

Topological difference between target and flankers alleviates crowding effect

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In the crowding effect, object recognition in the periphery deteriorates when other items flank the target, especially if they share similarities. Here, we report that the similarity defined by topological property (differences in number of holes) influences the crowding effect. Orientation discrimination tasks suggested that the crowding effect was weaker with a topological different (TD) flanker than a topological equivalent (TE) flanker and an existing inward-outward anisotropy phenomenon. In another experiment, both an outer and an inner flanker were used to constitute four different conditions. The performance of an outer TD flanker and an inner TE flanker was superior to that of an outer TE flanker and an inner TD flanker, even though the items of the stimuli were the same. Different stimuli were used to control for local features. To eliminate the possible explanation of confusability, we selected pairs of letters with matched confusability, but one pair was TD and another was TE. The letter identification performance was better for the TD condition. Lastly, we investigated the digit identification under four conditions with varied spacing. Regardless of different spacing, the crowding

effect was reduced by a topological different flanker. The results collectively suggest that topological property plays a role in the perceptual grouping, which modulates the crowding effect.

Introduction

The crowding effect, a ubiquitous perceptual phenomenon, refers to observers' deteriorated ability to recognize an object in their visual periphery when other items flank the target object. Previous studies have revealed that the spatial zone of crowding is proportional to eccentricity (Bouma, 1970; Levi, Hariharan, & Klein, 2002; Toet & Levi, 1992), inhomogeneous across the visual field (Feng, Jiang, & He, 2007; Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007; Petrov & Popple, 2007), asymmetric (Bouma, 1970; Banks, Larson, & Prinzmetal, 1979; Bex, Dakin, & Simmers, 2003; Chastain, 1982;

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Krumhansl & Thomas, 1977, Petrov, Popple, & McKee, 2007), invariant to the size of the test items (Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004; Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007; Tripathy & Cavanagh, 2002), and quite dissimilar from ordinary masking (Andriessen & Bouma, 1976; Levi, Hariharan, & Klein, 2002). Crowding is selective along several dimensions. It is stronger and more extensive when the target and flankers are similar in shape and size (Kooi, Toet, Tripathy, & Levi, 1994; Nazir, 1992), orientation (Andriessen & Bouma, 1976; Hariharan, Levi, & Klein, 2005; Leat, Li, & Epp, 1999; Levi, Hariharan, & Klein, 2002), spatial frequency (Chung, Levi, & Legge, 2001), depth (Kooi, Toet, Tripathy, & Levi, 1994), color (Bouma, 1969; Kennedy & Whitaker, 2010), and motion (Banton & Levi, 1993). The effect of similarity on the crowding effect is in part due to the perceptual grouping mechanism between target and flankers. The more the target groups with the flankers, the stronger the crowding (Herzog & Manassi, 2015; Herzog, Sayim, Chicherov, & Manassi, 2015). Perceptual grouping and gestalt play important role in comprehending crowding and object recognition in periphery (Herzog & Manassi, 2015; Herzog, Sayim, Chicherov, & Manassi, 2015). Studies shows that some grouping principles such as similarity, regularity, contour grouping, and good gestalt could result in a strong crowding or uncrowding (Herzog, Sayim, Chicherov, & Manassi, 2015; Manassi, Sayim, & Herzog, 2013). Spatial configuration could determine crowding effect by changing the layout of the stimulus, which could lead to strong changes in perception (Manassi, Lonchampt, Clarke, & Herzog, 2016). Grouping the flankers into a coherent unit or texture may relieve crowding in the periphery. However, when the target and flankers are less likely to be grouped due to dissimilarity in certain features such as color, polarity, or depth, crowding is greatly reduced (Poder, 2007; Scolari, Kohnen, Barton, & Awh, 2007).

The perceptual grouping has often been considered to follow the gestalt principles (Wertheimer, 1923). In addition, the topological perception theory (Chen, 1982) provides a formal and precise framework to elevate the vague intuitions of gestalt ideas regarding global versus local relationships. Chen (1982) first demonstrated that the visual system is highly sensitive to topological differences (such as introducing or deleting a hole). For example, two visual stimuli differing in topological properties (e.g., an open circle and a solid triangle) are more discriminable under a near-threshold condition than stimulus pairs that differ in various types of local features but are topologically equivalent (e.g., a solid disk and a solid triangle). The topological approach has been proposed to describe precisely the nature and rules of perceptual organization. The core idea of the topological approach is that perceptual organization should be understood in the perspective of transformation and perception

of invariance over transformation. A counterintuitive experiment on visual sensitivity to topological difference supported the topological hypothesis (Chen, 1982). The analysis of the phenomenon of shape-changing transformations observed in apparent motion led us to consider topological invariants as candidates for the correspondence tokens in apparent motion (Chen, 1985). The theory of early topological perception has demonstrated its applicability to a wide spectrum of phenomena in perceptual organization. Besides the ones previously mentioned, these phenomena concern the object superiority effect (e.g., Chen, 1986), texture discrimination (Chen, 1989), visual search (e.g., Zhou & Chen, 1996), competing organization (e.g., Chen, 1986), global precedence (e.g., Han, Humphreys, & Chen, 1999a), the relation between different organizational factors (e.g., Han, Humphreys, & Chen, 1999b), and hemispheric asymmetry (e.g., Lan & Chen, 1996).

On the basis of grouping by proximity (Chen, 2005; Han, Humphreys, & Chen, 1999b), similarities in topological properties, such as closure, number of holes, and inside-outside relationship, can be processed in a parallel way in determining the selection between global and local levels of hierarchical patterns for response. If topological properties do indeed play an important role in perceptual organization, then they might be perceived under the crowding condition, modulating crowding effect when the target and flankers shared local geometrical properties but were topologically different.

In the present study, we investigated whether target-flanker similarity based on topological properties influenced the crowding effect. We tested the extent of the crowding effect induced by two stimuli patterns of topological difference and topological equivalence. Moreover, we employed two stimuli patterns of the same items but different topological properties. The crowding effect was reduced if the target and flankers differed in their numbers of holes and with an outer topological different flanker and an inner topological equivalent flanker.

Method

Participants were tested individually in a dimly lit room, observing the stimuli from a distance of 56 cm. The stimuli were shown on a Dell computer with a 22-in. CRT monitor at a resolution of 1,024 × 768 pixels, whose frame rate equaled 16.67 ms. MATLAB software (MathWorks, Natick, MA) with Psychophysics Toolbox PTB-3 (USA) (Brainard, 1997; Pelli, 1997) was used to display the stimuli and record responses. The stimuli were black against a gray background. Observers were required to fixate on the fixation point throughout the experiment. The observer initiated each trial. Time interval between space bar

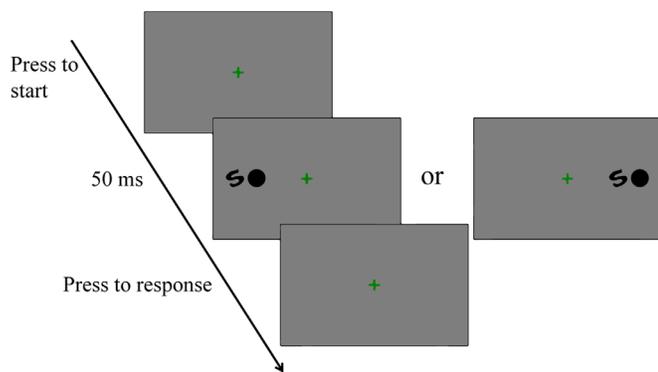


Figure 1. Trial structure for all the experiments in our study. The stimuli in this figure were the same as that in Experiment 1.

press and onset of stimuli was 250 ms. The conditions and trials were randomized. The stimuli were presented for 50 ms (Figure 1). The behavioral performance was quantified by the percentage of correct responses. The fixation point was in the middle of the screen. The target was presented either on the left or the right to the fixation point. The eccentricity of the target was 12° . In Experiments 1 to 3, the stimuli subtended a visual angle of $3.1^\circ \times 3.1^\circ$. The center-to-center distance between the target and the flanker was 3.25° . The luminance of the stimuli and background was 0 cd/m^2 and 0.48 cd/m^2 , respectively. We conducted our study in a lower light condition compared with other crowding experiments. The observers underwent a dark adaptation. Under a lower light condition, mainly rods mediate our visual system, and the very low lightness was in favor of the peripheral vision mediated by the rods system.

The observers were college students who were paid for their time and effort. All observers had normal or corrected-to-normal visual acuity and provided oral consent before the experiment and signed the subjects' information list after the experiment.

Experiment 1

Many previous studies (see Levi, 2008) indicated that the inward-outward anisotropy of the crowding effect could be used as a litmus test for crowding. In this experiment, we tested whether this characteristic exists in our study. Moreover, we used a set of well-controlled stimuli to investigate how the topological difference between the target and the flanker affected the crowding effect.

Observers

This experiment had 12 observers (6 females and 6 males).

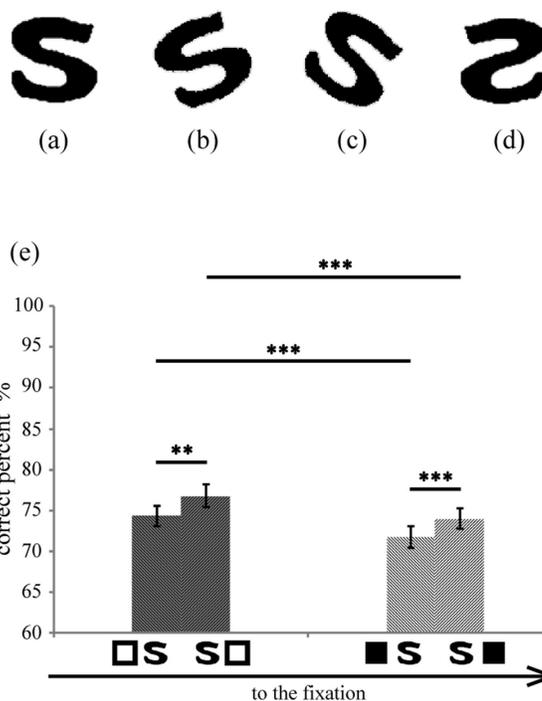


Figure 2. Target figures and results of Experiment 1. (a–d) The four possible orientations of target figures. (e) The columns on the left were topological different conditions, and the columns on the right were topological equivalent. For each target-flanker pair, we had an outer flanker condition and an inner flanker condition. Error bars indicate standard error of mean. $**p < 0.01$. $***p < 0.001$.

Stimuli

In each trial, the stimuli were composed of one target and one flanker beside the target. The target was an S-like figure tilted in different directions (upright, left, right, and reverse) (Figures 2a–d, Table S2). In this experiment, we tested two conditions: when the flanker was an inner one (closer to the fixation point) and when the flanker was an outer one (farther from the fixation point). The S-ring figures were made to have equal luminous flux, nearly the same spatial frequency components, equal perimeter length, equal averaged edge crossings, and other local features; the shape of S also was made irregular to eliminate the possible effects of subjective contours. The S and the solid disk differ extensively in shape but are topologically equivalent. The flankers with a hole also include a hollow square, a hollow parallelogram, and a hollow trapezoid, which do not share equal luminous flux, equal perimeter length, and equal averaged edge crossings. The flankers without a hole also include a solid square, a solid parallelogram, and a solid trapezoid. In the topological different condition, the flanker was a ring, a hollow square, a hollow parallelogram, or a hollow trapezoid. In the topological equivalent condition, the flanker was

a solid counterpart for the flankers in the topological different conditions.

Procedure

In this experiment, the task was to discriminate the orientation of the target S-figure (left, right, upright, or reversed). The flanker was either an outer or an inner one. The subjects completed 112 trials of a topological different condition (56 trials with an outer flanker and 56 trials with an inner flanker) and 112 trials of a topological equivalent condition (56 trials with an outer flanker and 56 trials with an inner flanker). The four “arrow” keys to different directions corresponded to different S-like figures.

Results

We conducted a two-way analysis of variance (ANOVA) test on the factors of target and flanker configuration (topological different or topological equivalent) by inward-outward anisotropy. The performance of the S-figure orientation discrimination showed a significant difference between the topological different and the topological equivalent condition (main effect of target and flanker configuration: $F(1, 11) = 77.15, p < 0.001, \eta^2 = 0.88$) (Figure 2e). A reduction of performance by an outward flanker existed when the target and flanker were both topological different and topological equivalent (main effect of inward-outward anisotropy: $F(1, 11) = 39.56, p < 0.001, \eta^2 = 0.78$). However, the interaction of these two factors was not significant, $F(1, 11) = 0.068, p = 0.80, \eta^2 = 0.006$ (Table S1).

Experiment 2

In light of the inward-outward anisotropy of the crowding effect revealed by Experiment 1, we developed two conditions that consisted of the same items but different configuration. Using the stimuli with same items but different configuration, we aimed to eliminate the possible confounding factors introduced by the characteristics of the figures, such as spatial frequency, luminous flux, and perimeter length. Here we specifically manipulated topological changes (introducing or removing holes within target and flankers) and compared the crowding effect brought by different configurations.

Observers

A total of 40 subjects were included in these three experiments (2I: 12 [7 females; 5 males]; 2II: 16 [8

females; 8 males]; 2III: 12 [6 females; 6 males]; 2IV: 12 [7 females; 5 males]).

Stimuli

In this experiment, we arranged two flankers horizontally next to the target. There were four target-flanker conditions: (a) Both flankers were topological different (condition a), (b) both flankers were topological equivalent (condition b), (c) one was a topological different outer flanker and one was a topological equivalent inner flanker (condition c), and (d) one was a topological different inner flanker and one was a topological equivalent outer flanker (condition d).

Procedure

The procedure was the same as in Experiment 1. The subjects completed 512 trials (128 trials for each of the four conditions). In all the four experiments, a Bonferroni adjustment was used for multiple comparisons.

Results

In Experiment 2I, we employed the same stimulus items as in Experiment 1, with four conditions of the flanker-target configuration. The behavioral performance between Condition a and Condition b was consistent with Experiment 1 in that the crowding effect was reduced when the flankers and the target were topological different (Condition a vs. Condition b: $t(11) = 14.55, p < 0.001, \text{Cohen's } d = 4.20$). The performance of Condition b was the worst among the four conditions (Condition b vs. Condition c: $t(11) = -8.13, p < 0.001, \text{Cohen's } d = -2.35$; Condition b vs. Condition d: $t(11) = -4.01, p = 0.002, \text{Cohen's } d = -1.16$). When the items were the same but with slightly different configurations, as in Condition c and Condition d, the crowding effect declined when the topological different flanker was an outer one and the topological equivalent flanker was an inner one ($t(11) = 9.10, p < 0.001, \text{Cohen's } d = 2.63$). However, the best performance was observed in Condition a, that is, with topological different flankers (Condition a vs. Condition c: $t(11) = 8.30, p < 0.001, \text{Cohen's } d = 2.40$; Condition a vs. Condition d: $t(11) = 11.45, p < 0.001, \text{Cohen's } d = 3.30$) (Figure 3).

In Experiment 2II, we used the widely adopted digits that shared spatial frequency and had a similar shape, as well as some letters that were similar to them. By topological definition, the difference between the figures of b, p, d, q (four flankers with a hole); 6, 9 (two targets); and those of 5, 2, \exists , E (four flankers without hole) is the number of holes. The target was

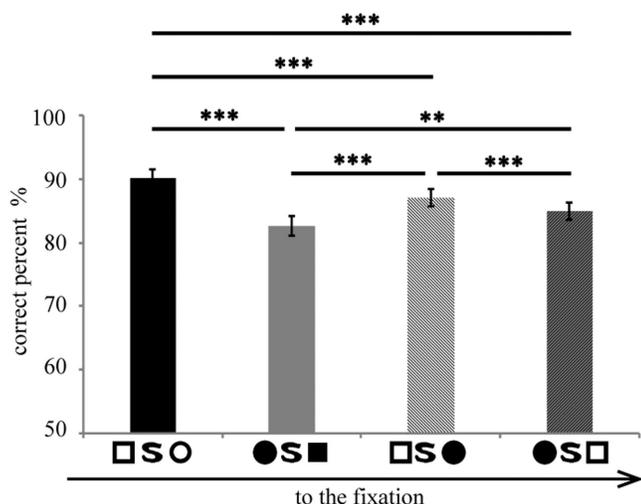


Figure 3. Results of Experiment 2I. The target S-like figure was flanked by two items. From the most-left column to the most-right column, there were four conditions in which both flankers were topological different, both flankers were topological equivalent, one was an outer topological different flanker and one was an inner topological equivalent flanker, and one was an inner topological different flanker and one was an outer topological equivalent flanker. Error bars indicate standard error of mean. $**p < 0.01$. $***p < 0.001$.

always a digit 6 or 9 (Table S3). The response key was up arrow for Target 6 and down arrow for Target 9. The differences of flankers either between categories or within category could be well controlled. The flankers shared the same area, luminous flux, nearly the same spatial frequency, and perimeter length. Meanwhile, it could still be argued that, because the S carries a horizontally oriented bar in the middle, there is more horizontal-edge energy and higher horizontal spatial frequencies in the S than in the ring; a neuron merely preferring horizontal edges or horizontal higher spatial frequencies could distinguish the S from the ring without the need to pay explicit attention to topology. To address this issue, the target figure 6 or 9 and the flankers share exactly the same horizontal line segments. Both the target and the topological equivalent flanker had a hole, which could eliminate the possible explanation that the reduction of crowding effect was induced by a hole in the flanker. If both flankers had no hole, that constituted Condition a. If both flankers had one hole, that constituted Condition b. Moreover, if one flanker had no hole and one flanker had one hole, it constituted either Condition c or Condition d. The best performance was observed in Condition a, that is, topological difference between the target and the flankers (Condition a vs. Condition b, $t(15) = 11.05$, $p < 0.001$, Cohen's $d = 2.76$; Condition a vs. Condition c, $t(15) = 5.77$, $p < 0.001$, Cohen's $d = 1.44$; Condition a vs. Condition d, $t(15) = 7.25$, $p < 0.001$, Cohen's

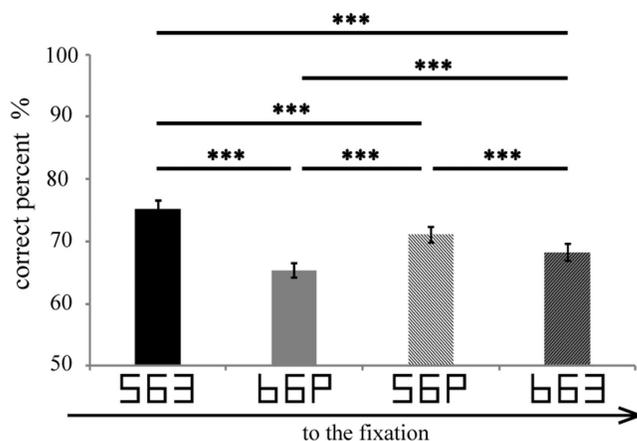


Figure 4. Results of Experiment 2II. The target was either digit 6 or 9. From the most-left column to the most-right column, there were four conditions in which both flankers were topological different, both flankers were topological equivalent, one was an outer topological different flanker and one was an inner topological equivalent flanker, and one was an inner topological different flanker and one was an outer topological equivalent flanker. Error bars indicate standard error of mean. $***p < 0.001$.

$d = 1.81$). The worst performance was observed in Condition b, that is, topological equivalence between the target and the flankers (Condition b vs. Condition c, $t(15) = -8.65$, $p < 0.001$, Cohen's $d = -2.16$; Condition b vs. Condition d, $t(15) = -5.40$, $p < 0.001$, Cohen's $d = -1.35$). Consistent with Experiment 2I, the performance in Condition c was better than that in Condition d ($t(15) = 5.51$, $p < 0.001$, Cohen's $d = 1.38$) (Figure 4).

The topological definition of perceptual objects has been tested against transitions between solid and hollow forms, including no hole to one hole and one hole to two holes. In Experiment 2III, we further generalize the topological change of one hole to two holes reflected in the change in the number of holes. The target was a ring with a bar in the center, which formed a two-hole figure. The response key was a left arrow for the left tilted bar in the target and a right arrow for the right tilted bar in the target. The topological different flankers were figures with one hole, such as a ring, a square with a hole, a parallelogram with a hole, and a trapezoid with a hole. The latter three figures with a bar in the center and a solid disk with two small holes in the center were the topological equivalent figures (Table S4). The sums of the areas of the two small holes contained in the two-hole disk were made to be equal to the area of the big hole contained in the ring, which controlled the luminous flux of these two figures. In Condition a, both flankers had one hole. In Condition b, both flankers had two holes. Moreover, if one flanker had one hole and another flanker had two holes, it was either Condition c or Condition d. The subjects were required

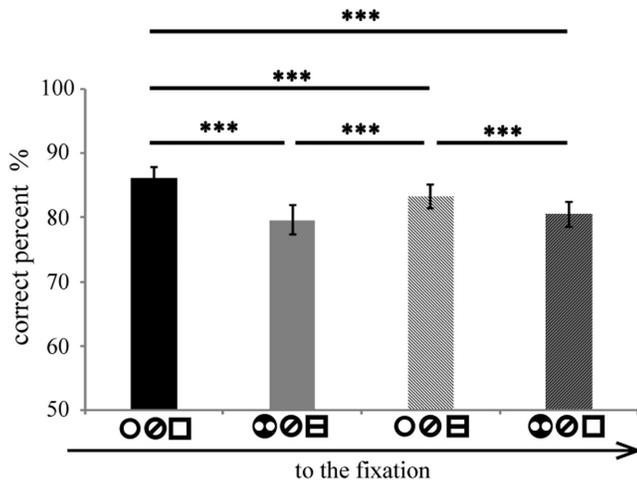


Figure 5. Results of [Experiment 2III](#). The target was a ring with a bar in the middle. From the most-left column to the most-right column, both flankers were topological different, both flankers were topological equivalent, one was an outer topological different flanker and one was an inner topological equivalent flanker, and one was an inner topological different flanker and one was an outer topological equivalent flanker. Error bars indicate standard error of mean. *** $p < 0.001$.

to discriminate whether the bar in the target was tilted toward the left or right. The performance in Condition a was superior to the other conditions (Condition a vs. Condition b, $t(11) = 7.82$, $p < 0.001$, Cohen's $d = 2.26$; Condition a vs. Condition c, $t(11) = 4.44$, $p < 0.001$, Cohen's $d = 1.28$; Condition a vs. Condition d, $t(11) = 7.59$, $p < 0.001$, Cohen's $d = 2.19$). The performance in Condition b was poorer than that in Condition c ($t(11) = -4.83$, $p < 0.001$, Cohen's $d = -1.40$). Placing a topological different flanker on the outer side and a topological equivalent flanker on the inner side could diminish the crowding effect as compared with its reverse condition (Condition c vs. Condition d, $t(11) = 5.70$, $p < 0.001$, Cohen's $d = 1.65$) ([Figure 5](#)). However, paired sample t test showed the performance of Conditions b and d was not significantly different ($t(11) = -1.15$, $p = 0.27$, Cohen's $d = -0.33$). The possible reason is that the reduction of a crowding effect led by an inner topological different flanker was not as great as that in Experiments 2I and 2II. There might be some contributions from other processes, rather than processing of topological properties.

The observed reduction of crowding effect induced by a topological different flanker in previous experiments could be attributed to the specificity of hole. It might be considered that the flankers with more “ink” are more effective in a crowding effect than flankers with less “ink.” Or, the filled figure will have lower luminance, edge contrast, and more low spatial frequency content than an open figure, which could account for the increased crowding effect. In Experiment 2IV, we used

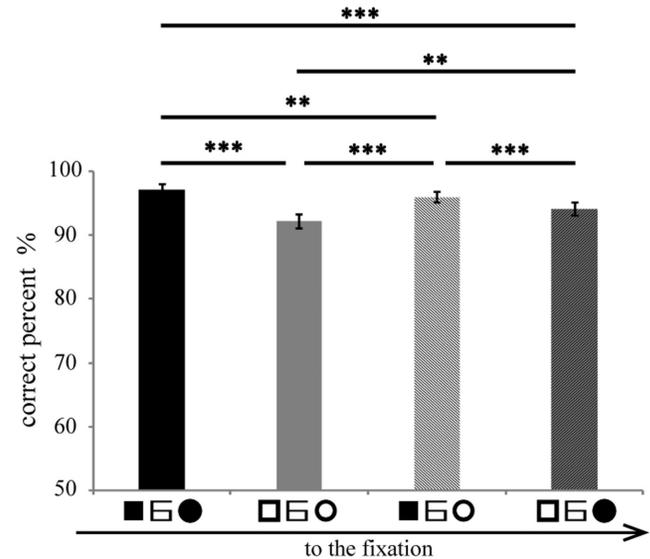


Figure 6. Results of [Experiment 2IV](#). The target was a 6-like or a 9-like figure in the middle. From the most-left column to the most-right column, both flankers were topological different, both flankers were topological equivalent, one was an outer topological different flanker and one was an inner topological equivalent flanker, and one was an inner topological different flanker and one was an outer topological equivalent flanker. Error bars indicate standard error of mean. ** $p < 0.01$. *** $p < 0.001$.

the same target figures as that in Experiment 2II, a 6 or a 9. The flankers were the same as that in Experiment 2I. However, in this experiment, a solid flanker and the target were topological different, while a hollow flanker and the target were topological equivalent. We tested four conditions: a, a target with two filled flankers, which were topological different; b, a target with two hollow flankers, which were topological equivalent; c, an outer filled flanker and an inner hollow flanker; and d, an outer hollow flanker and an inner solid flanker. The performance of Condition a was the best among these four conditions (Condition a vs. Condition b: $t(11) = 10.09$, $p < 0.001$, Cohen's $d = 2.91$; Condition a vs. Condition c: $t(11) = 3.89$, $p = 0.003$, Cohen's $d = 1.12$; Condition a vs. Condition d: $t(11) = 6.77$, $p < 0.001$, Cohen's $d = 1.95$). The worst performance happened on Condition b (Condition c vs. Condition b: $t(11) = 14.39$, $p < 0.001$, Cohen's $d = 4.15$; Condition d vs. Condition b: $t(11) = 10.69$, $p < 0.001$, Cohen's $d = 3.09$). A topological different flanker outward and a topological equivalent flanker inward led to less crowding effect compared with the condition of an outer topological equivalent flanker and an inner topological different flanker (Condition c vs. Condition d: $t(11) = 8.41$, $p < 0.001$, Cohen's $d = 2.43$) ([Figure 6](#)). The result was consistent with previous experiments. Neither the difference between the flankers nor the hole per se but the configuration of different topological

Target	Flanker	Category	Confusability
O	G	Topological different	0.153
O	Q	Topological equivalent	0.142
O	P	Topological equivalent	0.02
O	S	Topological different	0.023
P	G	Topological different	0.015
P	O	Topological equivalent	0.015
S	Q	Topological different	0.027
P	S	Topological different	0.021
S	O	Topological different	0.016
S	P	Topological different	0.017
G	S	Topological equivalent	0.023
Q	P	Topological equivalent	0.004
G	P	Topological different	0.009
Q	S	Topological different	0.028

Table 1. Selected letter pairs and their confusability.

property between the target and flankers modulates the crowding effect.

Experiment 3

It could be argued that the reduced crowding effect resulted from different levels of confusability between the target and the flankers in different conditions. The confusability matrix was well studied in previous studies. We adopted one of the studies (van der Heijden, Malhas, & Van Den Roovaart, 1984) and chose letter pairs that with matched confusability number for both topological different and topological equivalent conditions.

Observers

There were 12 subjects (8 females and 4 males) in Experiment 3I and 12 subjects (6 females and 6 males) in Experiment 3II.

Stimuli and procedure

We adopted the letters previously used and improved in another study (van der Heijden, Malhas, & Van Den Roovaart, 1984). The numbers of confusability were generated using continuous-line capitals in a fast display screen and based on summed responses. The number indicates the proportion of times that a stimulus letter was identified as a response (van der Heijden, Malhas, & Van Den Roovaart, 1984). In this experiment, we used one target on the inner side and one flanker horizontally next to the target. Table 1 presents the confusability between the target and flanker. In order to balance the presence of letters either as a target or as a

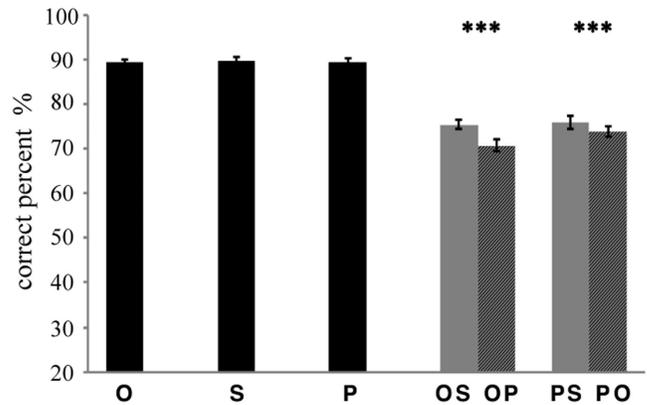


Figure 7. Results of Experiment 3I. Controlling for confusability and single-target versus flanker condition. Error bars indicate standard error of mean. *** $p < 0.001$.

flanker, we conducted two experiments (3I and 3II) and added a condition with no flanker in Experiment 3I as a baseline. In Experiment 3I, we employed the letters O, S, and P. Each letter was presented individually for 40 trials. The letter pairs we used in Experiment 3I were OS, OP, SP, SO, PS, and PO. Each pair was presented for 40 trials. The pairs OS versus OP and PS versus PO were matched to compare their performance. In Experiment 3II, we tested pairs PG, PO, OG, OQ, GS, QS, GP, QP, SO, and SQ. Each pair was presented for 40 trials. We compared the performance of matched pairs such as PG versus PO and OG versus OQ. The participants used a mouse to click on their choice among the letters' array at the bottom of the screen. The position of the letters' array did not overlap with the previous stimuli presentation. After the stimulus' offset and before its onset, there was a 250-ms time interval for the letters' array.

Results

In Experiment 3I, the performance of the single letter was significantly better than the flanked condition (for all comparisons, $p < 0.001$). We listed the statistical results of the stimuli pairs, which matched in confusability but belonged to different topological categories (Table 2). Consistently, the target letter flanked by a topologically different letter reduced the crowding effect, even though the confusability was almost similar to the topologically equivalent stimuli (Figures 7 and 8).

Experiment 4

The spacing between the target and the flankers influences the crowding effect. In previous experiments,

Topological different stimuli	Topological equivalent stimuli	Statistics
OS	OP	$t(11) = 10.27, p < 0.001, \text{Cohen's } d = 2.96$
PS	PO	$t(11) = 6.63, p < 0.001, \text{Cohen's } d = 1.92$
PG	PO	$t(11) = 9.75, p < 0.001, \text{Cohen's } d = 2.82$
OG	OQ	$t(11) = 5.21, p < 0.001, \text{Cohen's } d = 1.50$

Table 2. Results of the confusability matched stimuli pairs.

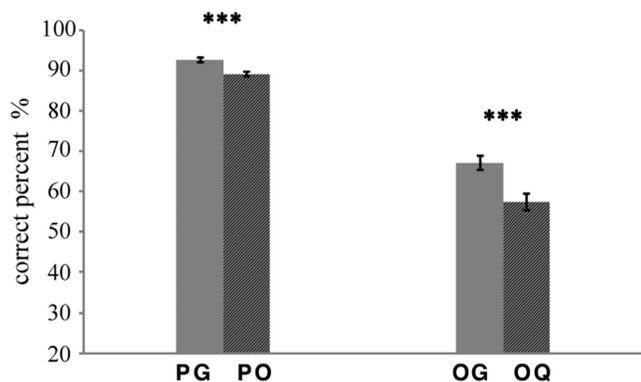


Figure 8. Results of Experiment 3II. Controlling for confusability and single-target versus flanker condition. Error bars indicate standard error of mean. $***p < 0.001$.

the spacing was fixed to be 3.25° . In this experiment, we measured the previously observed effect with varied spacing between the target and the flankers to investigate whether the previously observed effect remains.

Observers

This experiment had eight subjects (five females and three males).

Stimuli

In this experiment, the target-flanker configuration was the same as in Experiment 2II: a, both flankers were topological different; b, both flankers were topological equivalent; c, one was a topological different outer flanker and one was a topological equivalent inner flanker; and d, one was a topological different inner flanker and one was a topological equivalent outer flanker. The eccentricity of the target was 12° . The stimulus size was $3.0^\circ \times 3.0^\circ$. The center-to-center distance between the target and the flankers was $3^\circ, 3.25^\circ, 3.5^\circ, 3.75^\circ,$ and 4° , respectively.

Procedure

The procedure was the same as in Experiment 2II. The subjects completed 1,000 trials, including 50 trials

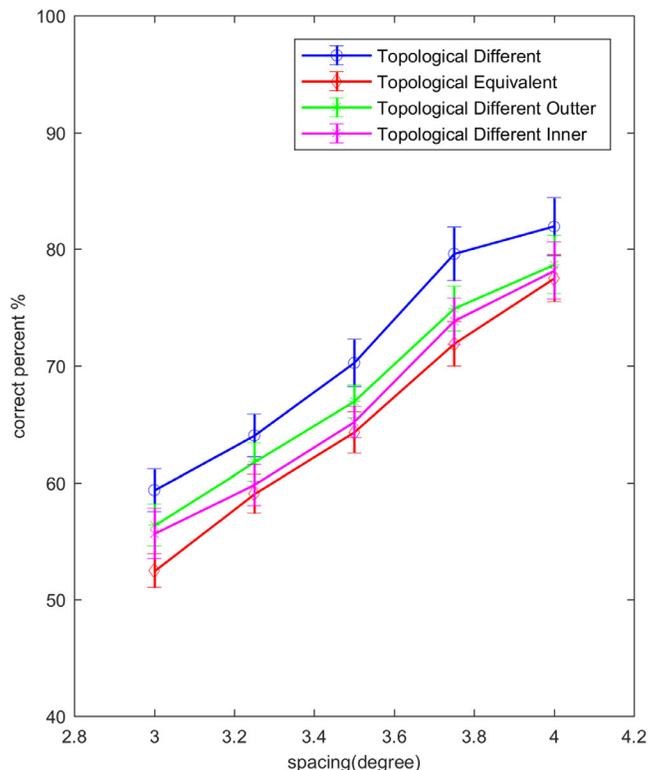


Figure 9. Results of Experiment 4. Measurement with varied spacing between the target and the flankers. The spacing was $3^\circ, 3.35^\circ, 3.5^\circ, 3.75^\circ,$ and 4° . Different colors indicate different conditions. Blue, both flankers were topological different; green, outer flanker was topological different and inner flanker was topological equivalent; magenta, outer flanker was topological equivalent and inner flanker was topological different; red, both flankers were topological equivalent. Error bars indicate standard error of mean.

for each of the 20 tested points (4 conditions \times 5 spacings).

Results

We applied repeated-measures ANOVA within subjects on a 4×5 design (Target-Flanker Configuration \times Spacing Distances). Both the configuration factor and the spacing factor showed a significant main effect (configuration: $F(3, 21) = 72.25,$

$p < 0.001$, $\eta^2 = 0.91$; spacing: $F(3, 21) = 103.25$, $p < 0.001$, $\eta^2 = 0.94$). Consistent with previous results, when the target and the flankers were topological different, regardless of the spacing distance, the performance was superior to the condition when they were topological equivalent (comparing the two conditions collapsing across spacing, $F(1, 7) = 87.64$, $p < 0.001$, a Bonferroni-corrected multiple-comparison post hoc test, $t(7) = 11.17$, Cohen's $d = 3.95$, $p_{\text{bonf}} < 0.001$). When the same items were arranged differently in Condition c or d, the performance was significantly better when the topological different flanker was an outer one and the topological equivalent flanker was an inner one (comparing the two conditions collapsing across spacing, $F(1, 7) = 28.46$, $p < 0.001$, a Bonferroni-corrected multiple-comparison post hoc test, $t(7) = 5.54$, Cohen's $d = 1.96$, $p_{\text{bonf}} < 0.001$). Among all four configuration conditions, the performance in Condition b was the worst (comparing the two conditions collapsing across spacing, $F(1, 7) = 101.66$, $p < 0.001$, a Bonferroni-corrected multiple-comparison post hoc test, $t(7) = -7.71$, Cohen's $d = -2.73$, $p_{\text{bonf}} < 0.001$; comparing the two conditions collapsing across spacing, $F(1, 7) = 29.18$, $p < 0.001$, a Bonferroni-corrected multiple-comparison post hoc test, $t(7) = -4.20$, Cohen's $d = -1.48$, $p_{\text{bonf}} < 0.001$) (Figure 8).

Discussion

Object recognition in peripheral vision proceeds through the selection and combination of features, governed by principles of grouping and crowding (Banks, Larson, & Prinzmetal, 1979; Banks & White, 1984; Herzog & Manassi, 2015; Herzog, Sayim, Chicherov, & Manassi, 2015; Livne & Sagi, 2007). Compared with single-target identification, crowding impairs the ability to identify an object in a clutter, an effect widely observed in discrimination tasks. Crowding has usually been explained by the substitution of the target by the flanker or the spatial pooling of both target and flankers under the frame of processing in hierarchical and feed-forward fashion from the analysis of low-level features (Levi, 2008; Levi, Klein, & Yap, 1987; Parkes, Lund, Angelucci, & Solomon, 2001; Pelli, 2008; Pelli et al., 2006; Suchow & Pelli, 2013). Some studies have shown that crowding was determined by the spatial configuration across the visual field. Perceptual grouping and gestalt are important to understand crowding. Subtle changes in the visual field can change object recognition (Herzog & Manassi, 2015; Herzog, Sayim, Chicherov, & Manassi, 2015; Manassi, Lonchampt, Clarke, & Herzog, 2016; Manassi, Sayim, & Herzog, 2013; Saarela, Westheimer, & Herzog, 2010).

Our results support the studies, which revealed that global stimulus configuration modulates crowding (Saarela, Sayim, Westheimer, & Herzog, 2009). Sayim's study found that crowding was strongly diminished when the flanking lines were part of a geometric shape (i.e., a good gestalt) (Sayim, Westheimer, & Herzog, 2010). They proposed that contextual modulation could be used as a quantitative measure to investigate the rules governing the grouping of elements into meaningful wholes. Generally, in terms of perceptual organization, strong crowding occurs when the target is perceptually grouped with the flankers so that they form a coherent pattern together. In our research, the topological approach provides specific grouping rules of a good gestalt. On the basis of grouping by proximity (Chen, 2005; Han, Humphreys, & Chen, 1999b), similarities in topological properties, such as closure, number of holes, and in-out relationship, can be processed in a parallel way in determining the selection between global and local levels of hierarchical patterns for response. Our findings systematically defined the difference between the two stimuli patterns by a topological approach, that is, the number of holes, and revealed the consistent reduction of the crowding effect. However, there are other processes in figural interaction that take place and lead to uncrowding (Manassi, Sayim, & Herzog, 2013).

Moreover, another study revealed that the brain's remapping for the anticipated eye movement unavoidably combines features from the target's current and future retinal locations into one perceptual object (Harrison, Retell, Remington, & Mattingley, 2013). The "remapped crowding" interference was stronger when the flankers were visually similar to the probe than when the flanker and probe stimuli were distinct. The visually distinct stimuli they used are similar to ours. The target and flankers had a distinct number of holes, and the visually similar stimuli had no hole. Our findings indicate that topological property plays an important role in perceptual grouping, which modulates the crowding effect.

Here, the confusability between the items cannot account for the difference among the conditions. In our control experiments, the confusability was matched between the topological different and topological equivalent conditions. The similarity could not operate on local features such as orientation, position, size, or contrast. The difference arose from topology per se.

The significant main effects in Experiment 1 suggested that the cortical geometry (Motter, & Simoni, 2007) and topological similarities independently contributed to the crowding effect. The interaction between the spatial pooling and the topological similarities needs to be investigated further. The crowding effect is accompanied by an unimpaired performance of reporting a statistical property of the ensemble (Parkes, Lund, Angelucci, & Solomon, 2001;

see Dayan & Solomon, 2010; Levi, 2008). Pooling models could explain reduced crowding effects in experiments where the target and flankers are different from each other, such as disks differing in size (Engel, 1974), lines or gabors of orthogonal orientation (Andriessen & Bouma, 1976; Wilkinson, Wilson, & Ellemberg, 1997), letters flanked by different shapes (Estes, 1972; Nazir, 1992), or letters of different colors or of contrasting polarity (Kooi, Toet, Tripathy, & Levi, 1994). The perception of the number of holes may not be averaged simply, since the topological property is a kind of discretely categorical variable (like gender, etc.), whereas the size and orientation are kinds of continuous variables. Our results indicated that topological differences are another dimension of similarity that can modulate crowding.

Our results provide evidence that crowding was the strongest when the target and the flankers shared the same topological property and were grouped to form a coherent texture. However, the crowding effect was reduced when the target and the flankers were topologically different. Especially when the flankers were the same items but in different configurations, the condition of a topological different outer flanker and a topological equivalent inner flanker showed a better performance than that of a topological equivalent outer flanker and a topological inner different flanker. This is because an outer flanker could impair the recognition more severely. With a topological equivalent outer flanker, the crowding effect was greater than that with a topological different outer one. Our results support the configural grouping account of crowding. Topological similarity grouped the target and the flankers and formed a coherent texture to deteriorate the recognition of the target.

Our experiments were conducted under a lower light condition, which is different from many other crowding studies. Our conclusion should be understood limitedly to condition of a nearly scotopic vision. For high-contrast stimuli, whether this conclusion is the same needs to be further investigated. Further research is needed to measure the pop-out in objective or subjective approaches of the grouping by topological properties. The dynamic and neural mechanism of the topological modulation in the crowding effect needs to be explored.

Keywords: crowding effect, object recognition, topological perception, perceptual grouping

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