The precedence of topological change over top-down attention in masked priming

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Recent data indicate that unconscious masked priming can be mediated by top-down attentional set, so that priming effects of congruence between a masked prime and a subsequent probe vanish when the congruence ceases to be task relevant. Here, we show that, while the attentional set determines masked priming for color and orientation features, it does not fully determine priming based on the topological properties of stimuli. Specifically, across a series of different choice-RT tasks, we find that topological congruence between prime and probe stimuli affects RTs for the probes even when other stimulus information (e.g., color or orientation) is required for the response, whereas congruence priming effects of color or orientation occur only when these features are response relevant. Our results suggest that changes in topological properties take precedence over task-directed top-down attentional modulation in masked priming.

Keywords: perceptual organization, masking, attention


Introduction

There is now abundant evidence that, despite being rendered invisible by masking, a prime can still exert reliable effects on the processing of a subsequent stimulus (a probe; e.g., Klotz & Wolff, 1995; Schmidt, 2002). This unconscious masked priming process has usually been considered to be automatic and independent of attention (see review by Schneider & Shiffrin, 1977). However, this view has been refuted by recent results revealing the essential role of top-down attention in masked priming (see review by Finkbeiner & Forster, 2008). For example, masked priming has been observed to be modulated by temporal expectation (Naccache, Blandin, & Dehaene, 2002), spatial attention (Lachter, Forster, & Ruthruff, 2004), and task-directed attention. Enns and Oriet (2007; see also Tapia, Breitmeyer, & Shoone, 2010) reported effects of color and orientation congruence between a masked prime and a probe, with responses to the probe being speeded when the color and orientation features of prime and probe matched. However, such feature congruence effects arose only when these features were relevant to the probe task. When color alone was task relevant, there was effect of color congruence but not orientation congruence, and when orientation alone was relevant, only orientation congruence effect was observed. Similar findings have also been observed for congruence effects based on shape and location (Ansorge & Neumann, 2005; Scharlau & Ansorge, 2003; Scharlau & Neumann, 2003). In sum, these data indicate an essential role of top-down attention in masked priming, by enabling the congruence effects only for task-relevant features.

In the present study, we demonstrate that top-down constraints on masked priming are themselves limited when topological rather than feature-based changes take place between masked primes and probes. The topological property of a figure is the holistic identity that remains constant across various smooth shape-changing transformations of an image (Chen, 1982, 2005). This topological transformation can be imagined as continuous rubber sheet deformations such as bending, twisting, and stretching but disallowing tearing it apart or gluing parts together. In this kind of rubber-sheet distortion, the number of holes (hereafter referred to as hole) remains unchanged and hence is a topological property. Chen
(1982) first demonstrated that the visual system is highly sensitive to topological difference. For example, two topologically different visual stimuli are more discriminable under a near-threshold condition than other stimulus pairs that differ in various types of local features but are topologically equivalent (e.g., a circle and a triangle). Through decades of research, the early topological perception hypothesis has been explored widely, using a variety of behavioral paradigms, including apparent motion (Chen, 1985; Zhuo et al., 2003), illusory conjunctions (Chen & Zhou, 1997), configural superiority effects (Todd, Chen, & Norman, 1998), global precedence (Han, Humphreys, & Chen, 1999), neuropsychological studies of extinction (Humphreys, 2001; Humphreys, Romani, Olson, Riddoch, & Duncan, 1994), and pattern discrimination in insects (honeybees; Chen, Zhang, & Srinivasan, 2003). In sum, those results have supported the “early topological perception” hypothesis that topological properties are first represented and processed and affect ongoing visual information processing (see review by Chen, 2005; Pomerantz, 2003). If topological properties do indeed have precedence in visual processing, then it is possible that they override any effects of top-down attentional set, influencing masked priming even when irrelevant to the task performed on the probe. This was evaluated here.

We report three experiments. In Experiment 1, we investigated congruence priming effects of various properties in different RT tasks, by manipulating congruence between prime and probe in three feature pairs: hole and color (1A), hole and orientation (1B), and color and orientation (1C). In Experiments 2 and 3, we made similar contrasts but used stimuli controlled for differences in flux/luminance deriving from the topological changes between prime and probe. We examined whether congruence effect of topological properties can occur when it is irrelevant to the probe task. Moreover, to assess the prime awareness for different properties, we also examined the prime identification accuracy in Experiments 1D, 2, and 3.

General methods

Participants

Eighty-four volunteers (14 per experiment; mean age = 21; 47 females) participated and gave their verbal informed consent. All had normal or corrected-to-normal vision and were naive to the purpose of the experiments.
Stimuli

Stimuli were presented within a 10.55° × 8.97° region in the center of a 19-inch CRT monitor (100-Hz refresh) that was viewed from a distance of 60 cm in a dimly lit room. The prime–probe pairs appeared at one of four corners on the screen (upper left, upper right, lower left, and lower right), at a distance of 5.6° from screen center. The stimuli were designed to have both low contrast and luminance in order to control the awareness of primes. In Experiments 1A, 1C, 2, and 3, the prime and probe stimuli were red [International Commission on Illumination (CIE) chromaticity coordinates and luminance value: x = 0.534, y = 0.276; 0.11 cd/m²] or blue (x = 0.146, y = 0.074, 0.11 cd/m²) on a gray background (0.84 cd/m²). In Experiment 1B, the prime and the probe were black (0 cd/m²) on a gray background (0.32 cd/m²). The prime and probe figures were 1.13° and 1.88° per side, respectively. For prime and probe stimuli containing a hole, the hollow parts were 0.68° and 1.13°, respectively, except that the hollow parts of the O-like primes and probes were 0.57° and 0.94°.

Procedure

Each choice-RT experiment included 768 trials. In each trial, a 20-ms prime was masked by a probe with a stimulus onset asynchrony (SOA) of 60 ms (see Figure 1a). The probe lasted until a response was given. The intertrial interval ranged from 0.5 s to 1.5 s. Participants reported certain properties of the probe in separate blocks (384 trials in a block). Task order was balanced across participants. Stimulus presentation and data acquisition were controlled by a custom program written in Matlab (6.5) using Psychtoolbox (2.5.4).

Results

Mean accuracy exceeded 97% in all tasks. Mean correct RTs between 200 and 1,000 ms were analyzed. For each experiment (1A, 1B, and 1C), a three-way analyses of variance (ANOVA) examining task and two types of congruence (e.g., hole congruence and color congruence in Experiment 1A) all revealed significant 2-way interactions between task and either type of congruence (p < 0.001), which indicated that the congruence effects of these properties were all modulated by task, i.e., the congruence effect was more potent when the task was relevant to the properties. There were no 2-way interactions between two types of congruence or 3-way interactions between task and two types of congruence (p > 0.1) in Experiments 1A, 1B, and 1C. Mean RTs for the two tasks had no difference in Experiments 1A and 1B (p > 0.1) but were shorter for responses to color than to orientation in Experiment 1C (p = 0.007).

Color and hole

RTs for responses to color and hole (Figure 2a) were submitted into two separate ANOVAs examining color congruence (color-congruent/-incongruent) and hole congruence (hole-congruent/-incongruent). For either task, RTs were significantly shorter when the prime and probe were congruent than when incongruent in a task-relevant property (p < 0.001). Consistent with the prior finding that the top-down attentional set determined the congruence priming effects, color congruence effects were eliminated when participants responded to hole [F(1, 13) = 0.334, p > 0.5]. In contrast, hole congruence between prime and probe still modulated RTs for color report [F(1, 13) = 13.343, p = 0.003]. No interaction between these two types of congruence was found in both tasks (p > 0.1).

Given the area difference between one-hole and no-hole probe stimuli may bring confusion to the finding, the RTs in Experiment 1B, the prime and probe were one of the four combinations of hole (one hole/no hole) and orientation (square/diamond; Figure 1c), and participants reported orientation and hole in two separate blocks. In Experiment 1C, stimuli have also four types of combinations of color (red/blue) and orientation (square/diamond; Figure 1d), and subjects were asked to report orientation and color in separate blocks. In Experiment 1D, we assessed the prime awareness for holes, color, and orientation in separate blocks. For prime identification of hole and color, we adopted the stimuli in Experiment 1A; for identification of orientation, we adopted the stimuli in Experiment 1B. In each identification block, participants viewed the same stimulus sequence as in the RT experiments except that here each block consisted of 192 trials.
for both tasks were entered into an ANOVA with factors of prime (one hole/no hole) and probe (one hole/no hole). There were significant interactions for both tasks ($p < 0.002$). The RTs for color report were shorter when the probe had no hole than when it had one hole [$F(1, 13) = 8.174$, $p = 0.013$]. Because of significant interactions, RTs for either task were split into two groups. For one-hole probes, RTs were shorter for one-hole than for no-hole primes in both tasks [$t > 4.35$, $p < 0.002$], and for no-hole probes, RTs were shorter for no-hole than for one-hole primes in hole task [$t(13) = 6.102$, $p < 0.001$], but this difference did not reach significance for color task ($p > 0.1$). These results indicated that it was topological congruence that affected RTs. At the same time, we can also see that the influence of stimulus area on RTs would obstruct the topological congruence effect under some conditions.

The accuracy for responses to probe color and hole were also entered into two separate ANOVAs with factors of color and hole congruence. As shown in Supplementary Figure 1a, there were no speed–accuracy trade-offs; on the contrary, overall, the accuracy was a little higher when the RTs were shorter. For color task, accuracy was significantly higher when the prime and the probe were congruent than incongruent in color [$F(1, 13) = 8.390$, $p = 0.012$], and a little higher when both stimuli were congruent than incongruent in hole [$F(1, 13) = 4.3$, $p = 0.059$]. For the hole task, accuracy was higher when both stimuli were congruent than incongruent in hole ($p = 0.001$), and there was no effect of color congruence ($p > 0.9$). No interaction between color and hole congruence was found in both tasks ($p > 0.4$).

**Orientation and hole**

Similar results were obtained for orientation and hole tasks (Figure 2b). RTs for both tasks were submitted into two separate ANOVAs with factors of orientation and hole congruence. Again, congruence effects of the task-relevant dimensions were significant ($p < 0.001$). As found in color task, there was no effect of orientation on hole report ($p > 0.9$). However, there was significant priming effect in orientation task, based on whether topological properties of the stimuli were congruent [$F(1, 13) = 10.610$, $p = 0.006$]. No interactions between these two types of congruence were found in both tasks ($p > 0.1$).

The interactions between prime and probe (one hole/no hole) in both tasks were significant too ($p < 0.007$), indicating that it was topological congruence rather than hole itself that affected RTs. For both tasks, when the probe had a hole, RTs were shorter for one-hole than for no-hole primes, and when the probe had no hole, RTs were shorter for no-hole than for one-hole primes ($p < 0.014$).

There were no speed–accuracy trade-offs either (see Supplementary Figure 1b). For both tasks, the accuracy for responses to probe was higher when the prime and probe stimuli were congruent than incongruent in the reported dimension ($p < 0.02$), but no effects from task-irrelevant congruence or interactions ($p > 0.2$).

**Orientation and color**

Color and orientation judgments in Experiment 1C (Figure 2c) were affected only by congruence of task-relevant features ($p < 0.001$), with no effects from task-irrelevant features ($p > 0.1$). No interactions were found for both tasks ($p > 0.1$).

There were no speed–accuracy trade-offs (Supplementary Figure 1c). The mean correct rates for responses to probe were also affected only by the congruence in the reported dimension (for color task, $p = 0.002$; for shape task, $p = 0.055$), with no effects from task-irrelevant congruence and no interaction ($p > 0.4$).

**Explicit identification of primes**

The averaged correct rates for reporting hole (mean: $48.77\% \pm 1.06\%$, range: $43.7\%–56.7\%$), color ($51.67\% \pm 1.28\%$, $45.8\%–60.9\%$), and orientation ($50.60\% \pm 1.27\%$, $46.8\%–65.1\%$) of the primes were not significantly different ($p > 0.1$). In addition, the three rates were not different from the chance level of 50% either ($p > 0.2$). The accuracy data for the three tasks were submitted into three separate ANOVAs with factors of prime (one hole/no hole) and probe (one hole/no hole), revealing that there were no effects or interactions ($p > 0.1$). Therefore, there was no evidence that prime could be discriminated for these properties or the effects of topological congruence occurred because topological properties of primes were more visible than prime color or orientation.

**Experiment 2: Controlling for differences in flux/luminance**

The results from Experiment 1 showed that topological congruence mediated the responses to probe even when the topological properties were not relevant to the task. However, a potential confounding factor is that the topological changes in the stimuli were accompanied by other non-topological changes, notably in luminous flux and shape. As indicated by the results from the color
report in Experiment 1A, besides the topological congruence, RTs were also affected by stimulus area (i.e., whether the probes had a hole or not). Therefore, Experiment 1A had its limitation in proving evidence for topological congruence effect in the irrelevant task. To control the luminous flux, Experiment 2 used stimuli matched for area across different conditions (see Figure 1e): O-like, a square frame, S-like, and H-like figures (hereafter referred to as O, □, S, and H, respectively). Primes and probes were chosen randomly from these stimuli: 4 shapes × 2 colors (red, blue). Apart from these changes in the stimulus configurations, we closely replicated Experiment 1A. Again, participants were asked to report hole (i.e., whether there is a hole in the probe regardless of its shape) or color (in separate blocks). O and S were adapted from our previous studies (e.g., Zhou, Luo, Zhou, Zhuo, & Chen, 2010), and they were made to match in many physical features such as luminous flux, spatial frequency components, perimeter length, and number of edge crossings. O and □ are topologically different from S and H, because O and □ have one hole and S and H have none. The prime–probe pairings were classified into two types according to topological congruence: “hole-incongruent” (e.g., S and O) and “hole-congruent” (e.g., S and H). When the stimuli were congruent in their topological properties, they could be “shape-congruent” (e.g., S and S) or “shape-incongruent” (e.g., S and H).

We also tested the prime identification for topological properties and color in separate blocks, with the same procedure as in the RT tasks except that each block consisted of 192 trials.

Results

Color and hole

As shown in Figure 2d, the results were similar to those in Experiment 1A. The 3-way ANOVA revealed significant interactions between task and either type of congruence (p < 0.001), but there was no interaction between hole and color congruence, 3-way interaction, or main effect of task (p > 0.4). For response to either color or hole, congruence effects of task-relevant properties were significant (p < 0.001). Importantly, topological congruence also influenced performance in color task [F(1, 13) = 26.845, p < 0.001], whereas color congruence did not affect responses to topological properties [F(1, 13) = 0.417, p > 0.5]. There was no interaction for either task (p > 0.2).

We also found that RTs for either color or hole report were shorter for one-hole than for no-hole primes when the probe had one hole and were shorter for no-hole than for one-hole primes when the probe had no hole (p < 0.04). These results indicated that it was topological congruence rather than other factors (e.g., stimulus area) that influenced performance.

There were no speed–accuracy trade-offs (see Supplementary Figure 1d). The average correct rates for responses to probe were higher when both stimuli were congruent than incongruent in the reported dimension (for color task, p = 0.014; for hole task, p = 0.072), with no effects from task-irrelevant congruence and no interaction, ps > 0.1.

Explicit identification of primes

The averaged correct rates for reporting hole (mean: 50.19% ± 0.727%, range: 46.3%–54.6%) and color (50.89% ± 1.41%, 43.7%–63.5%) of the primes were not different (p > 0.6) and were also not different from the chance level of 50% (p > 0.5). The accuracy data for both tasks were submitted into two separate ANOVAs with factors of prime (one hole/no hole) and probe (one hole/no hole), revealing no effects or interactions (p > 0.4).

Experiment 3: Controlling for differences in category

Even though we used area-matched stimuli, another potential confounding factor was the category difference between stimuli in Experiment 2, i.e., shape vs. letter. Therefore, in Experiment 3, we adopted an array of geometric stimuli that were also matched in area (see Figure 1f). As shown in Figure 2e, similar results were obtained. The 3-way ANOVA revealed significant interaction between task and color congruence (p < 0.001) and marginally significant interaction between task and hole congruence (p = 0.077), but there was no interaction between hole and color congruence, 3-way interaction, or main effect of task (p > 0.5). Congruence effects of task-relevant properties were both significant (p < 0.005). For irrelevant task, we only observed significant topological congruence effect [F(1, 13) = 16.006, p = 0.002] but neither color congruence effect (p > 0.9) nor interaction effect (p > 0.5). For both one-hole and no-hole probes, the topological congruence effects were significant (p < 0.023). There were no speed–accuracy trade-offs either (see Supplementary Figure 1e). The average correct rates for responses to probe were higher when both stimuli were congruent than incongruent in the reported dimension (for color task, p = 0.014; for hole task, p = 0.063), with no effects from task-irrelevant congruence and no interaction (p > 0.1).

The accuracy for discriminating hole (mean: 50.30% ± 1.15%, range: 44.7%–62.5%) and color (50.78% ± 1.12%, 43.7%–59.9%) of the primes had no difference, and all were not different from chance level (p > 0.1). ANOVAs
Discussion

According to the early topological perception hypothesis (Chen, 1982, 2005), the visual processing of topological properties is a fast, bottom-up process that does not require visual attention to be deployed to the stimuli. Based on the hypothesis, here we proposed that the topological congruence effect will still occur when there is no task-directed attention. Our data support this prediction. We found the reliable topological congruence effect when the task was irrelevant to topological properties (e.g., to report color or orientation), though the effect was weaker compared to that under relevant task (i.e., hole task). In contrast, the congruence effects of other properties totally vanish under irrelevant tasks. This also occurred with stimuli matched for flux/luminance (Experiments 2 and 3). Moreover, a potential confounding factor of shape change between both stimuli could be excluded by a further analysis applied to the RTs for the trials in which prime and probe had the same topological properties, with no effects of shape change ($p > 0.1$). These results indicate that it is indeed the extraction of abstract hole rather than other geometric factors (e.g., area or shape) or category that takes effect in the topological congruence effects. Figure 3 showed congruence priming effects of hole and color (or orientation) under irrelevant tasks for Experiments 1A, 1B, 2, and 3, respectively. The interactions between properties (e.g., hole/color) and congruence (congruent/incongruent) were all significant ($p < 0.05$), indicating that the congruence of topological properties and color (or orientation) had different effects under irrelevant tasks. Topological congruence had reliable effects on other irrelevant responses (mean effect size = 14.5 ms; $p < 0.006$), while the color (or orientation) congruence showed little effect when irrelevant to the task (color: 1.25 ms, orientation: 0.06 ms; $p > 0.5$).

Figure 3. The congruence effects of hole and color (or orientation) under respective irrelevant task in (a) Experiments 1A, (b) 1B, (c) 2, and (d) 3. The error bars show the standard errors of the means.
An influential explanation for these top-down modulatory effects in masked priming is the direct parameter specification (DPS) model (Neumann & Kloutz, 1994; Scharlau & Ansorge, 2003), in which the response parameters are directly specified without consciousness and are contingent on intention-mediated attention. In other words, such processes are top-down in essence rather than bottom-up. The present results that priming effects of all these properties (including topological properties, color, and orientation) were more robust when the task was relevant than irrelevant supported the DPS theory to some extent: Motion preparation is indeed affected by attention; however, the finding of topological congruence effects in irrelevant tasks cannot be solely explained by DPS.

Our previous work (Zhou et al., 2010) using multiple-object tracking (MOT) paradigm has shown that a topological change in a figure (e.g., the sudden appearance of a hole in a solid figure) should be represented as the onset of a new object. Todd and Kuzmova (2011) have also proposed holes as proto-objects in MOT process. Thus, the priming effect of topological congruence may reflect an object-level effect rather than the feature-level priming effects, e.g., congruence effects of color and orientation. Actually, masked priming has also been interpreted by an object updating theory (Enns, Lleras, & Moore, 2009; Lleras & Enns, 2004, 2005; Moore & Enns, 2004; Moore, Mordkoff, & Enns, 2007), which holds that an object representation (for the prime) is established first, and then the new input (the probe) is used (or not) to update existing representations according to whether or not the probe is perceived as the same object as the prime. According to the topological perception theory, the probe differing in topological properties from the prime will trigger the construction of a new object representation, with the processing of the prime’s properties transferring to the newly constructed object. The RTs for all the properties will be increased by a latency, which is spent for the construction of a new object and the information diversion from the first object. The present finding that such topological congruence effect remains potent even under irrelevant tasks suggests that initial object representations based on topological properties take effect before task-directed top-down attention. This is also consist with recent studies supporting theories of pre-attentive object formation (e.g., Cosman & Vecera, 2010; Lamy, Segal, & Ruderman, 2006; Müller et al., 2010; Russell & Driver, 2005; Wolfe & Bennett, 1997). On the other hand, the congruence effects of other local features (e.g., color and orientation) can be regarded as the results from feature updating, and these effects depend on the task-directed top-down attentional set, as suggested by the previous and present findings. Besides, the finding that under respective relevant task the color (or orientation) congruence had effects when the probe had different topological properties from the prime indicates that the feature updating processes do not cease but rather continue on the newly constructed representation; in other words, the construction of a new object brings extra consumption instead of interruption to the feature updating. In a word, the topological congruence influences the processing of object properties in a bottom-up manner, while the congruence effects of local features (e.g., color or orientation) rely on a top-down effect mediated by task demand.

Our proposal of stimulus-driven effects of topological properties on masked priming is also supported by the phenomenon that a task-irrelevant neutral prime could facilitate responses to a probe compared to a condition without a prime (e.g., Klotz & Wolff, 1995). Note that “presence or absence” of a prime is exactly one type of topological properties; the prime’s unspecific facilitation effect on the subsequent stimulus can be considered as another case of priming effects based on global topological properties of objects.

In conclusion, the masked priming induced by task-irrelevant topological changes indicates that object representations constrained by topological properties can take precedence over top-down attentional effects in non-conscious processing.

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