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Reduction of The Crowding Effect by Topological Difference Between Target and Flankers*

WU Rui-Jie[1, 2], WANG Bo[1)**], ZHUO Yan[1)]

([1)] *Key Laboratory of Brain and Cognitive Sciences, Institute of Biophysics, Chinese Academy of Sciences, Beijing* 100101, China;
[2)] *University of Chinese Academy of Sciences, Beijing* 100049, China)

Abstract The crowding effect refers to the fact that observers' ability to recognize an object in the periphery deteriorates when the target object is flanked by other items, especially if the target and flankers are similar. Here, a reduction of the crowding effect was caused by a topological difference between target and flankers. In three experiments using a number of different stimulus patterns (*e.g.*, triangles and arrows; digits and letters and geometrical shapes), results showed that the crowding effect was significantly reduced when the target and the flankers were topologically different. Control experiments showed that such a reduction of the crowding effect was not due to differences in subjective similarity, or differences in geometrical features such as area and shape. This finding suggests that topological properties play an important role in perceptual grouping which influences the crowding effect.

Key words crowding effect, topological perception, perceptual grouping, peripheral vision
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The crowding effect, a ubiquitous perceptual phenomenon, refers to observers' deteriorated ability to recognize an object in their visual periphery when the target object is flanked by other items. Previous studies have revealed that the spatial zone of crowding is proportional to eccentricity [1–3], inhomogeneous [4–6], asymmetric [7–10], invariant to the size of the test items [3–4, 11–12], and crowding is quite dissimilar from ordinary masking [3, 13]. Crowding is selective along a number of dimensions, with crowding being stronger and more extensive when the target and flankers are similar in shape and size [14–15], orientation [3, 13, 16–17], spatial frequency [18], depth [14], color [19] and motion [20]. 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. Grouping by similarity is crucially important to crowding. While grouping the flankers into a coherent unit or texture may also relieve crowding in the periphery, when the target and flankers are less likely to be grouped together by making them dissimilar in certain feature property such as color, polarity or depth, to the extent that the target "pops out", crowding is greatly reduced[21].

Perceptual grouping has often been considered following the principles of grouping first described by the Gestalt psychologists [22]. In addition, Chen [23] first demonstrated that the visual system is highly sensitive to topological difference. For example, two visual stimuli differing in topological properties 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 circle and a triangle). The topological property of a figure is the holistic identity that remains constant across various smooth shape-changing transformations of an image [23–24]. This topological transformation can be

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**Corresponding author.
Tel: 86-10-64888565, E-mail: bwang@bcslab.ibp.ac.cn

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imagined as continuous rubber sheet deformations such as bending, twisting, and stretching, without tearing the image apart or gluing parts together. In this type of rubber-sheet distortion, the number of holes remains unchanged and hence is a topological property. Some studies have been guided by the hypothesis of early topological perception [23], which assumes that a primitive function of the visual system is to encode the presence of topological difference in an image. Through decades of research, the early topological perception hypothesis has been explored widely, using a variety of behavioral paradigms, including apparent motion [25-26], illusory conjunctions [27], configural superiority effects [28], global precedence [29], neuropsychological studies of extinction [30-31], and pattern discrimination in insects [32]. In sum, those results have supported the "early topological perception" hypothesis that topological properties take higher priority to be represented and processed and affect ongoing visual information processing [24, 33]. If topological properties do indeed have precedence in visual processing, then it is possible that they might be perceived under the crowding condition, influencing crowding effect when the target and flankers shared local geometrical property but topologically different.

In the present study, we investigated whether target-flanker similarity based on topological properties had an influence on the crowding effect. We tested the extent of the crowding effect induced by two stimulus patterns, and hypothesized that topologically equivalent target and flankers lead to a stronger crowding effect than topological different target and flankers. Indeed, the threshold of target-to-flanker separation declined when the target and flankers were topologically different. The crowding effect was reduced if the target and flankers differed in their numbers of holes.

1 Experiment *1* and *2*

1.1 Methods

1.1.1 Participants. Twenty-two volunteers (10 males) participated the two experiments as paid subjects. All of them reported having normal or corrected-to-normal vision and were unaware of the purpose of the experiments. The experimental procedure was approved by the IRB of the Institute of Biophysics, Chinese Academy of Sciences. All of the subjects gave informed consent before the experiment.

1.1.2 Stimuli. The stimuli were black against a gray background. They were shown on a Dell computer with a 22-inch CRT monitor at a resolution of 1024× 768 pixels, whose frame rate equaled 9.99 ms. MATLAB software (Math Work Inc.) with Psychophysics Toolbox PTB-3[34-35] was used to display the stimuli and record responses. Participants were individually tested in a dimly lit room, viewing the stimuli from a distance of 56 cm. The stimuli subtended a visual angle of 3°× 3°. The luminance of the stimuli was 0 cd/mm^2, and the luminance of the background was 0.48 cd/mm^2.

1.1.3 Procedure. In both of the experiments, the stimuli were displayed at an eccentricity of 20° away from a fixation cross. The target was surrounded by three flankers, two of which were vertically arranged and the other one was horizontally displayed at the right. Observers were required to fixate on the fixation cross throughout the experiment. The trials were initiated by the subjects themselves. According to our previous studies, due to different task difficulty for these two patterns of stimuli, the display duration was different. The stimuli were shown for 60 ms in experiment *1* and 150 ms in experiment *2* (Figure 1). In experiment *1*, the task was to discriminate the orientation of the target. If the target was an arrow, it pointed to the left or the right, while if the target was a triangle, its right angle was on the left or the right. In experiment *2*, the observers were required to identify the digital number (Figure 2). The threshold of target-flanker spacing (center-to-center separation) was measured with an N-up-1-down staircase procedure. The step size is 0.22° (5 pixels), and the measurement starts from 0.4E (approximately 8° of target-flanker spacing) with an descending series. If the participant makes the correct response 3 times in a

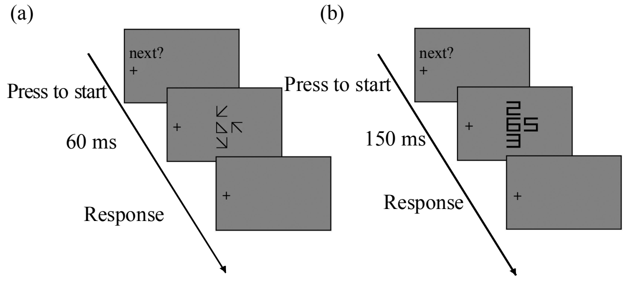

Fig. 1 Schematic depiction of the presentation sequence of one trial

The display duration for the stimuli pattern was different in experiment *1* and *2*. In experiment *1* (a), it was shown for 60 ms; while in experiment *2* (b) it was on for 150 ms.

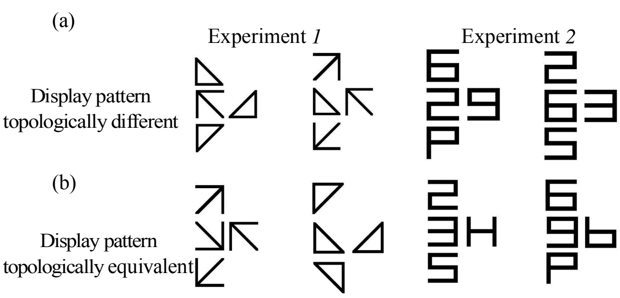

Fig. 2 Illustrations of the examples of display patterns used in the experiment *1* and *2*

It was presented based on topological property, in two conditions, ones with topologically difference (a) and the other ones being topologically equivalence (b).

row, the target-flanker spacing is reduced by the step size. If the participant makes an incorrect response the target-flanker spacing is increased by the step size. A threshold is estimated from the averaged value of all the 18 turning points.

1.2 Results

Experiment *1* measured the extent of crowding effect with two different target-flanker patterns based on the topological difference in closure (or holes). The "triangle-arrow pair" stimuli [24, 36] were used. The triangle was made up of exactly the same three line segments as the arrows, but its closed nature makes it topologically different from the arrows(↖,↗,↙,↘; ◺,◿,◸,◹). It will be defined as a topologically different pattern with a triangle (target) surrounded by arrows (flankers) or an arrow (target) surrounded by triangles (flankers). However, if the target and flankers were from the same category (four triangles or four arrows), it is a topologically equivalent pattern(Figure 2). The threshold of target-flanker spacing was quantified as the proportion of eccentricity. When the target and flankers were topologically different, the threshold was significantly smaller than when they were topologically equivalent (t (8) = −3.75, P < 0.01) (Figure 3). The result suggests that crowding depends strongly on target/flanker's topological similarity. However, it may be argued that the triangles and arrows belong to two different shapes or even sematic categories.

In experiment *2*, we used the widely adopted digits, which shared spatial frequency and had a similar shape, as well as some letters that were similar to them. The target was always a digit. By topological definition, the difference between the figures of 6, 9, b, P and those of 2, 5, 3, H is the number of holes. If the target had one hole and the flankers had none or if the target had no hole and each flanker had one, the context constituted a topologically different pattern. However, if the target and flankers all had a single hole or none, they exhibited a topologically equivalent pattern (Figure 2). The threshold of target-flanker spacing for identifying the digit was measured for both of the two patterns separately. The threshold was significantly reduced when the target and flankers were topologically different (t (12) = −4.86, P < 0.001) (Figure 3). Nevertheless, it remains unclear whether the reduction of crowding was due to the differences in subjective similarity or the topological difference of the stimuli.

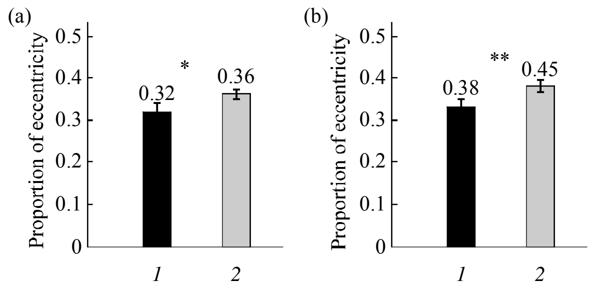

Fig. 3 Results of experiment *1* (a) and experiment *2* (b)

Error bars indicate SEM. *1*: Topologically different; *2*: Topologically equivalent. *P < 0.01, **P < 0.001.

2 Experiment *3*

To disentangle these possibilities, we ran a control experiment to examine the subjective similarity of the two stimulus patterns. The figures used were identical to those in experiment *2*, three of which were aligned vertically at an eccentricity of 20°. On each trial, the stimuli were randomly displayed for 150 ms on either the left or the right of the fixation cross. The subject made a 2AFC (2-alternative-force-choices) task regarding whether the upper figure or the lower figure was similar to the middle one in shape. The display was designed so that one of the figures was topologically different from the middle one, and the other figure was topologically equivalent with the middle one. Each subject was tested for 120 trials in total.

The result revealed that even if the two stimuli were topologically equivalent, they did not cause greater subjective similarity than if they were topologically different (t (11) = 0.595, P > 0.5). Therefore, we were able to rule out the argument that differences in subjective similarity were the greatest contributor to the reduction of crowding effect.

3 Experiment *4*

To further illustrate that the reduction of crowding effect is caused by the topological difference between the target and flankers, we ran experiment *4* to rule out one of the concerns that the difference in area and shape does not lead to a reduction in crowding effect. In this experiment, the S and the ring are topologically different in that the ring has one hole and the S has none. However, they were made to have equal luminous flux, nearly the same spatial frequency components, 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 [24]. Even though the S-ring pair controlled well for various local featural properties, the topological account still may be challenged by one further counterexplanation: This reduction might be caused not by the topological difference in holes per se but by the fact that the shape difference of S-ring is more extensive. Therefore, we used the S-disk pair that differs extensively in shape but is topologically equivalent. The other solid figures were generated similar to the disk, with approximately same area and the other hollow figures were generated similar to the ring, with approximately same area and same outer contour as its counter solid figure. The area difference between the S-like figure and ring is 0, while the area difference between the S-like figure and the disk is 314 mm^2 [24].

The procedure was identical with experiment *2*, except that the figure consisted of a target as well as one flanker on its left and another flanker on its right and they were only displayed for 120 ms (Figure 4a). In our previous experiments, the stimuli were grouped by parallelism due to the display pattern we used. This could increase the task difficulty for the discrimination task. In this experiment, the parallelism grouping was controlled by the extensive difference between the targets and flankers. And we applied a more widely used display pattern to examine the crowding effect, which could eliminate the effect brought by the flankers over and below the target. The target was always an S-like figure, with four different orientations to be discriminated. For a topological equivalent pattern, the flankers were randomly selected from flanker array a, while for a topological different pattern, the flankers were randomly selected from flanker array b(Figure 4b).

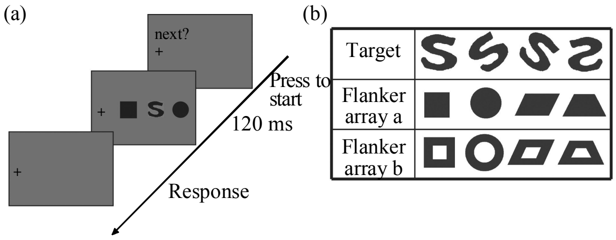

Fig. 4 Schematic depiction of the presentation sequence of one trial (a) and illustrations of the examples of targets and flankers used in the experiment *4* (b)

The display duration for the stimuli pattern was 120 ms. The target was surrounded by two flankers on its left and right.

The results showed that if each of the flankers had a hole, the crowding effect was reduced significantly compared with the condition that both flankers were solid without a hole(t(7) = −3.88, P < 0.01))(Figure 5). In this experiment, for the topological equivalent condition, the target and the flankers differ more greatly in area and shape than those for the topological different condition. This suggests that the difference in geometrical shape and area does not result in the reduction of crowding effect.

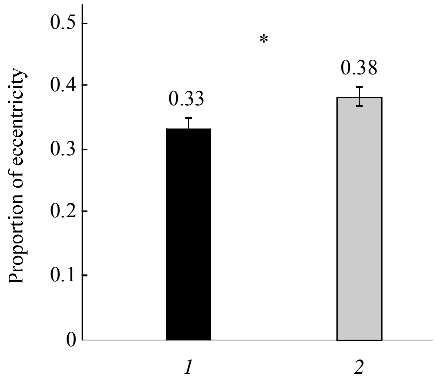

Fig. 5 Result of experiment *4*

Error bars indicate SEM. *1*: Topologically different; *2*: Topologically equivalent.

4 Discussion

Object recognition proceeds through the selection and combination of features, governed by rules of grouping and crowding [37-40]. Crowding impairs the ability to identify an object in a clutter, an effect widely found in discrimination tasks. Our results revealed that the topological difference between the target and flankers could reduce the crowding effect significantly, while they shared the local geometrical similarity.

Previous studies have also shown that crowding is reduced when the flankers group together[7, 41-43]. In our experiments, the flankers themselves always shared the same number of holes; in other words, they were always grouped. The crucial aspect was whether the target was grouped with the flankers. When the target had the same topological property as the flankers and was thus perceptually grouped with them, crowding was strong. When the target had distinct number of holes from the flankers, crowding was reduced. In all the experiments, although the onset of the stimulus was attributed to a kind of topological change, it occurred to both conditions of topological change and local geometrical change. Therefore, the difference in holes was an essential aspect represented topological difference.

Here, the topological equivalence did not influence subjective similarity judgment. The observed reduction of the crowding effect cannot be explained by the differences in subjective similarity. Simple spatial pooling cannot explain our result, either. 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[44], lines or gabors of orthogonal orientation[13, 45], and letters flanked by different shapes[15, 46] or letters of different colors or of opposite contrast polarity[14]. Our results indicate that the extent of crowding can be modulated by the topological difference when size, spatial frequency, and lines of the target and flankers are kept constant. Under the topological perception framework, if the target and the flankers were topologically different, that difference could be perceived prior to the other geometrical properties; therefore, the features could not be pooled together.

Our results support the studies, which revealed that global stimulus configuration modulates crowding[47]. Sayim' s study found when the flanking lines were part of a geometric shape (*i.e.*, a good Gestalt), the crowding was strongly diminished [48]. 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. We propose that if the target and the flankers are topologically different, even though they share same local geometrical properties, they cannot be grouped together, which reduces the crowding effect. Our finding indicates that topological property plays an important role in perceptual grouping which influences the crowding effect.

Moreover, from a recent study, it shows 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[49]. 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, that the target and flankers had distinct number of holes, and the visually similar stimuli had no hole. Our finding systematically defined the difference of the two stimuli patterns by mathematical method, and revealed the consistent reduction of crowding effect.

Further research will be needed to explore the relationship between the mechanism of crowding and that of object formation under the topological perception framework.

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目标和干扰子之间的拓扑性质差异可以削弱拥挤效应*

吴睿洁[1, 2] 王 波[1)**] 卓 彦[1)]

([1)]中国科学院生物物理研究所，脑与认知科学国家重点实验室，北京 100101；[2)]中国科学院大学，北京 100049)

摘要 “拥挤效应”被认为是外周视觉物体辨认过程中的一个重要瓶颈．它是指当目标被干扰子包围，在外周视野呈现时，观察者辨认目标的能力被大大削弱，尤其是当目标和干扰子之间存在某种相似性时．许多研究分别试图在不同层次上提出解释这一现象的机制．本文通过三个实验，使用了不同的视觉刺激图形的辨认任务(例如，三角形和箭头的朝向判断、数字和字母的辨认以及S形图形的朝向辨认)，测量了目标和干扰子之间中心距离的阈值，结果一致地发现，当目标和干扰子之间存在拓扑性质差异(洞的个数差异)时，拥挤效应会显著降低，并且排除了目标和干扰子之间的主观相似性、形状和面积差异等可能的因素．从知觉组织的角度验证了当目标和干扰子之间存在拓扑性质差异时，拥挤效应会显著降低，这是首次发现的一个影响拥挤效应的新的维度．本文结果不仅为拥挤效应的机制提供了一个新的解释，也为大范围首先拓扑知觉在知觉物体形成中的作用提供了支持性证据．

关键词 拥挤效应，拓扑知觉，知觉组织，外周视觉

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** 通讯联系人．

Tel: 010-64888565, E-mail: bwang@bcslab.ibp.ac.cn

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