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Spatial dynamics of the eggs illusion: Visual field anisotropy and peripheral vision

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ABSTRACT

The eggs illusion is a visual phenomenon in which bright circular patches located at the midpoints between the intersections of a dark grid are perceived as being elongated along the direction orthogonal to the grid line. In the four experiments we report here, we explored the spatial properties of the eggs illusion by manipulating retinal eccentricity and the location of the stimulus in the visual field. In Experiment 1, we examined whether central and peripheral configurations affected the illusory magnitude. In Experiment 2, we varied the spatial location of grid patterns and found that the eggs illusion was intensified when the pattern was presented in the horizontal, not vertical or diagonal position, relative to the fixation. In Experiment 3, we varied the retinal eccentricity of the pattern along the horizontal meridian and found that the illusion was enhanced in the retinal periphery. In Experiment 4, we manipulated the size of the stimulus and found that peripheral enhancement of the eggs illusion was more apparent for a larger pattern. The visual field anisotropy and the peripheral enhancement of the eggs illusion are discussed in relation to mechanisms underlying grid-induced illusions.

1. Introduction

The eggs illusion is a recently discovered visual phenomenon in which bright circular patches located at midpoints between adjacent intersections in a dark grid with a black background are perceptually deformed as elliptical (Qian & Mitsudo, 2016; Fig. 1). For example, perfect circular patches appear elongated at right angles to their embedding grid contours (Qian & Mitsudo, 2016, 2019). The visual illusions generated by grid patterns, such as the Hermann grid illusion (Brewster, 1844; Hermann, 1870), Bergen's illusion (Bergen, 1985), the blanking phenomenon (McAnany and Levine, 2004), and the scintillating grid illusion (Schrauf, Lingelbach, Lingelbach, & Wist, 1995; Schrauf, Lingelbach, & Wist, 1997), are related to the perception of brightness. Conversely, the eggs illusion relates to the perception of shape. Qian and Mitsudo (2016) first reported the eggs illusion and demonstrated that the magnitude of the illusion was affected by the patch size and grid luminance. A follow-up study explored the temporal features of the eggs illusion and revealed the role of orientation processing in generating the illusion (Qian & Mitsudo, 2019). These two studies suggested a remarkable similarity between the eggs illusion and the scintillating grid illusion, with evidence that both illusions are affected by the stimulus size, luminance contrast, presentation duration, and orientation information. The function of these factors on scintillating grid illusion have been demonstrated by a series of previous studies (Schrauf et al., 1997; Schrauf, Wist, & Ehrenstein, 2000; Qian, Yamada, Kawabe, & Miura, 2009; Qian, Kawabe, Yamada, & Miura, 2012). Based on these common features, Qian and Mitsudo (2016, 2019) proposed a tentative hypothesis that the eggs illusion shares the same underlying mechanism as the scintillating grid illusion in that processing local and relative orientation plays a critical role in generating the illusion. In this hypothesis, shape distortion in the eggs illusion appears to arise from a mechanism similar to orientation contrast (Suzuki & Cavanagh, 1998) from their embedding local grid contours and can be enhanced by the global grid configurations.

Orientation processing is an important part of spatial vision (De Valois & De Valois, 1980). The relevance of orientation processing to the eggs illusion implies the necessity of exploring the illusion further and within the context of spatial vision. For the scintillating grid illusion, VanRullen and Dong (2003) revealed that the illusion was stronger in peripheral vision than in foveal vision. Qian and Mitsudo (2016, 2019) noted the potential role of peripheral presentation in the eggs illusion based on informal observations, without support of experimental investigation. In the present study, we focused on the spatial properties of the eggs illusion by manipulating the location and eccentricity of the stimulus in the visual field. Based on the findings on the scintillating grid illusion and our informal observations of the eggs

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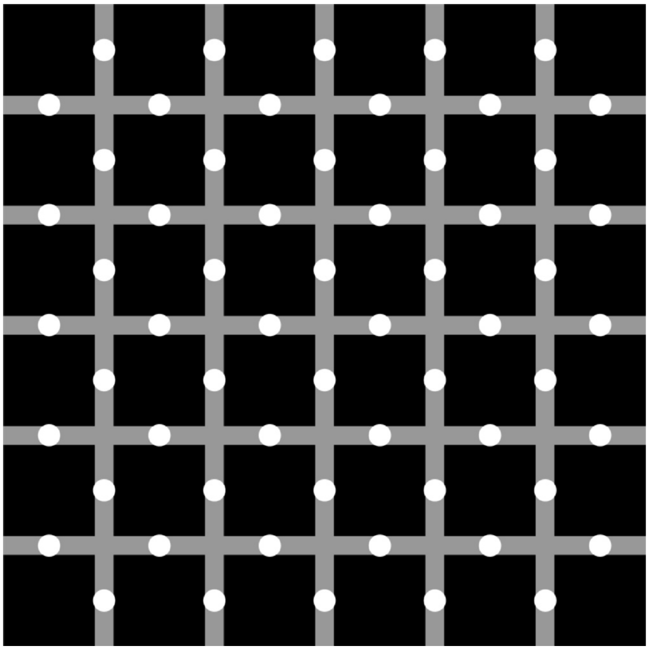

Fig. 1. A demonstration of the eggs illusion. The bright circular patches located on the dark grid lines are perceived as ellipses elongated at right angles to their embedding grid contours.

illusion, we hypothesized that the eggs illusion could also be strengthened in peripheral vision. Exploring a potential impact of retinal stimulus position is essential to understand the mechanisms underlying the eggs illusion, because it is unclear what stimulus is optimal for generating the eggs illusion. To examine this, we conducted four psychophysical experiments. In Experiment 1, we investigated a central and peripheral configuration of the eggs illusion. In Experiment 2, we systematically controlled the position and eccentricity of the stimulus display. The spatial properties of the eggs illusion discovered in Experiment 2 were investigated further in Experiments 3 and 4.

2. Experiment 1: Central/peripheral display of the eggs illusion

In this experiment, we exploratorily examined the effect of peripheral presentation on the eggs illusion. Fig. 2a shows our two stimulus configurations, in which the central part of the original pattern was presented (central condition) and removed (peripheral condition). We also varied the presentation duration because the illusion's magnitude changes over time, as found in Qian and Mitsudo (2019). Based on the informal observations stated above, we predicted that the illusion would not diminish, even at peripheral presentation.

2.1. Methods

2.1.1. Observers

Ten observers participated in Experiment 1 (five males and five females; mean age = 30.3 years; *SD* = 6.7 years). Every observer had normal or corrected-to-normal visual acuity and was naïve to the purpose of the experiment. Participants were recruited from the students, faculty members, and administrative staffs at Kyushu University. All the four experiments were approved by the Ethics Committee for Psychological Studies at the Institute of Decision Science for a Sustainable Society, Kyushu University (No. 2017/2-3, No. 2019/1-8). Written consent was obtained from each participant at the beginning of the experiment.

2.1.2. Apparatus and stimuli

The experiment was conducted using a computer (Apple, Mac Pro, MB871J/A) and a CRT monitor (EIZO, FlexScan F931, 1152 × 870 pixels, 75 Hz), and it was generated by MATLAB R2017a using Psychtoolbox (Brainard, 1997; Pelli, 1997). The viewing distance was 60 cm, and the observers' heads were stabilized by a chin-and-forehead rest.

The basic stimulus consisted of a black background, a gray grid, and an array of perfectly circular white patches, the same as what was used in Qian and Mitsudo (2016). The luminance values of the black background, gray grid, and white patches were 1 cd/m^2, 28 cd/m^2, and 94 cd/m^2, respectively. The grid was composed of 11 horizontal and 11 vertical bars that were spaced equally. Each bar in the rows or columns subtended 25° × 35.4′ and was placed 1.73° of visual angle apart from its adjacent bars. Ten white circular patches with diameters of 39.8′ were placed on each bar. Each patch was positioned at the midpoints between two adjacent intersections of the grid. All stimuli were drawn using the anti-aliasing method. We modified this basic stimulus into two experimental stimuli. For the central condition, we used the central part of the basic stimulus, a 3 × 3 grid pattern (6.8° × 6.8°), and we trimmed off all other elements. For the peripheral condition, the central 5 × 5 grid (11.4° × 11.4°) was erased from the basic stimulus. To replicate the findings of Qian and Mitsudo (2019), in this experiment, we set the presentation duration to 40, 67, 133, 213, 347, 493, 693, and 1000 ms.

A 9-point scale was used in the response display, which accompanied a series of patches under the scale. Under the leftmost point of the scale, two white circular patches with diameters of 44.4′ were presented in a column. At the third, fifth, seventh, and ninth points from the left, four sets of elliptic patches were presented. The two elliptic patches presented in each column had identical shapes and differed in their orientation. The major axis of the upper patch was vertical, and that of the lower patch was horizontal. All eight elliptical patches had the same minor-axis length of 44.4′. The major-axis lengths of the ellipses under the third, fifth, seventh, and ninth points from the left were 48.0′, 50.4′, 54.0′, and 57.6′, corresponding to aspect ratios of 1.08, 1.14, 1.22, and 1.30, respectively. Larger-sized patches were used in the matching task for better visibility, to make it easier to compare perceived shape (i.e., not presented in the matching display) with the presented ellipses. Almost the exact same response display was used in Qian and Mitsudo (2016, 2019).

2.1.3. Procedure

Each observer binocularly viewed the monitor in a darkened room. A black background was presented for 1000 ms at the beginning of each trial. After this, a red fixation cross (1.1° × 1.1° of visual angle) was presented for 213 ms, which was followed by the presentation of the test stimulus for one of the eight durations (40–1000 ms). The fixation cross remained on the screen until the test stimulus disappeared. Observers were required to view the fixation cross when it was displayed, regardless of whether the test stimulus was present or not. After the test stimulus and fixation cross disappeared, a black-and-white, random-dot pattern was displayed as a mask for 493 ms. The response scale was displayed after the mask disappeared. Observers were asked to choose from the nine options (points on a scale) and select the one that was most similar to the perceived shape of the white patches in the test stimulus. Observers were instructed to choose the option closest to the average shape if the patches were perceived in different shapes across locations. There was no time limit for observers' responses.

Sixteen experimental conditions (two display patterns × eight presentation durations) were tested five times each. Consequently, 80 experimental trials in total were run in a randomized order. The observers were asked to complete approximately 10 practice trials in advance to get accustomed to the task.

2.2. Results and discussion

Fig. 2 shows the perceived aspect ratios as a function of the

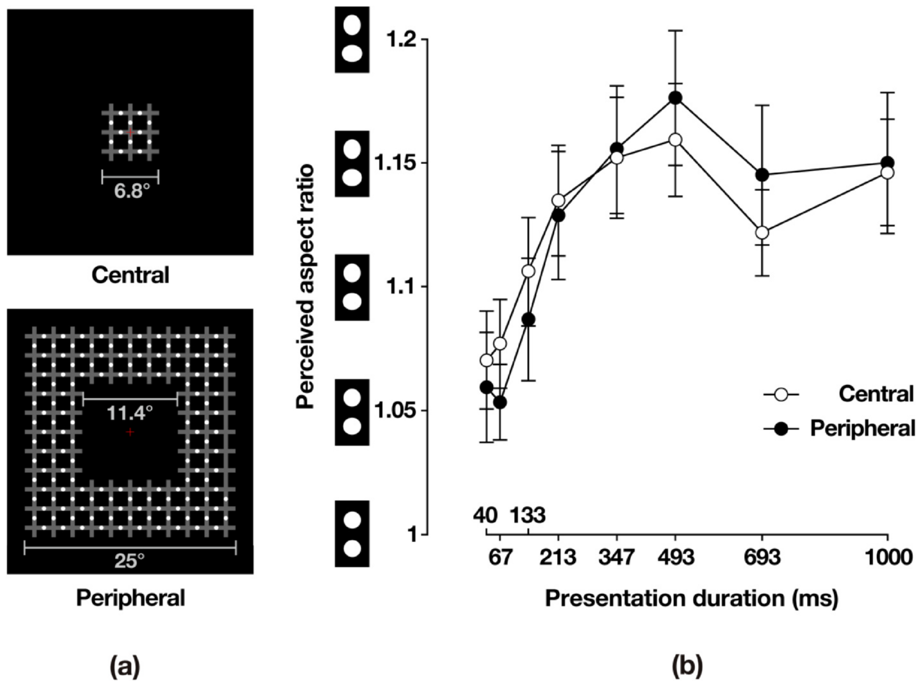

Fig. 2. Stimuli and results for Experiment 1. (a) Schematic illustrations of the test stimuli used in the central and peripheral conditions. (b) Results of Experiment 1. Mean perceived aspect ratios, averaged over the 10 observers, are shown as a function of presentation duration. Error bars denote standard errors of the mean.

presentation duration, which were averaged over the 10 observers in Experiment 1. A two-way within-participant analysis of variance (ANOVA) on the mean perceived aspect ratios, with factors of display pattern and presentation duration, resulted in a significant main effect of presentation duration [F (7, 63) = 9.648, p < .001, η_p^2 = .517]. However, neither the main effect of retinal position [F (1, 9) = 0.011, p = .92, η_p^2 = .001] nor the two-way interaction [F (7, 63) = 1.282, p = .27, η_p^2 = .125] was significant. Multiple comparisons revealed that the following pairs of presentation-duration combinations differed significantly: 40–213, 40–347, 40–493, 40–693, 40–1000, 67–213, 67–347, 67–493, 67–693, 67–1000, 133–347, and 133–493 ms (ps < .05).

In summary, the magnitude of the illusory deformation did not differ, irrespective of whether the stimulus was presented centrally or peripherally. In each configuration, the illusion increased up to around presentation durations of 200–300 ms. This result replicates that of Qian and Mitsudo (2019). In addition, based on informal interviews of six naive participants after the experiment, all participants thought that physically elliptical patches with variable aspect ratios were presented across trials. Therefore, we believe that the observers' response reflects their percept rather than response bias or expectations.

Why was no decrease or increase in the illusory magnitude found even in the peripheral presentation? One possibility is that the stimulus differed considerably between the two conditions. For example, both the size of the grid and the number of patches were greater in the peripheral condition than in the central condition. To examine this issue, we conducted Experiment 2.

3. Experiment 2: Manipulation of location and eccentricity in the visual field

The purpose of Experiment 2 was to systematically examine whether the magnitude of the eggs illusion changed across different retinal positions and eccentricities. We located the 3 × 3 grid pattern used in the central condition of Experiment 1 at one of several positions around the central fixation. To accurately control the stimulus position and eccentricity, we chose a stimulus duration of around 200 ms because this length of time is sufficient to produce the eggs illusion (as found in Experiment 1), and it is expected to prevent saccades that reduce retinal eccentricity. We predicted that the magnitude of the illusion would alter depending on different positions.

3.1. Methods

The methods were identical to those used in Experiment 1, except for those described below.

3.1.1. Observers

Twenty-five observers participated in Experiment 2 (nine males and 16 females; mean age = 20.8 years; SD = 2.8 years). One of them had participated in Experiment 1.

3.1.2. Stimuli and procedure

A constant stimulus duration of 212 ms was used throughout the experiment to avoid reflexive saccades to the test stimulus. There were two experimental variables in Experiment 2. One was the visual field of presentation, in which the center of the stimulus pattern was presented on one of four radial orientations: the horizontal axis (H), the vertical axis (V), and along axes oriented at +45° (R-tilt) and −45° (L-tilt) from the vertical axis. Fig. 3 shows the centers of the 3 × 3 grid pattern, which was located upright at one of the five intersections on each light gray scale. The two polar positions in the same radial direction were merged in our data analysis (e.g., the upper and lower position on the vertical axis). The other variable was retinal eccentricity (i.e., the distance between the centers of the screen and the grid pattern), selected from 4.8°, 6.1°, 7.4°, 8.7°, and 10° of visual angle. Four visual fields and five levels of eccentricity constituted 20 conditions in this experiment. Each condition was tested six times in a randomized order. In total, 120 trials were run in Experiment 2. The mask of a black-and-white, random-dot pattern was not used in Experiment 2.

3.2. Results and discussion

Fig. 4 shows the results of Experiment 2. A two-way within-participant ANOVA was conducted on the mean perceived aspect ratios with factors of visual field and eccentricity. The results of the ANOVA

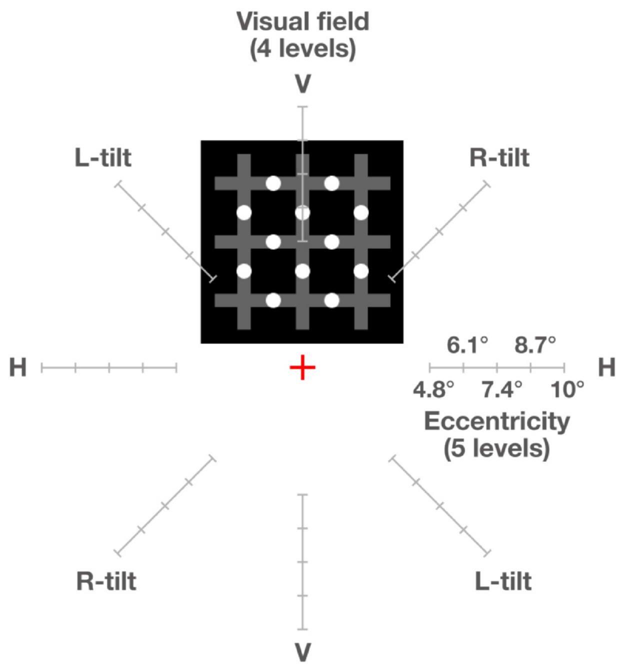

Fig. 3. Stimulus configuration in Experiment 2. The intersections on each light gray scale denote the positions where the center of the 3 × 3 grid pattern was located. This panel is based on a screenshot of the vertical visual field at an eccentricity of 4.8°. Light gray scales and all figure legends are included for explanation and were not presented in the actual experimental display. In the actual experiment, the background was black, identical to that of the gray grid shown in this figure.

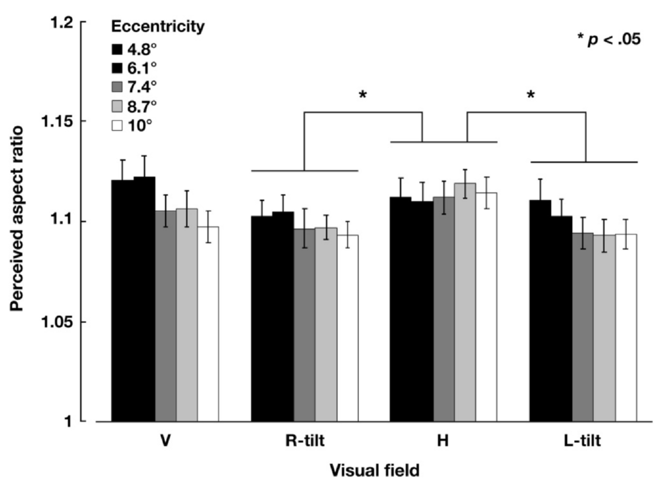

Fig. 4. Results of Experiment 2. Mean perceived aspect ratios averaged over the 25 observers are shown as a function of visual field. Error bars denote standard errors of the mean.

revealed significant main effects of visual field [F (3, 72) = 4.454, p = .006, η_p^2 = .157]. However, neither the main effect of eccentricity [F (4, 96) = 1.630, p = .173, η_p^2 = .064] nor the interaction of the two variables [F (12, 288) = 0.997, p = .452, η_p^2 = .040] was significant. Regarding the significant main effect of visual field, post-hoc tests in Tukey's method revealed significant differences between the H and R-tilt conditions (p = .028) and between the H and L-tilt conditions (p = .029). No other pairs were significant.

The prediction regarding the effect of stimulus position was supported by the results because we found a significant increase in the illusory magnitude when the grid was presented in the horizontal position as compared to the two oblique positions (R-tilt and L-tilt). However, no peripheral enhancement was demonstrated. Although a visual inspection of Fig. 4 suggests a decrease accompanied by increasing eccentricity in the vertical and two tilt positions, this tendency was not statistically significant.

The lack of impact of peripheral presentation on the eggs illusion might be due to a response bias possibly related to an anisotropy of visual acuity. For example, the observers might have chosen a more elliptic patch because visual acuity in the peripheral field is relatively higher along the horizontal meridian than along the vertical meridian (Kondo et al., 2008). To examine this issue, we conducted Experiment 3.

4. Experiment 3: Manipulation of eccentricity in the horizontal visual field

In Experiment 3, we examined the peripheral eggs illusion found in Experiment 2 using physically elongated patches on the grid line. The shape deformation in the eggs illusion occurs along the direction orthogonal to the grid line. We aimed to determine the degree to which the eggs illusion depends on local grid orientation, by assessing the impact of physical aspect ratio of the patches on the perceived patch shape. Qian and Mitsudo (2016, 2019) employed the same procedure and found a clear *slope* of the selected ellipse around an aspect ratio of 1.0 when the illusion was evident. We also modified the method of stimulus display because a one-sided presentation of the stimulus in Experiment 2 might have prevented observers from focusing their attention on the fixation cross.

4.1. Methods

The methods were the same as those in Experiment 2, except for the following.

4.1.1. Observers

Twenty-five observers participated in Experiment 3 (eight males and 17 females; mean age = 20.4 years; SD = 2.7 years). Twenty-three of them had participated in Experiment 2.

4.1.2. Stimuli and procedure

Two independent variables were used in this experiment. First, eccentricity was again manipulated in Experiment 3 with the same levels as those used in Experiment 2 (4.8°, 6.1°, 7.4°, 8.7°, and 10° of visual angle). Second, the shape of the white patches was varied at three levels. In addition to the perfect circle (circle condition), we employed two different types of elliptical white patches. In the parallel condition, the patches were elongated along the grid orientation (left panel in Fig. 5). In the orthogonal condition, the patches were elongated along the orientation orthogonal to the grid orientation. The lengths of the longer and shorter axes were 40.8′ and 39.0′, respectively (aspect ratio = 1.05). Based on Qian and Mitsudo (2016, 2019), it was expected that the illusion magnitude in the parallel condition would be weaker due to the cancellation of illusory deformation along the orientation orthogonal to the grid line.

In an attempt to prevent potential reflexive saccades to the stimulus, a grid without a patch (empty grid) was presented on the opposite side of the test eggs pattern (right side in Fig. 5). The locations of the empty and test grid patterns were counterbalanced. Sixty trials (5 eccentricities × 3 patch shapes × 4 repetitions with counterbalance) were conducted in a randomized order.

4.2. Results and discussion

Fig. 6 shows the perceived aspect ratios as a function of eccentricity. The results of a two-way, within-participant ANOVA revealed significant main effects of eccentricity [F (4, 96) = 6.145, p < .001, η_p^2= .204] and patch shape [F (2, 48) = 8.365, p < .001, η_p^2= .258] and a significant interaction [F (8, 192) = 2.058, p = .042, η_p^2 = .079].

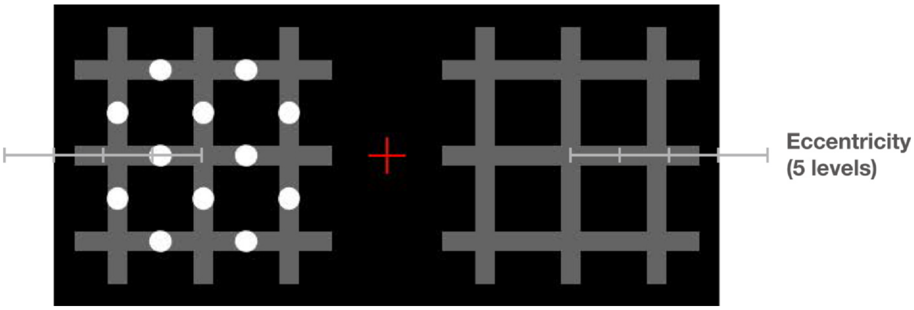

Fig. 5. Schematic illustration of stimuli used in Experiment 3. The intersections of each light gray scale denote the positions where the center of the grid pattern was located. This figure is based on a screen shot of the stimulus display with conditions of 4.8° as the eccentricity and parallel ellipse as the patch shape. Light gray scales and the figure legend are included for explanation and were not presented in the actual experimental display.

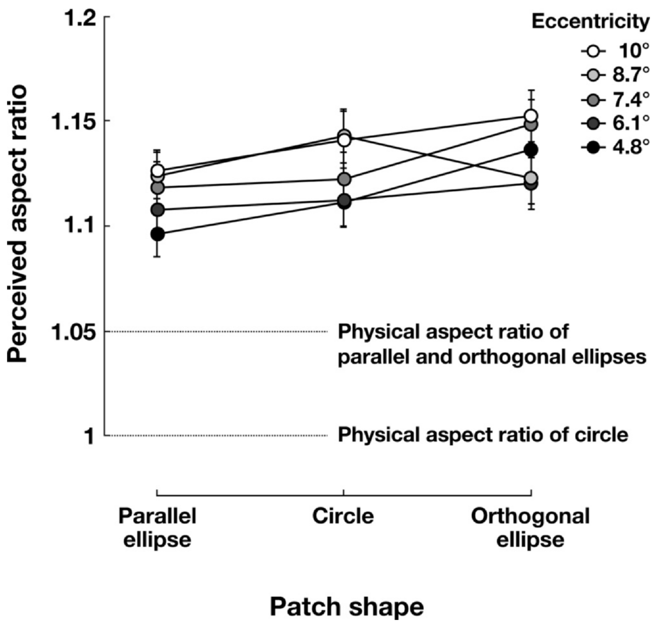

Fig. 6. Results of Experiment 3. Mean perceived aspect ratios, averaged over 25 observers, are shown as a function of eccentricity. Error bars denote standard errors of the mean.

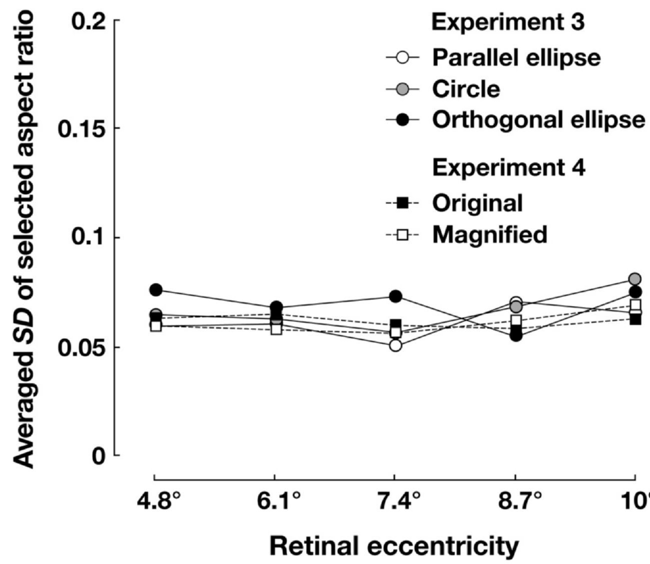

Fig. 7. Averaged *SD* of selected aspect ratio shown as a function of eccentricity.

Post-hoc tests with Tukey's method revealed significant differences between the parallel and orthogonal conditions ($p < .001$) for the shape patches, between 4.8° and 10° ($p = .001$), and between 6.1° and 10° ($p < .001$) for eccentricity. Tests of simple main effects showed that the effect of eccentricity was significant for each patch shape [parallel: F (4, 288) = 2.785, p = .027; circle: F (4, 288) = 4.158, p = .003; orthogonal: F (4, 288) = 3.780, p = .005]. The simple main effect of patch shape was significant when the eccentricity was 4.8°, 7.4°, and 10° [4.8°: F (2, 240) = 7.262, $p < .001$; 6.1°: F (2, 240) = 0.726, p = .485; 7.4°: F (2, 240) = 4.765, p = .009; 8.7°: F (2, 240) = 2.250, p = .108; 10°: F (2, 240) = 3.095, p = .047]. Multiple comparisons based on significant simple main effects showed a significant difference in the pair of 4.8°–10° for the condition of parallel ellipse; in the pairs of 4.8°–8.7°, 6.1°–8.7°, 4.8°–10°, and 6.1°–10° for the circle condition; and in pairs of 6.1°–10° and 8.7°–10° for the condition of orthogonal ellipse ($ps < .05$). At eccentricities of 4.8° and 7.4°, significant differences were found between the parallel and orthogonal conditions and between the circle and orthogonal ellipses; at an eccentricity of 10°, a significant difference was found between the parallel and orthogonal conditions ($ps < .05$).

The results of Experiment 3 replicated those of Qian and Mitsudo (2016, 2019) in that the eggs illusion could be systematically altered using patches deformed along the grid line. We found reliable and consistent slopes at almost all eccentricities, which suggests that the peripheral eggs illusion is not a response bias. Furthermore, we found that the eggs illusion could be rather enhanced as the stimulus eccentricity increased.

An anonymous reviewer commented on possible changes in confidence when considering the effect of eccentricity. We conducted an additional analysis of response variability in this experiment. We calculated the *SD* of selected ellipses in the response display for each condition. If the peripheral enhancement of the eggs illusion is entirely based on a decrease of response confidence, the averaged *SD* of the selected ellipses would be expected to increase as a function of eccentricity. However, as shown in Fig. 7, there was no systematic change in response variability. Therefore, we believe that confidence is unlikely to play a critical role in the peripheral enhancement of the eggs illusion.

5. Experiment 4: Manipulation of eccentricity and stimulus size

The purpose of Experiment 4 was to further examine whether the eggs illusion could occur strongly in the peripheral visual field. One technical problem contrary this purpose is that small patches in the eggs pattern are almost invisible in peripheral vision, where visual acuity is much lower than in foveal vision (Mandelbaum & Sloan, 1947; Anderson et al., 1991). Therefore, to increase the visibility of a pattern, enlarging the stimulus size is necessary (Anstis, 1974; Kondo et al., 2008). In the experiment, a magnified size of the eggs pattern was added to explore the interaction between stimulus size and eccentricity. Qian and Mitsudo (2016) reported that when viewed at the perifovea, larger patches on the grid produced a weaker eggs illusion. Therefore, we predicted that a magnified eggs pattern would produce a weaker illusion in central vision, but produce a stronger illusion in peripheral vision.

5.1. Methods

The methods were identical to those in Experiment 3, except for the following.

5.1.1. Observers

Twenty-five observers participated in Experiment 4 (10 males and 15 females; mean age = 20.5 years; *SD* = 2.7 years). Twenty-three of them had participated in Experiment 3.

5.1.2. Stimuli and procedure

The two independent variables were eccentricity and stimulus size. Eccentricity was manipulated in the same way as in Experiments 2 and 3. For the stimulus size, we prepared two levels: the original and the magnified patterns. The original pattern was identical to the 3 × 3 grid with white patches used in Experiments 2 and 3. The magnified pattern was overall one-and-a-half times as large as the original one. Different from Experiment 3, we did not present an empty grid without patches. The shapes of the white patches were always perfect circles. Five levels of eccentricity and two levels of stimulus size yielded 10 experimental conditions. Each condition was tested six times, including the counterbalance for the stimulus position (the right and left side of the fixation). In total, 60 trials were conducted in a randomized order.

5.2. Results and discussion

Fig. 8 shows the perceived aspect ratios as a function of eccentricity. We ran a two-way, within-participant ANOVA with factors of eccentricity and stimulus size. The results of the ANOVA revealed a significant main effect of eccentricity [F (4, 96) = 3.009, p = .022, η_p^2 = .111] and a significant interaction between the two variables [F (4, 96) = 4.736, p = .002, η_p^2 = .165]. The main effect of stimulus size was not significant [F (1, 24) = 2.984, p = .097, η_p^2 = .111]. Tests of simple main effects showed that the effect of eccentricity was significant for the magnified pattern [original: F (4, 192) = 0.728, p = .574; magnified: F (4, 192) = 6.812, $p < .001$]. The simple main effect of stimulus size was significant when the eccentricity was 4.8° and 6.1° [4.8°: F (1, 120) = 6.276, p = .014; 6.1°: F (1, 120) = 8.016, p = .005; 7.4°: F (1, 120) = 1.165, p = .283; 8.7°: F (1, 120) = 1.862, p = .175; 10°: F (1, 120) = 0.631, p = .429]. Multiple comparisons based on significant simple main effects showed significant differences for pairs of 4.8°–10°, 6.1°–8.7°, 6.1°–10°, and 7.4°–10° for the magnified pattern (*ps* < .05).

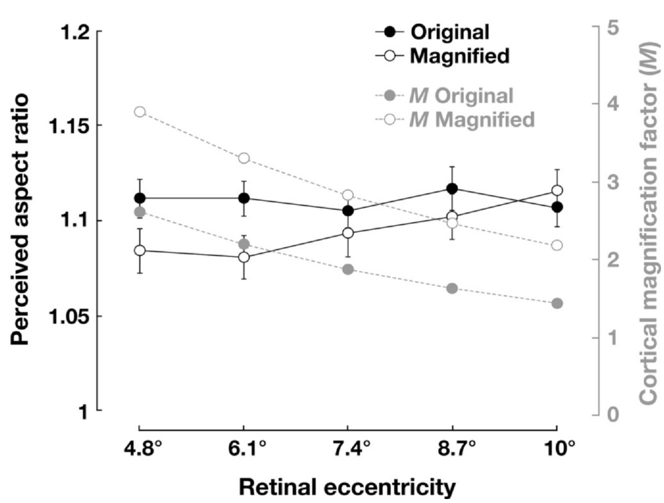

Fig. 8. Results of Experiment 4. Mean perceived aspect ratios, averaged over 25 observers, are shown as a function of eccentricity. Error bars denote standard errors of the mean. The cortical magnification factor for each experimental condition is displayed in light gray color.

Similar to Experiment 3, an additional analysis of response variability was conducted. As shown in Fig. 7, there was no systematic change in response variability in Experiment 4. Therefore, confidence is unlikely to play a critical role in the peripheral enhancement of the eggs illusion.

The results of Experiment 4 revealed the influence of stimulus size on peripheral enhancement of the eggs illusion. Our prediction was partially supported in that the illusion magnitude increased as a function of stimulus eccentricity only when the stimulus was magnified. Although Fig. 8 shows that magnified stimulus seemed to produce a weaker illusion than the original one, the difference between magnified and original conditions was not significant. We estimated the cortical representation sizes of the stimuli at each eccentricity condition by calculating the cortical magnification factor (*M* values), using the same method as that in a previous study (Carrasco & Frieder, 1997). As shown in Fig. 8, the cortical representation size of the original stimulus at eccentricities of 4.8°-6.1° was approximately equal to that of the magnified stimulus at eccentricities of 8.7-10°, and the illusory deformation was similar in these conditions. Thus, we speculate that the eggs illusion may occur when the cortical representation size of the stimulus patch is *smaller* than a particular value.

6. General discussion

The present study examined the spatial properties of the eggs illusion by manipulating the position of the stimulus in the visual field. In Experiment 1, we replicated findings on the temporal properties of the eggs illusion (Qian & Mitsudo, 2019), in which the magnitude of the illusion reached the peak and showed no significant changes when the presentation duration was longer than around 200 ms. In Experiment 2, we controlled the position and eccentricity of the grid pattern in detail and found a visual field anisotropy of the eggs illusion, in which the illusion was strengthened in the horizontal visual field. However, the main effect of eccentricity was not significant. In Experiment 3, we concentrated on the horizontal visual field, in which a stronger illusion was generated, and found that the illusion was enhanced as eccentricity increased. Lastly, in Experiment 4, we varied the stimulus size to accommodate a property of peripheral vision, i.e., lower spatial resolution and visual acuity, and found that peripheral enhancement of the eggs illusion occurred with a larger stimulus size. Taken together, we demonstrated that the eggs illusion is anisotropic across the visual field and can be enhanced in peripheral vision.

As noted in the introduction section, peripheral enhancement occurs in the scintillating grid illusion (VanRullen & Dong, 2003). In this study, we demonstrated a similar peripheral enhancement of the eggs illusion only in the horizontal visual field, which provides partial support for the common features between the eggs illusion and the scintillating grid illusion. Referring to the discussion presented by VanRullen and Dong (2003) regarding the scintillating grid illusion, we consider that peripheral enhancement of the eggs illusion might also be related to the spatial dynamics of visual attention between the central and peripheral visual field (Posner, 1980; Carrasco, 2011).

Furthermore, the present study demonstrated visual field anisotropy of the eggs illusion, which has not been reported for the scintillating grid illusion. Visual field anisotropy has been clarified in basic geomatical illusions on length perception (Bertulis & Bulatov, 2005; Mikellidou & Thompson, 2013); the illusion of motion direction (Loffler & Orbach, 2001); illusory motion (Ehrenstein, 1997); and perceptual filling-in (Sakaguchi, 2003). Bertulis and Bulatov (2005) demonstrated the visual field anisotropy of length perception using the Müller-Lyer pattern (Müller-Lyer, 1889) and the Oppel-Kundt pattern (Oppel, 1855; Kundt, 1863), by controlling the relative angle between test and references parts of the stimuli. However, unlike Bertulis and Bulatov (2005) and Loffler and Orbach (2001), the present study manipulated the presentation positions in the visual field but not the orientation of stimuli. Sakaguchi (2003) found that perceptual filling-in required more time in the horizontal position, which implies that illusory filling-in is more difficult in the horizontal visual field when compared with the other visual fields. This tendency is contrary to the case of the eggs illusion reported here. Thus, the anisotropy found in the eggs illusion is likely to be different from that reported in the other illusions.

Experiment 2 found that the eggs illusion was stronger in the horizontal position than in the oblique positions. This is somewhat similar to the oblique effect—a relative deficiency in visual perception of oblique lines when compared with that of the horizontal or vertical lines (Mach, 1861; Appelle, 1972). In addition, Hubel and Wiesel (1959) provided neurophysiological evidence that the orientation-selective neurons of V1 that respond to horizontally or vertically oriented bars are much numerous than those that respond to oblique ones. However, our results should be distinguished from the oblique effect, because the previous studies are involved in the processing for oblique orientations, not processing in oblique positions of the visual field.

Why did peripheral enhancement of the eggs illusion occur particularly in the horizontal visual field? Interestingly, a visual field anisotropy of peripheral sensitivity is also reported for moving patterns in which perceptual sensitivity is less impaired by eccentricity in the horizontal visual field (Tynan & Sekuler, 1982). Although the eggs pattern is essentially static, we speculate that the eggs illusion involves transient visual processing that operates a large portion of the visual field, because this illusion is likely to be enhanced by voluntary saccades (Qian & Mitsudo, 2016) and to occur at brief stimulus presentations (Qian & Mitsudo, 2019). According to this tentative interpretation, no peripheral enhancement in Experiment 1 may be due to visual crowding (Whitney & Levi, 2011), in which simultaneously presented flankers can reduce target visibility (i.e., white small patches in this study).

There were several limitations in this study, which suggest directions for future studies on the eggs illusion. An anonymous reviewer advised systematic manipulation of contrast and context. For contrast, we have demonstrated how luminance of the grid, which eventually altered both patch and grid contrasts, affected the eggs illusion (Qian & Mitsudo, 2016, 2019). However, we did not alter patch luminance and grid luminance independently. For context, the effect of crowding and density, as well as the association with perceived deformation of textures (i.e. the honeycomb illusion, Bertamini, Herzog, & Bruno, 2016) calls for further investigations in the future. One may think that the eggs illusion arises from lateral inhibition or orientation repulsion. As to lateral inhibition, we believe that its contribution to the eggs illusion is limited because lateral inhibition primarily involves brightness, not shape. Even for brightness (i.e., the Hermann grid and scintillating grid illusions), psychophysical data do not necessarily support the theory of lateral inhibition (Schiller & Carvey, 2005; Qian et al., 2012). Furthermore, the tilt angle of orientation repulsion (Westheimer, Shimamura, & McKee, 1976), i.e. 10°–20° was considerably different from the orientation of deformation in the eggs illusion (orthogonal). However, experimental investigations on lateral inhibition and orientation repulsion are necessary for future studies.

In conclusion, we experimentally demonstrated visual field anisotropy and peripheral enhancement of the eggs illusion. These characteristics may provide insights into the mechanisms underlying the family of grid-induced illusions, such as the Hermann and scintillating grid illusions.

CRediT authorship contribution statement

Kun Qian: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Hiroyuki Mitsudo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing - review & editing.

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