Figure 1f), the target was either a solid or hollow D-shape figure with a truncated flat orienting up, down, left, or right, and the mask was either a solid or hollow square figure, locating to the peripheral side of the target. Participants reported the orientation of the target with the distance between the mask and target being equal to or larger than 0.6° (0.77° for Experiments 2 and 3, 1° for Experiment 4, and 0.6° to 3.6° for Experiment 5). To investigate whether the topological effects on masking vary with the target–mask distance, in Experiment 5, we manipulated this spatial distance from 0.6° to 3.6° at a step of 1° and stimulus onset asynchronies (SOAs) at 20, 60, and 100 ms. Otherwise, it was the same as in Experiment 4.

The two colors (red and yellow) of stimuli in Experiments 1 through 3 were matched for subjective luminance. The luminance value of the red color was fixed (International Commission on Illumination chromaticity coordinates and luminance value: $x = 0.534$, $y = 0.276$; 0.11 cd/m^2), and the yellow was determined through a subjective luminance-equivalence procedure for each participant. The achromatic stimuli were black (0 cd/m^2) on a gray (0.32 cd/m^2) background. The stimuli were designed to have both low contrast and luminance in order to control the awareness of targets.

Procedure

In each trial, participants were required to maintain their fixation at a central spot, and stimuli were presented in one of four possible positions. In Experiment 1 (Figure 2a), we used a modified OSM paradigm, i.e., common-onset masking, in which target and mask appeared simultaneously (SOA = 0), and after the target disappeared, the mask was either turned off simultaneously (unmasked condition) or delayed by 500 ms (masked condition). For each participant and each similarity condition (e.g., color similarity × orientation similarity in Experiment 1A), we calculated masking effects by subtracting scores in the masked condition from those in the unmasked condition. In Experiments 2 and 3 (Figure 4a), a 20-ms target appeared first, and then after a 60-ms stimulus interval, the 150-ms mask was presented to the peripheral side of the target. In Experiment 4, the target was presented for 10 ms, and the mask was onset after a varied SOA (0, 20, 40, 60, 80, and 100 ms) and lasted for 300 ms. For Experiments 2 through 4, the mean accuracy for the target was computed for each condition. There were 640 trials for Experiments 1 through 3 and 384 trials for Experiment 4. All possible combinations of variables were presented with equal frequency. Different tasks were arranged in separate blocks, and the task order was balanced across participants. Stimulus presenta-

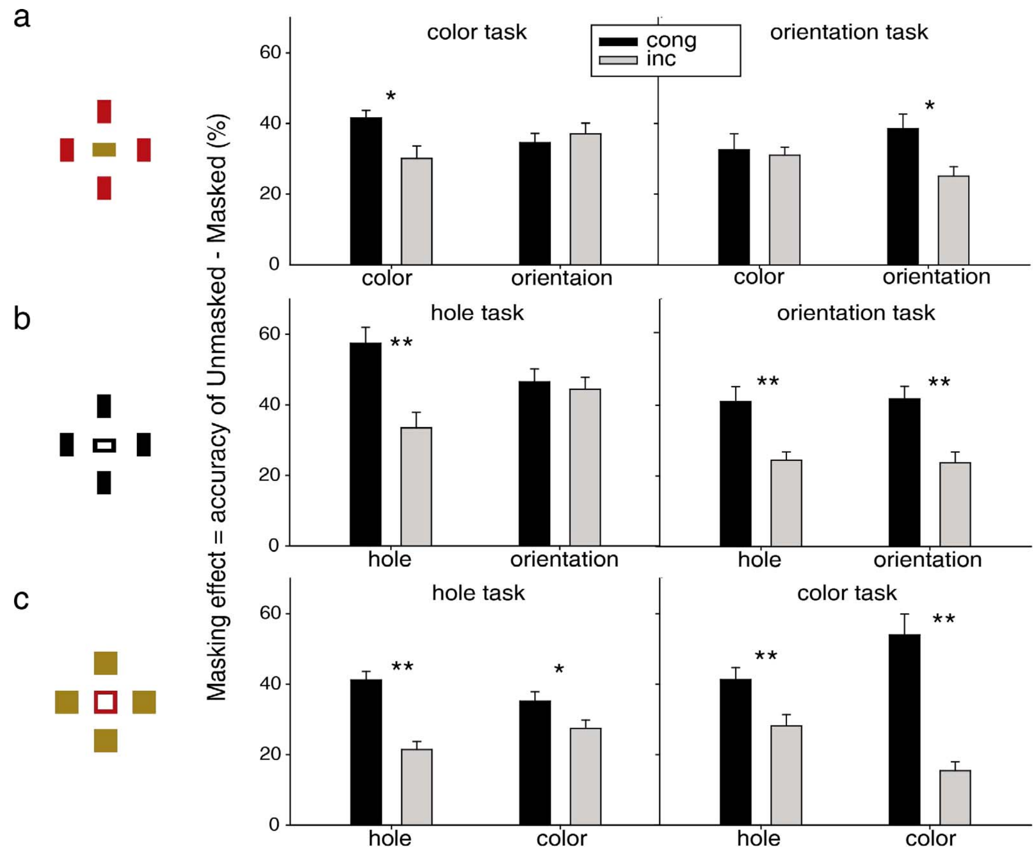

Figure 3. Results from Experiment 1. The graph shows the masking effects for different tasks under different target–mask similarity conditions in Experiments 1A (a), B (b), and C (c). Masking effect is computed from the accuracy difference (percentage) between unmasked and masked trials. Cong = congruent, inc = incongruent. Error bars represent 95% confidence intervals. Asterisks indicate significant differences between congruent and incongruent conditions (*$p < 0.05$, **$p < 0.01$).

tion and data acquisition were controlled by a customized program written in Matlab using Psychtoolbox (Brainard, 1997).

In Experiments 1 through 3, participants pressed the left or right key to indicate the number of holes, the color, or the orientation of the target or the z key if they did not know. They were instructed not to guess if they were uncertain but to press the z key. Responses of this kind are referred to as *omission* responses as opposed to *correct* responses (reporting correctly for the property) or *error* responses (reporting incorrectly for the property). This method was also used in previous research (e.g., Gellatly et al., 2006). We chose this method rather than a two-alternative, forced choice decision, to avoid possible response biases, e.g., participants reporting for a near-threshold target the features of the mask that remains on the screen. Different from the above three experiments, in Experiment 4, participants were required to make forced choice judgments for the orientation of the target given that the mask stimuli of squares do not carry any misleading information for the orientation.

Results

Experiment 1: Similarity effects of hole, color, and orientation

Responses were either correct, omissions, or errors. The average proportion of correct responses was 89% (88%~90%) in unmasked conditions and 56% (54%~58%) in masked conditions. The average proportion of omission responses was 7.7% (6.7%~8.7%) in unmasked conditions and 38.4% (36.5%~42.3%) in masked conditions.

Analysis on errors revealed that participants were able to follow the instruction, i.e., not to guess when uncertain. The average error rates were very low (about 4% for all the trials) in Experiments 1A through C. Even in such cases, guessing corrections, which aimed to avoid the possible effects of uneven guessing, were applied to individual data if errors were not evenly distributed across conditions (refer to Supplementary Materials for details). A three-way ANOVA examining the factors of the task and the similarity (e.g., color and

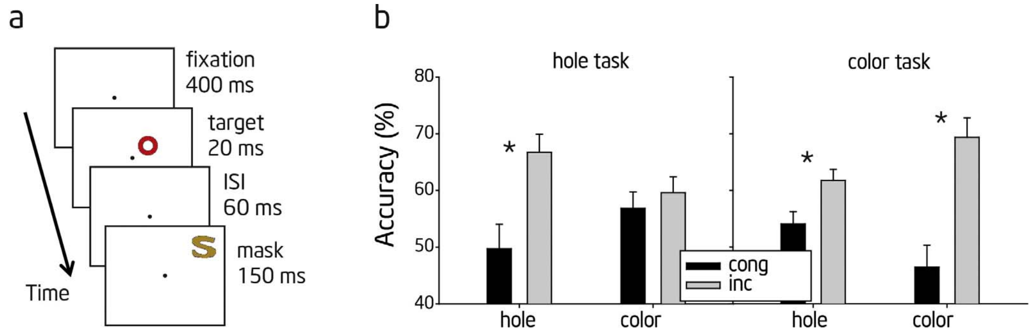

Figure 4. Stimulus sequence and results from Experiment 2. As shown in (a), a backward masking paradigm was adopted in Experiment 2. The graph (b) shows the accuracy for hole and color report as a function of target–mask similarity based on hole and color, respectively. Cong = congruent, inc = incongruent. Error bars represent 95% confidence intervals. Asterisks indicate significant differences in accuracy between congruent and incongruent conditions (*$p < 0.01$).

orientation similarity in Experiment 1A) revealed significant two-way interactions between the task and the color (or orientation) similarity ($p < 0.05$) and marginally significant interactions between the task and the hole similarity ($p = 0.071$ for Experiment 1B, $p = 0.086$ for Experiment 1C), indicating that the similarity effects of these properties were different for the two tasks. There were no two-way interactions between two types of similarity or three-way interactions between the task and two types of similarity in Experiments 1A through C ($p > 0.1$). The size of masking effect was not different for the two tasks in Experiments 1A and C ($p > 0.1$), but a smaller effect was found for reporting the orientation (33%) than that for the hole (45%) in Experiment 1B, $F(1, 11) = 5.48$, $p = 0.039$, $\eta^2 = 0.33$. These masking scores were further entered into separate 2 × 2 ANOVAs for different tasks in each experiment, examining the effects of two types of similarity. As there were no interactions between the two types of similarity for all Experiments 1A through C ($p > 0.1$), we show only the main effects of each type of similarity in Table 1.

Color and orientation

A two-way ANOVA with factors of color (congruent/incongruent) and orientation similarity (congruent/incongruent) was separately applied to masking scores for reporting the color and the orientation (Figure 3a). Consistent with previous findings (e.g., Gellatly et al., 2006), masking for reporting each feature was affected only by a target–mask difference for that feature ($p < 0.02$) and not by a difference for the other ($p > 0.1$). Namely, color similarity only affected masking when the task was to discriminate the colors, and the effect of orientation similarity was found only in the orientation task.

Hole and orientation

Similarly, for both hole- and orientation-related tasks, the masking effect in the task of one property was significantly affected by the target–mask difference in that property ($p < 0.002$) (Figure 3b). Surprisingly, we found a remarkable effect of hole similarity in the orientation task, indicated by a stronger masking when the target and the mask were of the same topological property ($p = 0.001$). In contrast, orientation similarity had no influence in the hole task ($p > 0.2$).

Hole and color

Similar results were observed for the hole and color tasks (Figure 3c). Both hole and color similarity had significant effects of masking on their own, and again, a hole similarity effect was found in the color report ($p < 0.001$). In addition, a color similarity effect was found in the hole task ($p = 0.041$).

Experiment 2: Controlling for differences in flux/luminance

The results from Experiment 1 showed that target–mask similarity based on topological property (hole) modulated the masking effects not only in the task of reporting for the hole, but also for other properties, such as color and orientation, with a weaker masking when the target and mask were topologically different compared to that when topologically equivalent. However, a potential confounding factor is other nontopological differences that accompanied the topological changes in the stimuli, notably the luminous flux (stimulus area) and shape. In addition, as indicated by the results in Experiment 1C, performance in the hole report was also affected by the color similarity. Thus, there is a possibility that the color similarity may affect the perception of stimulus area difference, which

		Relevant task		Irrelevant task	
	Property	Similarity effect	*F* test	Similarity effect	*F* test
Experiment 1A	Color orient	11.5 [3.3, 19.6]	$F(1, 11) = 7.53$, $p = 0.019$, $\eta^2 = 0.41$	−0.5 [−3.3, 2.2]	$F(1, 11) = 0.28$, $p = 0.61$, $\eta^2 = 0.02$
		13.8 [5.1, 22.4]	$F(1, 11) = 9.68$, $p = 0.01$, $\eta^2 = 0.47$	−2.5 [−8.2, 3.2]	$F(1, 11) = 0.74$, $p = 0.41$, $\eta^2 = 0.06$
Experiment 1B	Hole orient	24.0 [17.9, 29.6]	$F(1, 11) = 17.79$, $p = 0.001$, $\eta^2 = 0.62$	16.6 [9.2, 23.9]	$F(1, 11) = 19.56$, $p = 0.001$, $\eta^2 = 0.64$
		18.0 [11.4, 24.6]	$F(1, 11) = 28.63$, $p < 0.001$, $\eta^2 = 0.72$	2.1 [−1.0, 5.2]	$F(1, 11) = 1.75$, $p = 0.213$, $\eta^2 = 0.14$
Experiment 1C	Hole color	19.7 [14.2, 25.1]	$F(1, 11) = 50.05$, $p < 0.001$, $\eta^2 = 0.82$	13.1 [8.3, 17.8]	$F(1, 11) = 28.87$, $p < 0.001$, $\eta^2 = 0.72$
		38.5 [25.3, 51.7]	$F(1, 11) = 32.84$, $p < 0.001$, $\eta^2 = 0.75$	7.7 [1.2, 14.2]	$F(1, 11) = 5.38$, $p = 0.041$, $\eta^2 = 0.33$
Experiment 2	Hole color	17.0 [6.2, 27.8]	$F(1, 11) = 9.50$, $p = 0.01$, $\eta^2 = 0.46$	7.7 [3.3, 12.0]	$F(1, 11) = 11.82$, $p = 0.006$, $\eta^2 = 0.52$
		22.9 [10.3, 35.5]	$F(1, 11) = 12.65$, $p = 0.004$, $\eta^2 = 0.53$	2.8 [−1.3, 6.8]	$F(1, 11) = 1.77$, $p = 0.210$, $\eta^2 = 0.14$

Table 1. Similarity effects (percentage) under property-relevant and -irrelevant conditions of Experiments 1 and 2. *Notes*: Similarity effects of a property are referred to as differences in masking effects (for Experiment 1) or in accuracy (for Experiment 2) between the conditions in which target and mask stimuli are congruent or incongruent in that property. Values in brackets are 95% confidence intervals.

may account for the similarity effect observed in topological manipulations. To rule out this possibility, we designed area-matched stimuli in Experiment 2 and manipulated the similarity between the target and the mask on both hole and color dimensions as in Experiment 1C. In addition, to examine whether the findings were constrained by a specific masking paradigm or mask pattern (e.g., common-onset masking with a four-item mask used in Experiment 1), we adopted another masking paradigm, typical backward masking with the one-item mask that is presented after the target offset (see Figure 4a). We categorized the target–mask pairs into two types depending on topological similarity: hole incongruent (e.g., S and O) and hole congruent (e.g., S and H). For the hole-congruent condition, stimuli could be shape congruent (e.g., S and S) or shape incongruent (e.g., S and H). Therefore, besides the topological similarity effects, we could also investigate the similarity effects from these topologically equivalent shape pairs.

The average accuracy is shown in Figure 4b. The lower accuracy indicates the stronger masking effects. An ANOVA with factors of task, hole, and color similarity was applied to the accuracy data. The three-way interaction, two-way interaction between color and hole, and the main effect of task were not significant ($p > 0.1$). No difference was observed in the mean accuracy for hole report (58.2%) and for color report (57.9%). Interestingly, we found a significant interaction between task and color, $F(1, 11) = 10.89$, $p = 0.007$, $\eta^2 = 0.50$, but not for interaction between task and hole ($p > 0.1$), suggesting that the effects of hole similarity were somewhat independent of task. ANOVAs examining hole and color similarity were applied to accuracy for the two tasks separately. Results indicated again that both hole and color similarity had significant effects of masking on their own ($p < 0.01$). Importantly, color similarity did not influence hole report ($p > 0.2$) whereas hole similarity influenced color report ($p = 0.006$). There were no interactions ($p > 0.1$).

Further, to test whether shape difference interfered with the results, we applied, for both tasks, separate ANOVAs with factors of shape and color to the data of trials in which target and mask had congruent topological properties but incongruent shapes (i.e., S and H, O and □). Shape difference had no effect in masking and did not involve in any interactions ($p > 0.1$).

Experiment 3: Generalizing to two holes and testing nontopological shape similarity

In Experiment 3, we tested topological similarity effects with another form of topological difference (two holes vs. one hole). In spite of the area-matched stimuli we adopted, there were other potential confounding factors, such as category (letter vs. geometric figure) and nontopological shape differences. To address this question, we adopted an array of geometric stimuli that were matched in area and investigated explicitly the effect of shape similarity in Experiment 3. Stimulus similarity in three dimensions, including hole, color,

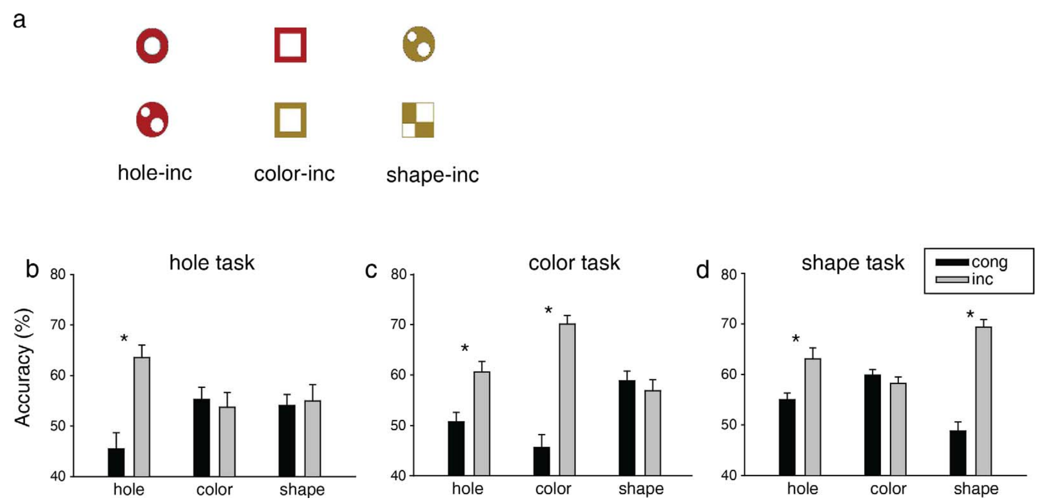

Figure 5. Stimulus examples and results from Experiment 3. Upper panel (a) shows stimulus pairs that are incongruent in one property (i.e., hole, color, or shape) while congruent in the other two properties. Percentage of correct responses is shown for reporting hole (b), color (c), and shape (d) as a function of target–mask similarity based on hole, color, and shape, respectively. Cong = congruent, inc = incongruent. Error bars represent 95% confidence intervals. Asterisks indicate significant differences between accuracy in the two conditions, i.e., similarity effects (*$p < 0.05$).

and shape, was manipulated between the target and the mask.

An ANOVA with factors of task, hole, color, and shape was applied to accuracy data, revealing significant two-way interactions between task and each type of similarity ($p < 0.005$). The performance was not different for the three tasks, and there was no three-way interaction ($p > 0.1$). ANOVAs with factors of hole, shape, and color similarity were applied to three tasks separately. Similar results were observed (see Figure 5 and Table 2). The similarity effect of each property modulated the performance in property-relevant tasks ($p < 0.001$). Hole similarity mediated the performance in the color and shape tasks ($p < 0.02$), and similarity based on color or shape had no effect on property-irrelevant tasks ($p > 0.1$).

Experiment 4: Topological similarity effects at different SOAs

The SOA between the target and the mask is known as an important factor for visual masking. A masking effect will monotonically decrease or initially increase and then decrease with increasing SOA (B. Breitmeyer & Öğmen, 2006). Here we examined whether the topological similarity effects on masking varied with masking effects. We tested the effects of hole similarity on orientation discrimination at the SOAs varying from 0 to 100 ms at a step of 20 ms. Mask stimuli could be hole congruent or incongruent from the target. The accuracy for orientation report is shown in Figure 6b, revealing an increasing accuracy (ranging from 43.0% to 89.6%) with SOAs for both hole-congruent and -incongruent conditions. An ANOVA with variables of

	Hole task		Color task		Shape task	
Prop	Simi effect	*F* test	Simi effect	*F* test	Simi effect	*F* test
Hole	18.1 [11.4, 24.5]	$F(1, 11) = 27.56$, $p < 0.001$, $\eta^2 = 0.71$	9.8 [6.4, 13.3]	$F(1, 11) = 20.58$, $p = 0.001$, $\eta^2 = 0.65$	8.1 [2.4, 13.7]	$F(1, 11) = 7.82$, $p = 0.017$, $\eta^2 = 0.42$
Color	−1.5 [−6.9, 3.7]	$F(1, 11) = 0.34$, $p = 0.574$, $\eta^2 = 0.03$	24.5 [20.6, 28.3]	$F(1, 11) = 151.41$, $p < 0.001$, $\eta^2 = 0.93$	−1.6 [−3.9, 0.7]	$F(1, 11) = 1.84$, $p = 0.202$, $\eta^2 = 0.14$
Shape	0.9 [−5.4, 7.3]	$F(1, 11) = 0.08$, $p = 0.777$, $\eta^2 = 0.01$	−2.0 [−4.7, 0.8]	$F(1, 11) = 1.93$, $p = 0.192$, $\eta^2 = 0.15$	20.6 [15.4, 25.8]	$F(1, 11) = 60.45$, $p < 0.001$, $\eta^2 = 0.85$

Table 2. Similarity effects (percentage) under different tasks of Experiment 3. *Notes*: Similarity effects of a property are referred to as differences in accuracy between the conditions in which target and mask stimuli are congruent or incongruent in that property. Values in brackets are 95% confidence intervals.

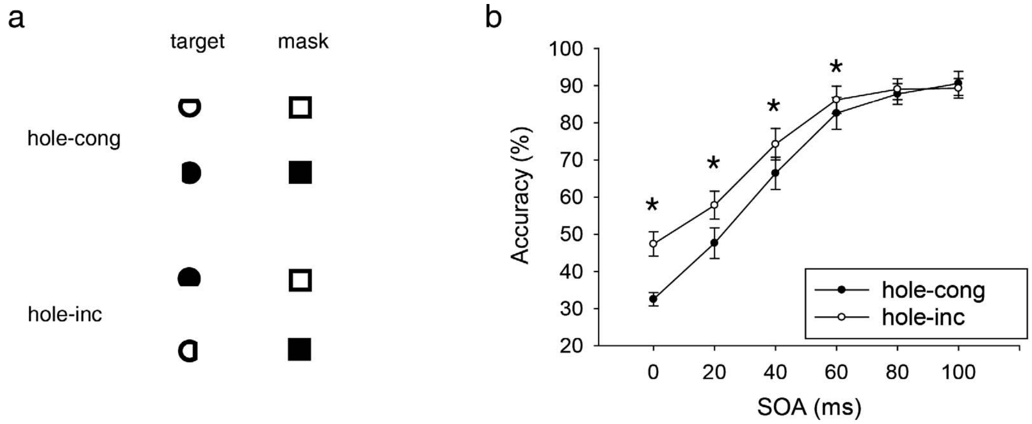

Figure 6. Stimulus sequence and results from Experiment 4. Left panel (a) shows the hole-cong condition in which the target and mask are congruent in topological property (i.e., hole), and the hole-inc condition in which they are incongruent in topological property. The graph (b) shows the percentage of correct responses for orientation report as a function of hole similarity and SOA. Cong = congruent, inc = incongruent. Error bars represent 95% confidence intervals. Asterisks indicate significant differences in accuracy between hole-congruent and -incongruent trials (*$p < 0.05$).

hole similarity and SOA revealed a significant interaction, $F(5, 55) = 5.201$, $p < 0.001$, $\eta^2 = 0.32$, and main effects of the two factors ($p < 0.001$). A paired-sample t test showed performance was significantly improved in the hole-incongruent condition compared with that in the hole-congruent condition at the SOAs of 0 (similarity effect = 13.0 ± 4.7%), $t(11) = 5.43$, $p < 0.001$, $d = 2.57$; 20 (similarity effects = 13.5 ± 5.3%), $t(11) = 5.01$, $p < 0.001$, $d = 3.04$; and 40 ms (similarity effect = 7.3 ± 5.7%), $t(11) = 2.53$, $p = 0.028$, $d = 0.94$, but not at the larger SOAs ($p > 0.1$), at which the accuracy was more than 80%.

Experiment 5: Topological similarity effects at different spatial distances

Spatial distance between the target and the mask is another important factor for masking (B. Breitmeyer & Öğmen, 2006), e.g., the masking effect decreases with the increase of the target–mask distance. To investigate whether the topological effects on masking vary with the target–mask distance, we manipulated this spatial distance from 0.6° to 3.6° at a step of 1° and SOAs at 20, 60, and 100 ms. Otherwise, it was the same as in Experiment 4. The accuracy is shown in four panels of Figure 7. A three-way ANOVA with variables of hole similarity, SOA, and distance revealed that all the main effects were significant ($p < 0.001$), the two-way interactions between SOA and distance and between SOA and hole similarity were also significant ($p < 0.05$). The three-way interaction was not significant; nor was the interaction between distance and hole similarity ($p > 0.5$). A paired-sample t test showed performance was all significantly improved for four different distances in the hole-incongruent condition compared with that in the hole-congruent condition at the SOA of 20 ms ($p < 0.05$). For an SOA of 60 ms, the hole similarity effects were significant for distance of 0.6° and 1.6° but not for the other two distances, e.g., 2.6° and 3.6°. We then investigated especially the influence of spatial distance on topological similarity effects. We showed the topological similarity effects as a function of spatial distance and SOA (see Figure 7). A two-way ANOVA with spatial distance and SOA revealed that only the main effect of SOA was significant ($p < 0.05$), and there was no significant main effect of distance and no interaction ($p > 0.5$). Even at an SOA of 20 ms at which the masking effect was strongest, distance did not affect the magnitude of topological similarity effect.

Discussion

OSM is supposed to occur at an object level, at which the target is updated by the mask as they share the same object representation. We hypothesize that a topological change between target and mask triggers the onset of a new object representation and hence decreases the masking effects of the whole target. In the present study, we show that whereas similarity based on a topological property (hole) modulates masking effects of properties that are not related to the topological property, e.g., color, orientation, and shape discrimination, similarity of a nontopological property only affects masking of that property. Furthermore, we show that topological similarity effects remain when we adopt the backward masking paradigm with loose target–mask contour proximity (Experiments 2 through 5) and when we removed potential confounding

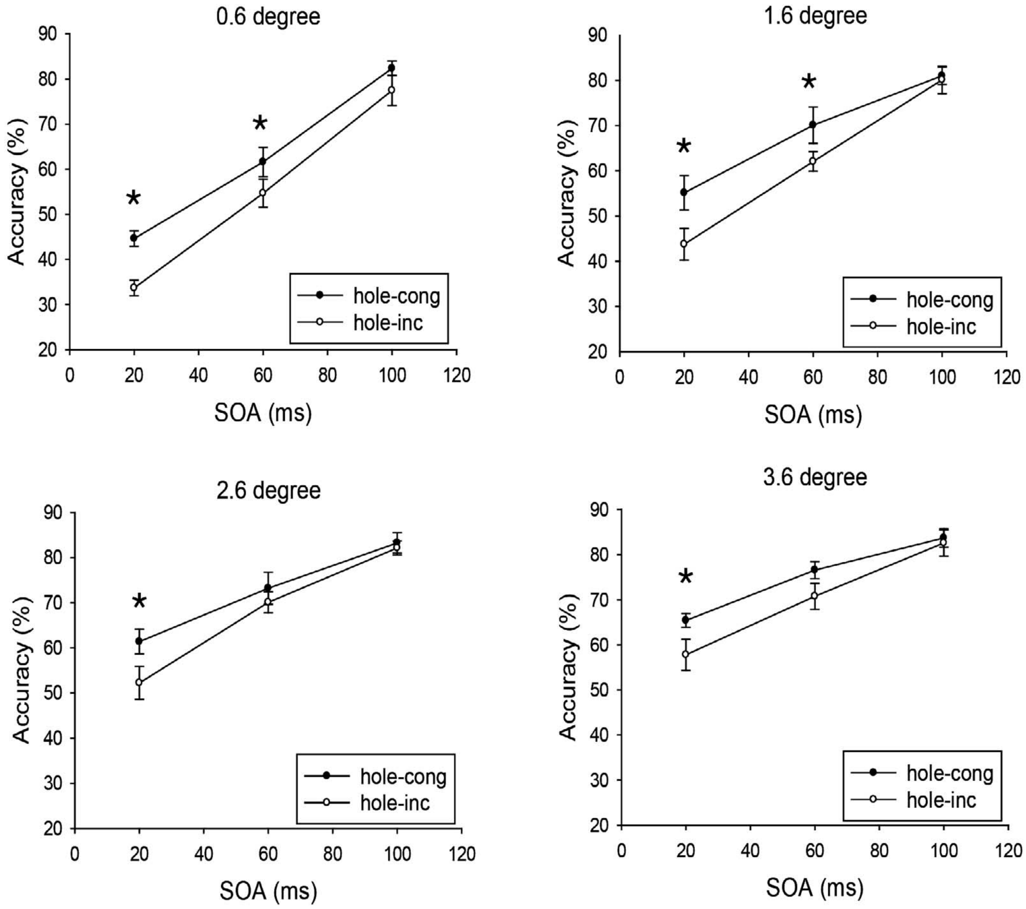

Figure 7. Results from Experiment 5. The four panels show the percentage of correct responses for orientation report for different spatial distance as a function of hole similarity and SOA. Cong = congruent, inc = incongruent. Error bars represent 95% confidence intervals. Asterisks indicate significant differences in accuracy between hole-congruent and -incongruent trials (*$p < 0.05$).

factors, e.g., luminance flux and category and non-topological shape differences that accompany the topological change (Experiments 2 and 3). Last, we show that topological effects on masking tolerate to some extent the spatial and temporal separation between the target and the mask (Experiments 4 and 5).

Target–mask similarity

Target–mask similarity was investigated as early as in the 1970s (e.g., Breitmeyer, et al., 1984; Growney & Weisstein, 1972; Kallman & Massaro, 1979; Oyama, Watanabe, & Funakawa, 1983; Uttal, 1970; Yellott & Wandell, 1976). The role of target–mask similarity in visual masking in different tasks remains unclear. Recent evidence from masking studies and related research, e.g., priming, suggests that only task-relevant similarity takes effect (Ansorge & Neumann, 2005; Enns & Oriet, 2007; Gellatly et al., 2006; Lleras, Rensink, & Enns, 2007; Tapia, Breitmeyer, & Shooner, 2010). The present study, however, reveals that the topological similarity between target and mask modulates the masking effect for both topology-relevant and -irrelevant tasks, e.g., reporting on color and orientation of the target. The topological modulation in the processing of other properties is consistent with the results reported in our previous priming study (Huang et al., 2011).

Topological account of OSM

As Goodhew (2017) mentioned, manipulations that encourage the visual system to infer that the target and the mask are different objects should reduce masking, according to the object-updating perspective. The present findings are in agreement with this prediction. The topological change from target to mask prompts the visual system to treat them as different object representations, thus decreasing the masking effects of all the target features.

Within the object-updating framework, Gellatly et al. (2006) proposed that OSM operates at distinct levels: object level and feature level. They found evidence for feature-level components (Gellatly et al., 2006). We designate the topological similarity effect as an object-level masking, contrasting feature-level masking, such as color and orientation similarity effects. When the mask differs in topological properties from the target, a new object representation is constructed. The ongoing processing of the features of the mask, e.g., color and orientation, become input to the newly constructed object instead of interfering with the initially established target, thus resulting in a better recognition of the target. In contrast, when the mask shares its topological properties with the target, the subsequent processing of the mask features are used to renew the established target, thereby affecting the target information report. We refer to topological similarity as a global object-level effect because of the blanket influence of topological similarity on an object representation and its feature dimension. The global object-level effect of topological similarity contrasts the processing of features that exhibit local and independent masking influence and other domains, e.g., priming (Gellatly et al., 2006; Livingstone & Hubel, 1987). In conclusion, we propose that OSM consists of two levels: a topology-constrained object level and a mutually independent feature level. Furthermore, we suggest that the feature-level masking is mediated by the object-level masking.

One might argue that once a new object representation is triggered by a topological change, masking should not be observed any more. It should be noted, however, that feature-level masking is not extinguished, but can occur even between different object representations. Therefore, topological changes would not reduce masking to zero. A second argument is that the similarity effect of a topological property can be modulated by task relevance, similarly to those of nontopological properties. Although the initial formation of object representations constrained by topology could be a bottom-up process, the performance under specific tasks for discriminating topological properties could be unavoidably modulated by top-down attention.

Topological account in other studies

Our proposal of a topology-constrained object level of masking implies that topological perception can influence the subsequent processing of other properties. This idea is supported by the finding that detection of a target (judging whether the target is present or absent) is more difficult to mask than discrimination of a target feature (e.g., Fehrer & Biederman, 1962; Gellatly et al., 2006). Note that "presence or absence" is exactly one type of topological changes. A recent study revealed that whereas rhombuses (one-hole figures) are strongly masked by rhombuses themselves, they are only weakly masked by lines (no-hole figures) or angles (no-hole figures; Lo & Zeki, 2014). Angles and lines, however, were well masked by each other. The study by Lo and Zeki (2014) can be considered another case of topological similarity effects because rhombuses are topologically different from lines and angles, but lines and angles are topologically equivalent.

Preattentive object

The topological account is consistent with theories of preattentive object formation (e.g., Bachmann, 2000; Muller et al., 2010; Rensink, 2000; Russell & Driver, 2005). In Rensink's (2000) coherence theory, preattention yields "proto-objects," which are coherent over small spatial and temporal extents and are regenerated when there are big spatiotemporal gaps. The object representations in the topological account have much in common with the proto-objects of preattentive object formation, which, according to topological theory, are regenerated when the topological changes are detected.

There is plenty of evidence for OSM involving masking of object tokens and object files (Goodhew, 2017; Kahneman, Treisman, & Gibbs, 1992; Lleras & Moore, 2003). For instance, the masking was reduced when the mask appeared to slide across the target because distinct object representations were established for target and mask. The object representation within the frame of object files, however, is created relatively late in the visual processing, which is different from the topological account that the object representation is formed at the very beginning of vision.

In conclusion, the present findings indicate that object representations constrained by a topological property influence the ongoing visual processing of other properties. Enns et al. (2009) have pointed out that an important future goal is to better understand what causes the difference between representations that are vulnerable to updating versus those that are immune to updating. Topology-constrained objects appear to be a promising solution.

Keywords: visual masking, *object representation*, *topological property*, *similarity*, *task relevance*

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