

# Effect of Shape on the Magnitude of the Delboeuf Illusion

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## Research Article

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# Abstract

Three experiments to discuss the applicability of the contour attraction and the parallel attraction to different shapes in the Delboeuf illusion. The contour attraction suggests that the contours of the test figure and the inducer have an effect of interattraction in the Delboeuf illusion, and the parallel attraction suggests that the attraction between non-intersecting contours was maximal when they were parallel. In Experiment 1, the shape of the test figures and the inducers changed simultaneously and formed parallel lines. In Experiment 2, the test figures remained circles while the inducers changed shape. Experiment 3 was identical to Experiment 2 except that the areas of the inducers remained equal. The results demonstrated that the illusion is influenced by shape. Importantly, the effect of shape on the magnitude of the Delboeuf illusion is based on the contour attraction and the parallel attraction. Configurations with circles or shapes more similar to a circle were related more to the contour attraction, whereas shapes that were dissimilar to a circle were related more to the parallel attraction. We suggest that the contour attraction may be a circular modality of the parallel attraction.

## Introduction

Shape can be considered an important factor in visual perception (Livingstone & Hubel, 1987, 1988), perception and representation of object shape through vision are basic to thought, action, and learning (Baker & Kellman, 2018). This suggests that research on visual illusions cannot ignore the role of shape. The Delboeuf illusion is a visual phenomenon was first described by the Belgian philosopher Franz Joseph Delboeuf. In this illusion, when two circles (test figures) of equal radius are presented next to each other and surrounded by concentric circles (inducers) of different radii, the test figure surrounded by a slightly larger inducer is overestimated or underestimated (Murray, 2012; O'Halloran & Weintraub, 1977; Weintraub & Cooper, 1972; Weintraub & Schneck, 1986). The left and right test figures are also called the target and probe, respectively (see Figure 1A). If the target's inducer is much larger than the target, the target's size will be underestimated (i.e., size contrast); in contrast, if the target's inducer is only slightly larger than the target, the target's size will be overestimated (Mruczek, Blair, Strother, & Caplovitz, 2017). In the present study, we explored only the overestimate of the illusion. The Delboeuf illusion has been extensively studied among humans (Shoshina & Shelepin, 2014), and studies have shown that viewers' size perception is strongly influenced by the luminance (Daneyko, Zavagno, & Stucchi, 2014) and color (McClain et al., 2014) of the background and stimulus. The Delboeuf illusion has been shown to influence food selection behavior in animals such as chimpanzees (*Pan troglodytes*), monkeys, domestic dogs, bantams, and fish (guppies [*Poecilia reticulata*]); food intake in humans (Byosiére et al., 2017; Lucon-Xiccato, Santacà, Petrazzini, Agrillo, & Dadda, 2019; Nakamura, Watanabe, & Fujita, 2014; Parrish & Beran, 2014; Parrish, Brosnan, & Beran, 2015); and is also found in insects (Howard, Avarguès-Weber, Garcia, Stuart-Fox, & Dyer, 2017). Both animals and humans are susceptible to geometrical illusions. Animal research may shed light onto the evolutionary and environmental influences of perception (Byosiére et al., 2017); however, human research on attribute perceptions of illusion, such as shape is essential to clarify the mechanism and factors that have not yet been explored.

Previous research has largely ignored the role of shape in the Delboeuf illusion. The shape of the test figures or inducers might have a strong effect on the illusion (Roberts, Harris, & Yates, 2005; Rose & Bressan, 2002; Surkys, Bertulis, & Bulatov, 2006). Among the few researchers who have examined this topic, Weintraub & Schneck (1986) created new models by changing the shape of the inducers from a circle to a discontinuous circle, a discontinuous line (four-fragment concentric cases), a square, or several forms around the circle and then compared them with the Delboeuf illusion models of different sizes. They found that the magnitude of the illusion differed while the inducer is a circle or square. In Surkys et al.'s (2006) study, the test circle and the inducers had the same shape, changed simultaneously; the results showed that the strength of the illusion differed between squares and circles, indicating that shape might influence the illusion's magnitude. Weintraub and Schneck (1986) and Surkys et al. (2006) suggested that their findings could be explained by the theory of contour attraction, which proposes that the proximal contours of the test figure and the inducer have a perceptual effect of interattraction, which would lead to overestimating the size of the test figure, whereas the interattraction diminishes as the distance between the test and inducer increases, thus, distal contours perceptually repel after a certain distance. That is, the magnitude of the Delboeuf illusion is affected by the distance between the test and inducer; the greater the distance the greater the magnitude, but the less attraction within a certain distance (Kawahara, Nabeta, & Hamada, 2007; Nakamura et al., 2014; Surkys et al., 2006; Weintraub & Cooper, 1972; Weintraub & Schneck, 1986). This theory fits well with the characteristics of lateral inhibition of neurons in early visual pathways and the known properties of activation as measured with fMRI (Schwarzkopf, Song, & Rees, 2011).

Rose and Bressan (2002) researched the Ebbinghaus illusion (see Fig 1B), which is closely related to the Delboeuf illusion (Girgus, Coren, & Agdern, 1972; Mruczek et al., 2017; Picon, Dramkin, & Odic, 2019; Roberts et al., 2005), by same-shape illusions (i.e., with an identically shaped test and inducer) and different-shape illusions (i.e., the test figure was a circle and the inducers were circles, hexagons, triangles, or angular shapes). The results showed that inducer shape had a significant effect; same-shape illusions were significantly larger than different-shape illusions with circles or triangles as the test stimuli. The effect of the distance between the test figure and the inducer in the Ebbinghaus illusion showed many commonalities with the Delboeuf illusion, in other words, the distance between the test figure and the inducer was affected in both the Ebbinghaus and Delboeuf illusions. Roberts et al. (2005) attempted to simplify the complexity of influence factors in the Ebbinghaus illusion and found the completeness of the inducer ring was a primary factor; furthermore, smaller inducers constructed more complete annuli and consistently increased the magnitude of the illusion.

The studies by Weintraub and Schneck (1986) and Surkys et al. (2006) showed that the Delboeuf illusion occurs even when the test and inducer are not circles. Rose and Bressan (2002) showed that the shape of the inducer played a vital role, and Roberts et al. (2005) suggested that the completeness of the inducer had a major effect. Based on the contour attraction theory, completeness in the Delboeuf illusion refers to the inducer's subjective similarity (Li, Liang, Lee, & Barense, 2019) to a circle: the more subjectively similar it is to a circle, the more complete. In other words, a regular octagon is more complete than a regular hexagon, a regular hexagon is more complete than a square, and a circle is the most complete, different

shapes lead to different completeness. Actually, the completeness is due to the shape of the inducer in Delboeuf illusion.

However, Roberts et al. (2005) proposed that the similarity of test figures and inducers is not a major factor in explaining the Ebbinghaus illusion, but the effect of parallel attraction. Pollack (1964) found that attraction between non-intersecting contours was maximal when they were parallel and gradually decreased as the angle of the projected intersection of boundaries increased (Rose & Bressan, 2002). As the regular polygons become subjectively similar to a circle, the sides of the test and the inducer would or close to be parallel in the Delboeuf illusion configuration, we can even think of the concentric circles of the Delboeuf illusion as special parallel lines. Therefore, the parallel attraction would be an effect in the Delboeuf illusion with polygons. But how will the contour attraction or the parallel attraction impact the magnitude when configurations of Delboeuf illusion with circles or regular polygons?

Surkys et al. (2006) showed that the magnitude of the illusion differed by the shape of the test figure (circle or square) as well as when the inducers changed simultaneously into a circle or square. However, they did not explore whether other shapes influence illusion magnitude or whether the illusion is maintained when the inducers change shape and the test figure remains a circle, and have not taken into account the parallel attraction in the square. Weintraub and Schneck (1986) adopted configurations that combined four squares or other shapes around test circles; these configurations were closer to the Ebbinghaus illusion than the Delboeuf illusion (Foster & Franz, 2014; Hamburger, Hansen, & Gegenfurtner, 2007). Because of the use of fragmented and complex combinations, Weintraub and Schneck's (1986) study should have made some improvements.

Furthermore, in Surkys et al.'s (2006) study, the minute of the arc of the inducers changed at discrete intervals, which caused the data to become discontinuous; this was similar to Weintraub and Schneck's study (1986) but with different step sizes. In most previous studies, although different procedures were used, their methods had the same problem. In particular, while they all changed the size of the inducer in steps, the step size differed across studies. Additionally, in Weintraub and Schneck's (1986) study, participants had to use multiple fixed-size graphics for comparison with the reference target stimulus and select the graphic they perceived to be the closest in size to the reference target stimulus. This could have resulted in inaccuracies when judging the magnitude of the illusion. However, neither study has examined how the magnitude of the Delboeuf illusion changes when the inducers are gradually modified to resemble a circle, nor research has considered the relation of the contour attraction and the parallel attraction in the Delboeuf illusion, though these are essential questions to explore the mechanisms of this illusion.

To fill the above gaps in the existing research, we adopted a quasi-Delboeuf configuration, in which regular polygons replace the test circles or inducers of the classical Delboeuf illusion configuration. The regular polygons were graphics incircled within the test or inducing circles (more details see Appendix). The inner polygon was also called the test figure and the outer one the inducer. The radius of the polygon

was measured as its circumcircle, to ensure the distance between the test polygon and the inducer polygon be closed to the distance between circles.

Based on previous findings, we selected the following shapes as independent variables: circle, regular octagon, regular hexagon, square, and equilateral triangle. These shapes are perceived as distinct figures, however, they are equivalent in the present quasi-Delboeuf illusion configurations from the viewpoint of topology (Chen, 1982) and suitable to the subjective similarity of the configurations constructed by themselves (Li, Liang, Lee, & Barense, 2019). This series of shapes create the condition which can examine the contour attraction and the parallel attraction by the shape in the Delboeuf illusion.

In our study, participants compared the target stimulus and adjusted the size of the probe stimulus arbitrarily until they perceived them as equal. The difference value between the radii of the probe stimulus and target stimulus determined the magnitude of the illusion. We created two shape-changing situations in experiments 1 and 2. In Experiment 1, the shape of the test figure and the inducers changed simultaneously, and parallel straight lines were formed from regular polygons in illusion configurations, the results would demonstrate the effect of shape and the parallel lines on the quasi-Delboeuf illusion. In Experiment 2, the inducer shape changed from circle to equilateral triangle while the test figure remained a circle and there were no parallel straight lines in illusion configurations. Both Experiment 1 and 2 would demonstrate the effect of shape. Comparing Experiments 1 and 2 would demonstrate the effect of parallel lines in the Delboeuf illusion and the effect of the inducer's shape. In Experiments 1 and 2, the test figures and inducers of the quasi-Delboeuf illusion were polygons, and their radii were equal to those of the circles resulted in that their areas and the distance between the test figure and the inducer decreased from the circle to the equilateral triangle. The area is a vital impact in size estimation and germane to distance directly, it is impossible to maintain the distance between the test figure and the inducer equal in varied shapes, yet maintain the areas of shapes equal is feasible. In Experiment 3, the inducer shapes changed while their areas remained equal caused that the distances between the test and the inducer increased as the shape progressed from an octagon to an equilateral triangle and were all larger than those in Experiment 2, comparing Experiments 2 and 3 would demonstrate which the inducer shape or the distance between the test figures and inducers affect more on the illusion, the distance is a vital factor of the contour attraction. Therefore, the first hypothesis: the illusion magnitudes significantly differed by shape, all three experiments would demonstrate this hypothesis; the second hypothesis: the illusion magnitudes of polygons in Experiment 1 are significantly larger than the identical shape in Experiment 2, the shapes of polygons more subjective similar to a circle the less difference quantity; the third hypothesis: the illusion magnitudes of polygons in Experiment 3 are significantly larger than these in Experiment 2, the shapes of polygons more subjective similar to a circle the less difference quantity.

In present study, we explored whether the parallel attraction or the contour attraction holds for inducers of varying shapes using polygons and how the shape of the test figures and inducers of a Delboeuf illusion configuration influence the illusion magnitude. Accordingly, we would explore the relationship between the contour attraction and the parallel attraction in the Delboeuf illusion, and the effect of shape on the magnitude of the Delboeuf illusion.

# Methods

## Experiment 1

This experiment, using quasi-Delboeuf configurations, explored whether illusion magnitude differs by shape. We expected that the magnitude of illusion in different shape configurations would have significant differences.

## Participants

Participants were 64 undergraduates (32 female; mean age = 20.31 years,  $SD = 0.96$  years), who had normal or corrected-to-normal vision. All were right-handed and were unfamiliar with or unaware of the Delboeuf illusion. All provided informed consent and were given a gift (equivalent to about \$4) for their participation. The study design conformed to relevant ethical statements and was approved by the academic council of the School of Educational Science and Management, which has been approved by the ethical committee of Yunnan Normal University, and we confirm that the present experiment was performed following relevant guidelines and regulations.

## Materials and procedure

We adopted a repeated-measures, single-factor, within-subject design. The independent variable was the shape of the configuration: circle, regular octagon, regular hexagon, regular quadrilateral (square), and equilateral triangle. Participants completed a total of 25 trials, with five trials per shape. In each trial, participants were allowed to make multiple minor adjustments (i.e., each trial contained many micro-trials). The order of trials was counterbalanced using a Latin square design. The target stimulus, probe, and inducers shared the same shape in each trial, which could be one of the following: circle, regular octagon, regular hexagon, square, and equilateral triangle (see Figure 3A).

Stimuli were displayed on a 19-inch LCD monitor with a resolution of  $1440 \times 900$  pixels. Black configurations were displayed and operated using Geometer's Sketchpad 5.03 against a white background. The line weight was 0.5 points. Participants were seated about 60 cm from the computer individually in a quiet room. We asked them to adjust the size of the probe stimulus to explore the magnitude of the illusion caused by the inducer of different shapes.

At the beginning of each trial, a target stimulus was presented on the left side of the screen, surrounded by a circle or another regular polygon. On the right side was a large circle or another large regular polygon without the test figure (i.e., the probe stimulus). Participants created a new probe stimulus within the right circle or polygon and adjusted it until they perceived that its size was equal to that of the target stimulus. There was no time limit.

We termed the radius of the target stimulus " $r$ " and that of the new probe stimulus as " $R$ " (measured in pix). Thus, the magnitude of the illusion was  $R - r$ . To prevent participants from completing the task by aligning the lines of the configurations instead of adjusting the size, the positions of the target and

created probe stimuli differed by 5-10 pixels. The experimental procedure was tested in a pilot experiment. Throughout the main experiment, participants were asked to pay attention to the target stimulus and adjust the size of the new probe stimulus based on their initial impressions without deeper consideration of the task. Figure 2 shows the procedure of one trial in each experiment.

## Results

The average values of the magnitude of the illusion for each shape were calculated and analyzed by PASW Statistics 18. The data showed that the magnitude of the illusion clearly differed by shape (see Figure 3B).

The significance threshold applied to our data was  $p < .05$ . A repeated-measures analysis of variance (ANOVA) showed that illusion magnitude significantly differed by the shape,  $F(4, 252) = 2.880$ ,  $p = .023$ ,  $\eta_p^2 = 0.044$ .

The magnitude of the illusion was highest for the equilateral triangle. Post-hoc LSD tests showed significant differences between the circle and the regular octagon ( $p = .049$ ) and equilateral triangle ( $p = .011$ ), and between the square and the regular octagon ( $p = .035$ ) and equilateral triangle ( $p = .023$ ). Mean accuracy for the circle was 6.68, 95% confidence interval (CI) [5.42, 7.93], for the regular octagon was 7.85, 95% CI [6.37, 9.33], for the square was 6.77, 95% CI [5.50, 8.04], for the equilateral triangle was 8.08, 95% CI [6.56, 9.61]. Shape had an impact on magnitude for the regular octagon, square, and equilateral triangle in this experiment.

However, the results did not reveal more influence factors. There were requisite elements of the contour attraction or the parallel attraction in the configurations of Experiment 1, but it was impossible to distinguish the effects. To further understand the impact of the contour attraction, we examined whether illusion magnitude was affected by the contour attraction when the parallel lines absent in polygons.

## Experiment 2

The contour attraction theory suggests that the magnitude of the Delboeuf illusion increases with the pattern's similarity to a circle. However, in Experiment 1, the magnitudes were affected by the parallel lines when the shapes of the test figure and the inducers changed simultaneously, and the results did not match this assumption. Thus, we attempted to determine how the magnitude would change if the parallel lines were absented in Delboeuf illusion configurations, as in Weintraub and Schneck's (1986) study, the shape of the inducers changed while the test figure remained a circle.

## Participants and procedure

Participants were the same as in Experiment 1. The method and procedure were identical to those of Experiment 1, except that the test figure was consistently a circle; only the shape of the inducers changed (see Figure 3A). The study design conformed to relevant ethical statements and was approved by the

academic council of the School of Educational Science and Management, which has been approved by the ethical committee of Yunnan Normal University, and we confirm that the present experiment was performed following relevant guidelines and regulations.

## Results

The average values of the magnitude of the illusion for each shape were calculated and used in the analyses (see Figure 3B). The magnitude of the illusion differed by shape from circle to equilateral triangle (except for the regular octagon), and fewer the sides, the lower was the magnitude of the illusion.

A repeated-measures ANOVA showed that illusion magnitude significantly differed by shape,  $F(4, 256) = 22.998, p < .001, \eta_p^2 = 0.267$ . Post-hoc LSD tests showed significant differences between any two shapes ( $ps < .01$ ), except between the circle and regular octagon and between the square and equilateral triangle. Mean accuracy for the circle was 8.43, 95% confidence interval (CI) [7.02, 9.85], for the regular octagon was 8.68, 95% CI [7.18, 10.18], for the regular hexagon was 7.33, 95% CI [6.06, 8.60], for the square was 4.87, 95% CI [3.58, 6.17], for the equilateral triangle was 4.44, 95% CI [2.94, 5.93].

## Comparison of the Results of Experiments 1 and 2

Comparing the results of Experiments 1 and 2 would indicate the influence in the magnitude of the Delboeuf illusion by parallel lines and the shape. The results showed that illusion magnitude was influenced by shape both when the shapes of the test figures and inducers changed simultaneously (Experiment 1) and when only the shape of the inducers changed (while the test figure remained a circle; Experiment 2). This shows that the magnitude of the quasi-Delboeuf illusion differed by shape. The change in illusion magnitude was markedly clearer in Experiment 2 than in Experiment 1. In Experiments 1 and 2, the magnitude was the highest for the equilateral triangle and regular octagon, respectively. In the latter experiment, the magnitude declined from the regular octagon to the square. A comparison of the magnitude between Experiments 1 and 2 is shown in Figure 3B.

A repeated-measures ANOVA comparing the results of Experiments 1 and 2 confirmed that inducer shape significantly influenced illusion magnitude,  $F(4, 488) = 10.694, p < .001, \eta_p^2 = 0.081$ . Furthermore, there was non-significant effect between the two experiments,  $F(1, 126) = 0.442, p = .507$ . The interaction between shape and test figure was significant,  $F(4, 504) = 12.692, p < .001, \eta_p^2 = 0.092$ . In Experiments 1 and 2, the magnitudes of the equilateral triangle,  $t(126) = 3.412, p < 0.001$ , and the square,  $t(126) = 2.091, p = 0.039$ , were significantly different. Mean accuracy for the equilateral triangle was 8.08, 95% confidence interval (CI) [6.56, 9.61] in Experiment 1, and 4.44, 95% CI [2.94, 5.93] in Experiment 2; for the square was 6.77, 95% CI [5.50, 8.04] in Experiment 1, and 4.87, 95% CI [3.58, 6.17] in Experiment 2. The subjective similarity of both shapes is further from the circle than others, and that of the other polygons and the circle display non-significant differences. These results indicated that the magnitude of the Delboeuf illusion was influenced significantly by both parallel lines and the shape. Importantly, the

effects on illusion were different in shapes. The attraction of parallel lines was significantly larger than the contour attraction in the square and the equilateral triangle.

In Experiments 1 and 2, the test figures and inducers of the quasi-Delboeuf illusion were polygons, and their radii were equal to those of the circles. Consequently, their distance between the test figures and the inducers decrease from the circle to the equilateral triangle. This leads us to the question: the distance between the test figures and the inducers or the shape of configurations, which one would have a greater impact on the magnitude of Delboeuf illusion? But it is impossible to maintain the distance between the test figure and the inducer equal in varied shapes, yet maintain the areas of shapes equal is feasible, and the area is germane to distance directly.

### **Experiment 3**

#### **Participants and procedure**

The participants were the same as in Experiments 1 and 2. The method, procedure, and materials were identical to those in Experiment 2, except that the areas of all the inducers were equal (in contrast to the areas of the inducers in Experiment 2, which decreased as the shapes progressed from circles to triangles). Thus, the radii of the inducers' circumcircles increased as the inducers progressed from an octagon to an equilateral triangle, and they were all larger than that of the circle (see Figure 4A). The study design conformed to relevant ethical statements and was approved by the academic council of the School of Educational Science and Management, which has been approved by the ethical committee of Yunnan Normal University, and we confirm that the present experiment was performed following relevant guidelines and regulations.

#### **Results**

Average values for the illusion magnitude of each shape were calculated and used in the analyses. The magnitudes followed the same tendency as in Experiment 2 but with higher absolute values in the square and the equilateral triangle (see Figure 4B).

A repeated-measures ANOVA showed that illusion magnitude significantly differed by shape,  $F(4, 252) = 3.336$ ,  $p = .011$ ,  $\eta_p^2 = 0.05$ . Post-hoc LSD tests revealed that the magnitude significantly differed between the regular octagon and the circle ( $p = .047$ ) and square ( $p < .001$ ), and between the regular hexagon and square ( $p = .040$ ). Pairwise comparisons for the other shapes revealed no significant differences. Mean accuracy for the circle was 6.98, 95% confidence interval (CI) [5.52, 8.45], for the regular octagon was 7.71, 95% CI [6.28, 9.14], for the regular hexagon was 7.06, 95% CI [5.51, 8.62], for the square was 5.93, 95% CI [4.49, 7.37].

#### **Comparison of the Results of Experiments 2 and 3**

Comparing the results of Experiments 2 and 3 would indicate whether the shape of the illusion configurations or the distance between the test figure and the inducer had a greater effect on the illusion,

the effect of distance rooted in the contour attraction. The areas of all the inducers were equal in Experiment 3, thus, the inducer radius increased from the circle to the equilateral triangle, and the distances between the test figure and the inducer also increased. The results of Experiments 2 and 3 showed that the magnitude of the quasi-Delboeuf illusion changed across the shape of configurations. In other words, illusion magnitude changed with the shape when the test figure remained a circle and the inducers changed shape (Experiment 2) as well as when the inducers changed shape but their areas remained constant (Experiment 3). A comparison of Experiments 2 and 3 is shown in Figure 4B.

A repeated-measures ANOVA confirmed that the main effect of shape was significant for illusion magnitude,  $F(4, 504) = 20.874, p < .001, \eta_p^2 = 0.142$ . There was non-significant effect between the two experiments,  $F(1, 126) = 0.037, p = .848$ . The interaction effect of shape and area of the inducers was significant,  $F(4, 504) = 8.723, p < .001, \eta_p^2 = 0.065$ . An independent-samples test between the polygons in Experiments 2 and 3 showed that the magnitude of the equilateral triangle in Experiments 2 and 3 was significantly different,  $t(126) = 2.402, p = .018$ ; the other polygons and circle showed non-significant differences. Mean accuracy for the equilateral triangle was 4.44, 95% confidence interval (CI) [2.94, 5.93] in Experiment 2, and 6.92, 95% CI [5.49, 8.35] in Experiment 3. These results show that the magnitude of the quasi-Delboeuf illusion was significantly influenced by the shape and the interaction effect of the distance between the test figure and the inducer.

## Discussion

We investigated the effect of shape on the magnitude of the Delboeuf illusion and probed into the contour attraction and the parallel attraction. Our study extends previous research using three conditions: (1) the test figures and the inducers were identical shapes and parallel lines were formed, (2) the inducers' shape changed and the test figures remained circles, and (3) the inducers' shape changed but their area remains constant. All the three conditions would indicate the effect of shape and demonstrate the relationship between the contour attraction and the parallel attraction in the Delboeuf illusion.

In our experiments, we used five types of polygons with varying levels of resemblance to a circle: the regular octagon, regular hexagon, square, equilateral triangle, and circle; previous studies explored the magnitude of the quasi-Delboeuf illusion using only two shapes (circle and square). Participants were asked to create a probe stimulus using their own judgment rather than select forms from a predetermined list. This ensures that the measured magnitude of the illusion is more accurate because it corresponds with the participants' subjective perception rather than a predetermined selection. This allowed us to successfully address the problem of discontinuous presentation of data in previous experiments (e.g., Surkys et al., 2006), and thus, ensure that the measured magnitude of the illusion reflected participants' continuous subjective perception.

Additionally, our experiments introduced the concept of the quasi-Delboeuf illusion configuration, thereby enabling the standardization of the classification of configurations for this illusion. The manner in which we used the radii of the configurations to measure illusion magnitude is consistent with that described in

past research on size illusions (O'Halloran & Weintraub, 1977; Weintraub & Cooper, 1972; Weintraub & Schneck, 1986). In our experiments, the ratios of the radii of the test figures and the inducers were between 2:3 and 2:5, which is known to be the range of overestimate for the quasi-Delboeuf illusion. Thus, we could ensure that overestimate rather than contrast occurred in our experiments.

### **Impact of the Inducer Shape on Illusion Magnitude**

When the shape of the test figures and the inducers were changed simultaneously (Experiment 1) and when only the inducers were changed (Experiment 2), the magnitude of the illusion differed across shapes: the shape of the test figures and the inducers had a significant effect on illusion magnitude, and the inducer shape had a more obvious impact on illusion magnitude. This impact offset the distance between the test figure and the inducer, as evidenced by the results of Experiments 1 and 2. As shown in Experiment 3, shape continued to exert an influence on illusion magnitude even when the test figures and inducers were equal in area. Thus, we demonstrated that the magnitude of the quasi-Delboeuf illusion is greatly influenced by the shape of the inducers.

### **Contour Attraction**

One explanation for why changes in inducer shape led to differences in illusion magnitude comes from the contour attraction theory, which suggests that the proximal contours of the test and inducer have a perceptual effect of interattraction. In our experiments, completeness refers to the inducer shape's subjective similarity to a circle. The circle is the most complete shape, followed by the regular octagon, regular hexagon, square, and equilateral triangle. According to the contour attraction theory, the more complete a shape the more the proximal contours, and therefore, the greater the attraction. Thus, the circle should have had the lowest assessment accuracy and greatest overestimation of target stimulus size. In our results, as the shape progressed to the regular hexagon, square, and equilateral triangle, the assessment gradually became more accurate (i.e., as the illusion magnitude decreased), this explanation applies well to the data from Experiments 2 and 3 (except the circle in Experiment 2 and the circle and equilateral triangle in Experiment 3).

Of course, no shape is closer to a circle than a circle itself; however, importantly, the configuration with circles did not have the greatest magnitude in our results. This is inconsistent with the contour attraction theory, wherein if the test figure and the inducers are circles, the illusion magnitude should be maximal. However, in all of our experiments, the magnitudes of circles were not significantly higher than those of regular octagons. This suggests that the contour attraction theory alone cannot adequately explain how shape influences the magnitude of the quasi-Delboeuf illusion.

For the circles, one explanation may be familiarity. In daily life, individuals tend to be more exposed to circles than to regular hexagons or octagons, and it has been demonstrated that attentional resources are reduced when performing familiar tasks; this helps in allocating more attention to other tasks (Huang, Guo, & Nie, 2003). In the present experiments, the participants were familiar with the circle, and thus, may have paid more attention to evaluating illusion magnitude (Shulman, 1992). The other explanation may

be that neurons sensitive to curvature importantly for processing visual form (Salmela, Henriksson & Vanni, 2016; Schmidtman & Freund, 2019). Consequently, the size of the test figure would more accurately reflect the target, and hence, the magnitude of the quasi-Delboeuf illusion would be smaller for circles than for regular octagons or regular hexagons.

The contour attraction theory also suggests that the distance between the inducers and test figure is a significant factor; within a certain distance, illusion magnitude increases as the distance increases, whereas as the distance between the test and inducer increases, the interattraction of the test figure and the inducer diminishes until disappears. In Experiment 2, when the test figure consistently remained a circle, distances gradually decreased as the inducers changed from a regular octagon to an equilateral triangle. Meanwhile, as the distances reduced, the illusion magnitudes decreased. This result validates the contour attraction theory, except for the circle. For the equilateral triangle in Experiment 3, the contours of the inducers were larger than those in Experiment 2 (see Figure 4A.), leading to greater distances between the tests and the inducers, the greater the distance, the greater the magnitude, and thus resulting in a greater illusion magnitude.

### **Parallel Attraction**

It is possible the contour attraction theory unsuitable for all polygons. In Experiment 1, the lines (sides) of polygonal test figures and inducers constituted parallel lines. The magnitude of the equilateral triangle was significantly greater than that of the square and circle, and the square than the regular octagon; this is because of the parallel attraction. There were three pairs of parallel lines (sides) in the equilateral triangle and four in the square. The pairs of parallel lines in the equilateral triangle are the longest for the four polygon shapes, followed by the square (see Figure 3A); the strongest parallel attraction was therefore for the equilateral triangle and then followed by the square. Moreover, their illusion magnitude was stronger than that in Experiment 2, where the test figures were circles and the inducers were an equilateral triangle and a square, the estimation of illusion magnitude is depended on the effect of the contour attraction; however, both of these polygon types are quite different from the circle, and so the effect of the contour attraction is weaker than the parallel attraction for the equilateral triangle and square in Experiment 1. In other words, the effect of the contour attraction transforms into the parallel attraction as shapes change from the circle to the equilateral triangle and square, or a shape similar to a circle changes to the square and equilateral triangle—both shapes that are dissimilar to the circle and with parallel lines.

Moreover, there were six pairs of parallel contours (sides) in the regular hexagon, eight in the regular octagon, and an infinite number of infinitesimal side segments in the circle. As the shapes begins to resemble a circle, the regular hexagon, regular octagon, and circle have non-significant different attraction between Experiment 1 and 2—i.e. that the contour attraction and the parallel attraction differ non-significantly. The classical Delboeuf illusion, in which ‘adjacent’ contours can be said to run in parallel (Rose & Bressan, 2002), and the magnitude of the quasi-Delboeuf illusion was influenced by the two types of attraction. It is possible that the contour attraction is a circular modality of the parallel attraction.

## Contour Attraction, Parallel Attraction or Shape?

In Experiment 3, the areas of the regular octagon, regular hexagon, square, and equilateral triangle were equal to the circle's and larger than the corresponding shape areas in Experiment 2. The distances between the inducer and test figure were also greater in Experiment 3 than in Experiment 2. As per the contour attraction theory, the attraction would cause the illusion magnitude of the configurations increase when the distance between the test figure and the inducer increased. Regarding the array of shape types, the illusion magnitude of only the equilateral triangle was significantly greater in Experiment 3 compared to Experiment 2; however, the illusion changing trend of other shapes conforms to the contour attraction. Therefore, the effect of shape type existed both in Experiments 2 and 3, and the effect is based on the contour attraction.

Despite affecting the magnitude of the quasi-Delboeuf illusion, both the contour attraction and the parallel attraction alone do not offer a comprehensive explanation that includes all shapes. Because all of the above variables of illusion magnitude were based on changing the shape of the inducer or test figure, we propose that the effect of inducer shape on the magnitude of the quasi-Delboeuf illusion is based on the contour attraction and the parallel attraction. Thus, the shape of the inducers exerts a decisive impact on the magnitude of the illusion.

## Limitations

In Experiment 1, the illusion magnitude of the regular octagon is larger than the circle, a finding that contradicts the contour attraction theory or the parallel attraction theory. This might be related to differences in the representation of various orientations in the human visual cortex. Research has shown that humans evaluate horizontal or vertical lines (cardinal orientations,  $90^\circ$  and  $180^\circ$ ) more accurately compared to oblique lines ( $45^\circ$  and  $135^\circ$ ), which might be explained by the uneven representation of such orientations in the visual cortex. In our experiments, when the inducers were regular octagon, regular hexagon and equilateral triangle, some of their lines were tilted (not horizontal or vertical) inevitable, and thus, the visual cortex was less activated; as such, the illusion magnitude would be affected in a certain (Deng, Liu, & Zhou, 2013; Fermüller & Malm, 2004; Furmanski & Engel, 2000; Mannion, McDonald, & Clifford, 2010; Schwarzkopf & Rees, 2013; Sugihara, 2014). Although this is a reasonable explanation for the phenomena we observed, the present design does not allow us to avoid it; thus, the topic should be investigated in future research.

In addition, the Delboeuf illusion can influence consumer judgments with respect to the size of goods (Bauer, 2015; Block et al., 2013; Libotte, Siegrist, & Bucher, 2014). These findings might have practical implications, as shape is known to influence consumer behavior, such as by confusing consumers' judgments about the size of goods. However, we did not present real objects and used simple configurations, which might be considered a limitation. This topic should be addressed in future research on the Delboeuf illusion.

Furthermore, we collected data using resolution-defined (px) stimulus sizes instead of visual angle (deg), which measures the magnitude of illusion accurately but has low repeatability among different types of monitors—a matter we will improve in future research.

## **Conclusion**

The present study examined the Delboeuf illusion and obtained several important findings when using polygons as stimuli. First, the illusion is influenced by shape. Second, the effect of shape on illusion magnitude is based on both the contour attraction and the parallel attraction. Third, configurations with circles or shapes more subjectively similar to a circle were related more to the contour attraction, whereas configurations with shapes that were dissimilar to a circle were related more to the parallel attraction. The results indicate that the contour attraction could be a circular modality of the parallel attraction.

## **Declarations**

### **Compliance with Ethical Standards**

Ethical approval: The study design conformed to relevant ethical statements and was approved by the academic council of the School of Educational Science and Management, which has been approved by the ethical committee of Yunnan Normal University. We confirmed that all experiments of the present study were performed following relevant guidelines and regulations.

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### **Author Contributions**

Shujie Li and Xiaolin Zhang contributed conception and design of the study and organized the database. Keli Yin performed the statistical analysis and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version. The views expressed in the paper represent the views of the individual authors and do not represent an official position of the Organization and Development.

### **Informed consent**

Informed consent was obtained from all individual participants included in the study.

### **Competing interests**

The authors declare no competing interests.

### **Data availability**

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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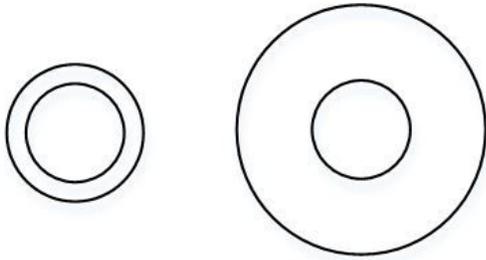
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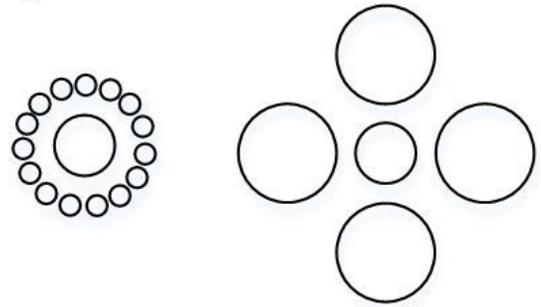
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## Figures

**A** Delboeuf illusion

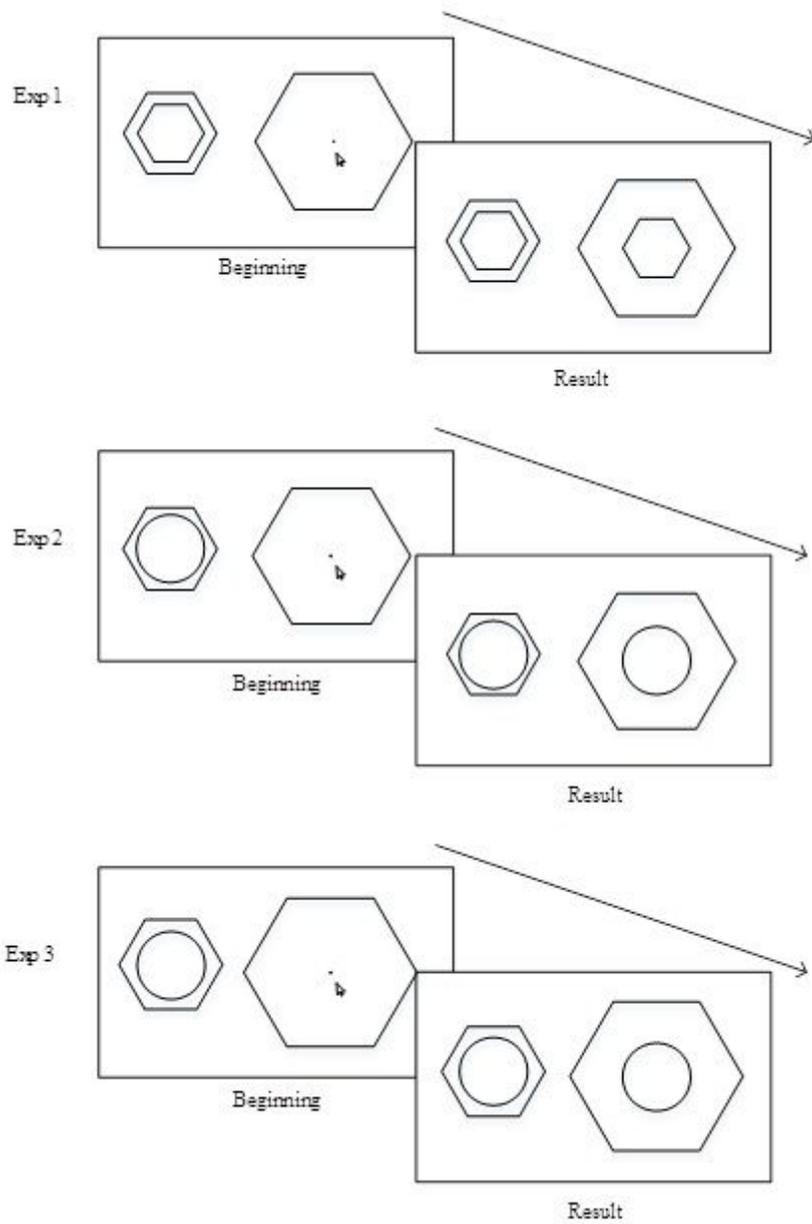


**B** Ebbinghaus illusion



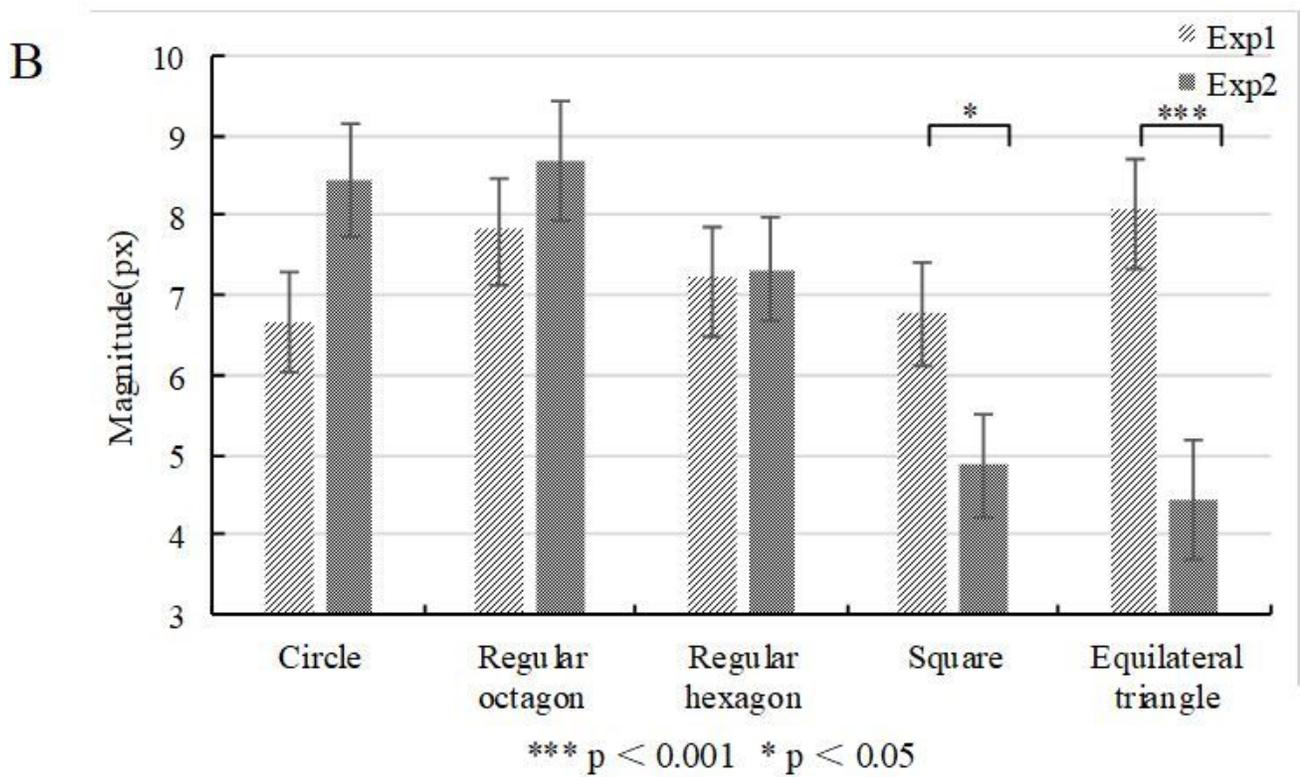
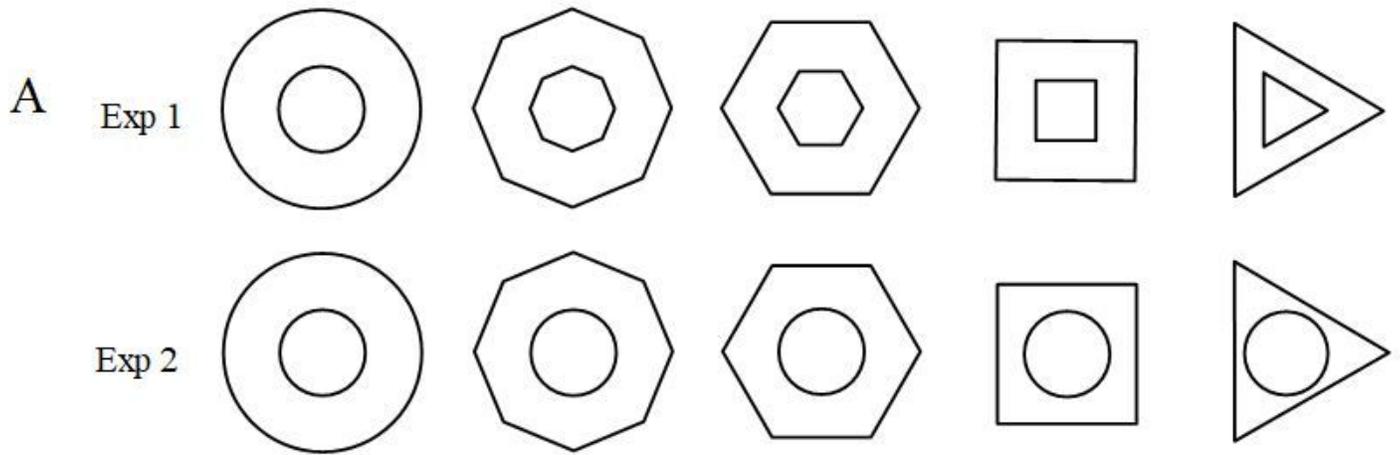
**Figure 1**

(A) Delboeuf illusion. (B) Ebbinghaus illusion.



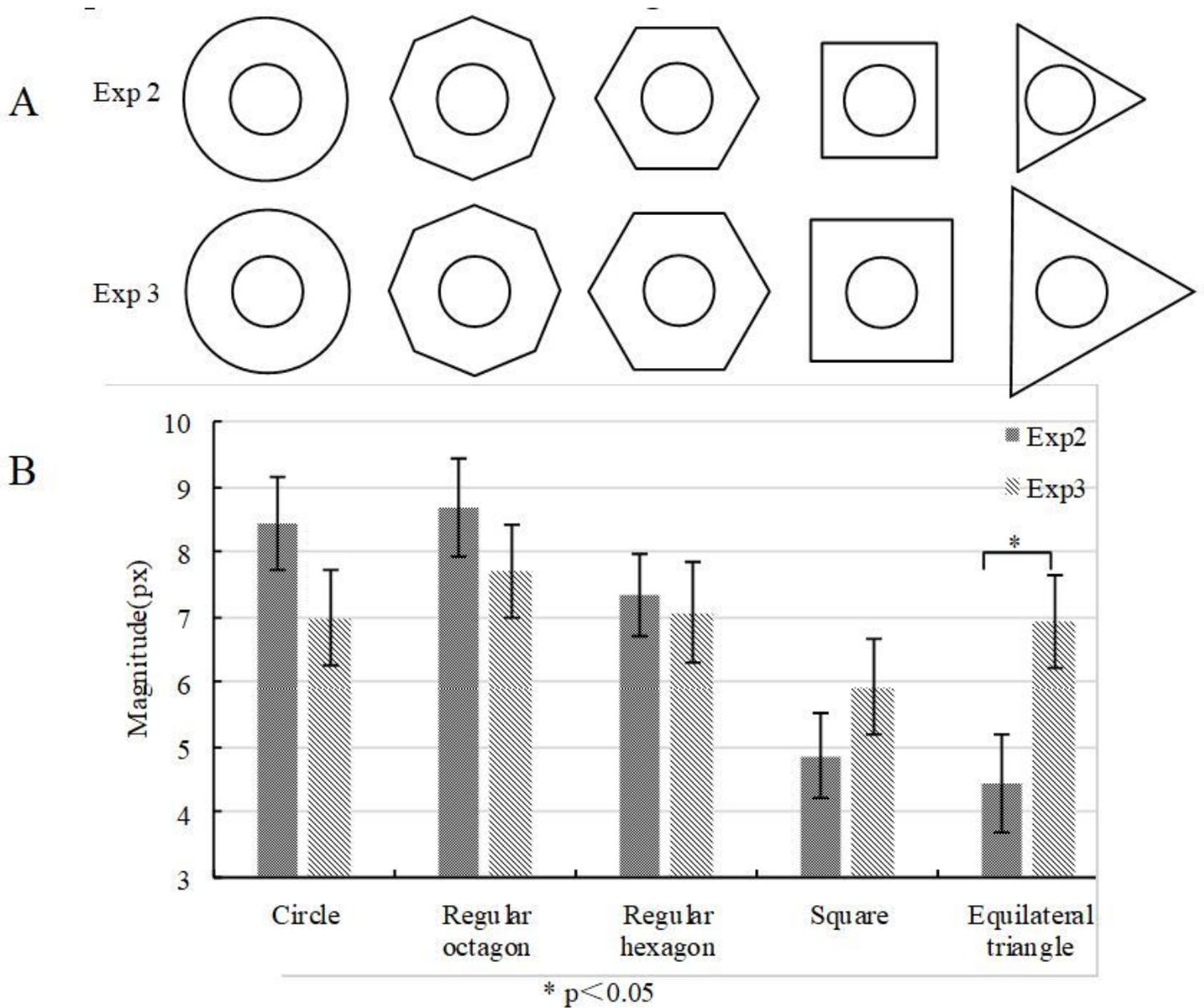
**Figure 2**

The procedure of one trial presented a target stimulus with an inducer on the left side of the screen and the outline of the probe stimulus on the right side of the screen.



**Figure 3**

(A) The illusion configuration in Experiments 1 and 2. (B) A comparison of the magnitude between Experiments 1 and 2.



**Figure 4**

(A) The illusion configuration in Experiments 2 and 3; the radii of the polygonal inducers' circumcircles in Experiment 3 are larger than those in Experiment 2. (B) A comparison of the magnitude between Experiments 2 and 3.

## Supplementary Files

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- [Appendix.tif](#)