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Role of Orientation Processing in the Eggs Illusion

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Abstract
In the eggs illusion, small patches perceptually deform when placed at the midpoints between the intersections of a regular grid. In this study, we explored the role of orientation processing in the illusion, by manipulating some spatiotemporal stimulus parameters using three psychophysical experiments. In Experiment 1, we manipulated grid luminance and presentation duration as independent variables and found that the illusion occurred even with a brief presentation of approximately 200 to 300 ms. In Experiments 2 and 3, besides presentation duration, we also systematically varied the orientation information of the stimulus. In addition to the original grid pattern, stimuli with only horizontal or vertical bars were employed in Experiment 2. The magnitude of the illusion was significantly weakened under the bar conditions. In Experiment 3, we varied the orientation of the bars stepwise and revealed that the local orientation information around the circular patches and the relative orientation information provided by the orthogonal bars of the grid are contributing factors to the illusion. Based on these results, we discussed the role of orientation processing in generating the eggs illusion.

Keywords
visual illusion, shape perception, orientation processing

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Introduction

Two-dimensional, regular grid patterns can produce visual illusions concerning brightness, such as the Hermann grid illusion (Brewster, 1844; Hermann, 1870), Bergen's illusion

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(Bergen, 1985), and the blanking phenomenon (McAnany & Levine, 2004). Schrauf and colleagues (Schrauf, Lingelbach, Lingelbach, & Wist, 1995; Schrauf, Lingelbach, & Wist, 1997) reported a striking brightness illusion produced by a grid, in which white patches located at the intersections of a gray grid appear darkened and scintillating. The scintillating grid illusion is influenced by the luminance contrast and size relationship among the stimulus elements (i.e., white circular patches, gray grid, and black background squares; Schrauf et al., 1997). Spatial and temporal characteristics of the scintillating grid illusion have been also explored. In the spatial domain, orientation information is important for generating the scintillating grid illusion, because the illusory effect is weakened by changing orientation information, such as curving (Levine & McAnany, 2008), breaking (Qian, Kawabe, Yamada, & Miura, 2012), or partially removing (Qian, Kawabe, Yamada, & Miura, 2010) the grid. Another spatial feature is the retinal location, because the scintillating grid illusion typically occurs in the retinal periphery and is enhanced by voluntary eye movements (Schrauf et al., 1997; VanRullen & Dong, 2003). In the temporal domain, Schrauf, Wist, and Ehrenstein (2000) reported that the scintillating grid illusion occurs even at brief presentations. Considering these results, Qian et al. (2012) emphasized that orientation processing greatly contributes to the scintillating grid illusion and proposed a theoretic mechanism of the scintillating grid illusion based on the activities of S1-type simple cells in the primary visual cortex.

Whereas the scintillating grid illusion is related to the perception of brightness, the eggs illusion—a grid-induced illusion relating to geometric shape—has been recently discovered (Qian & Mitsudo, 2016). In this illusion, unlike in the scintillating grid illusion, white circular patches are located at the *midpoints* between adjacent intersections of a gray grid pattern. In this configuration, the patches are perceived as elliptic (Figure 1). In the first investigation of this illusion, Qian and Mitsudo (2016) showed that the occurrence and magnitude of the eggs illusion were influenced by the patch size and grid luminance. The effect of both variables suggests a similarity between the eggs illusion and the scintillating grid illusion, because the strength of the scintillating grid illusion was also affected by the size of the white patches and the luminance magnitude of the grid (Qian, Yamada, Kawabe, & Miura, 2009; Schrauf et al., 1997). This similarity is surprising because the visual attributes of the two illusions are quite different. The eggs illusion involves shape perception, whereas the scintillating grid illusion involves brightness perception. In addition to the scintillating grid illusion, Qian and Mitsudo (2016) also discussed other perceptual phenomena (e.g., the apparent size illusion [Helmholtz, 1867; van Erning, Gerrits, & Eijkman, 1988], the shape-contrast effect [Suzuki & Cavanagh, 1998], and the Orbison illusion [Orbison, 1939]), which might be related to the eggs illusion. Nevertheless, the mechanisms underlying the eggs illusion remain unclear.

As to the scintillating grid illusion, Qian et al. (2012) suggested that orientation processing is important. Considering some common features between the scintillating grid and eggs illusions (Qian & Mitsudo, 2016), in this study, we investigated the role of orientation processing on the eggs illusion to provide insights into its underlying mechanisms. Based on the previous studies of the scintillating grid illusion, we manipulated the spatiotemporal features of the eggs illusion to explore the processing of orientation information. Schrauf et al. (2000) found that a brief presentation (around 200 ms) enhanced the scintillating grid illusion. To examine the temporal properties of the eggs illusion and their relationship with orientation processing, in all experiments of this study, we systematically varied the presentation duration and stimulus configuration of the pattern that produces the eggs illusion. Especially in Experiments 2 and 3, we varied the spatial configuration to thoroughly investigate the role of orientation information, to examine the interactions between spatial and temporal properties, and finally to compare them with those of the scintillating grid illusion.

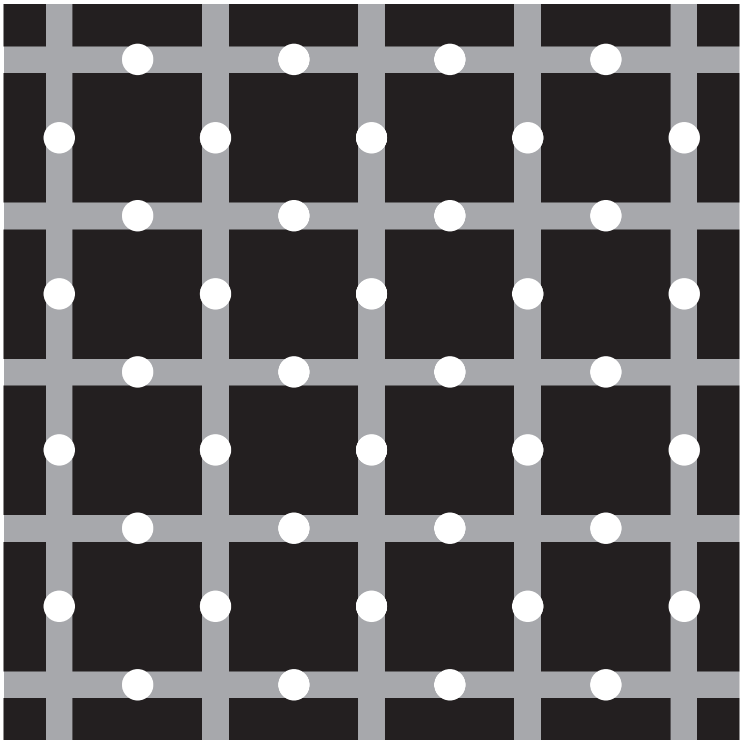

Figure 1. The eggs illusion. White circular disks located on a gray grid are perceived as egg-like ellipses.

Experiment 1a: Presentation Duration Alters the Eggs Illusion

In this experiment, we manipulated the presentation duration of the eggs illusion. To examine the magnitude of the illusion, we used the same method as in Experiment 1 of Qian and Mitsudo (2016). We manipulated the presentation duration in the range of 40 to 2,000 ms, according to previous research on the scintillating grid illusion (Schrauf et al., 2000). We predicted that the eggs illusion had similar temporal properties to those of the scintillating grid illusion and occurred under conditions of brief exposure.

Methods

Observers. Ten observers participated in Experiment 1a (eight men and two women; mean age = 29.9 years; $SD = 4.5$ years). All observers, with normal or corrected-to-normal visual acuity, were naïve to the purpose of the experiment. The experiments in this study were approved by the Ethics Committee for Psychological Studies in Institute of Decision Science for a Sustainable Society, Kyushu University, Japan (No. 2017/2–3). Written informed consent was provided by each participant at the beginning of the experiment.

Apparatus and stimuli. Stimuli were generated by a computer (Apple, Mac Pro, MB871J/A) and displayed on a 21-in. CRT monitor (EIZO, FlexScan F931, 1,152 × 870 pixels, 75 Hz). The experiment was conducted using MATLAB R2017a with Psychtoolbox (Brainard, 1997; Pelli, 1997). Observers viewed the monitor binocularly with a chin-and-forehead rest, at a viewing distance of 60 cm. The experiment was conducted in a darkened room.

The test stimulus consisted of a black background, a grid, and an array of perfectly circular white patches. The luminance values of the black background and the white patches were 1 cd/m^2 and 94 cd/m^2, respectively. The gray grid was composed of 11 horizontal and 11 vertical bars spaced equally (each bar subtended 25° × 35.4′ of visual angle). The distance between adjacent bars was 1.73°. Ten white circular patches with a diameter of 39.8′ were arranged on each bar. Each patch was positioned at the midpoint between the two adjacent intersections of the bars. All stimuli were drawn using the antialiasing method.

The luminance of the grid and the presentation duration of stimuli were varied as independent variables. The luminance of the grid was selected from 7, 13, and 28 cd/m^2, and the presentation duration of stimuli was selected from 40, 133, 280, 413, 693, 973, 1,400, and 2,000 ms. These parameter values were similar to those used in previous studies (Qian & Mitsudo, 2016; Schrauf et al., 2000).

The display for response consisted of a 9-point scale (Figure 2). Two circular patches with a diameter of 44.4′ and a luminance value of 94 cd/m^2 were presented under the leftmost point of the scale. Four different sets of elliptic patches were similarly presented under the third, fifth, seventh, and ninth points from the left of the scale. In a column, two elliptic patches had the same shape but were orthogonal to each other (i.e., vertically or horizontally oriented). All eight ellipses in the four sets had an identical minor-axis length of 44.4′ (the same as the diameter of the circular patches in the leftmost set). The major-axis lengths of the ellipses in the third, fifth, seventh, and ninth sets from the left were 48.0′, 50.4′, 54.0′, and 57.6′, respectively (corresponding to aspect ratios of 1.08, 1.14, 1.22, and 1.30).

Procedure. At the beginning of each trial, a black background was presented for 1 s, followed by a fixation cross (1.1° × 1.1° of visual angle, 94 cd/m^2) that was presented for 200 ms. After the presentation of the fixation cross, the test stimulus was presented for one of the eight durations (40–2,000 ms). Observers were instructed to view the stimulus without

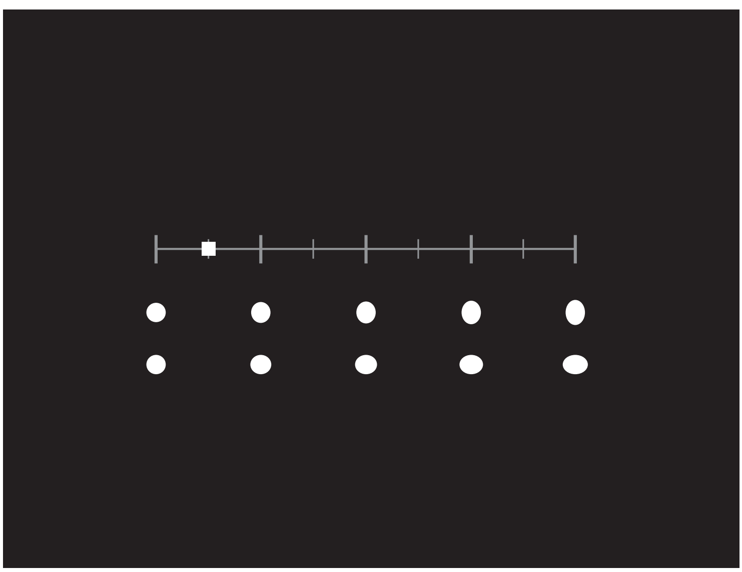

Figure 2. The response display of Experiment 1a. Observers were asked to make a judgment by moving the square indicator horizontally. Circular and elliptic patches under the response scale were references for the shape judgment.

keeping their eyes on a particular position, particularly when the presentation duration was long. After the disappearance of the test stimulus, a black-and-white random-dot pattern was displayed for 493 ms. The response display appeared after the disappearance of the random-dot mask. Observers were asked to choose the patch from the nine given options that was closest to the perceived shape of the patches in the test stimulus. If the patch shapes were perceptually different across locations, observers were instructed to choose the one closest to the averaged shape. The observers were not required to respond fast. The next trial automatically started 500 ms after observer's response.

Three levels of grid luminance and eight levels of presentation duration yielded 24 conditions. Each condition was tested 5 times. In total, 120 experimental trials were conducted in a randomized order. Approximately 10 practice trials were randomly selected from the 24 experimental conditions.

Results and Discussion

Figure 3 shows the perceived aspect ratios as a function of presentation duration averaged over the 10 observers in Experiment 1a, with three curves each for the three grid luminance values. A two-way within-participant analysis of variance (ANOVA) was performed on the mean aspect ratios, with the factors of grid luminance and presentation duration. We found significant main effects of grid luminance—$F(2, 18) = 35.303$, $p < .0001$, $\eta_p^2 = .797$—and presentation duration—$F(7, 63) = 5.162$, $p < .001$, $\eta_p^2 = .365$—and a significant interaction—$F(14, 126) = 8.15$, $p < .0001$, $\eta_p^2 = .475$. Tests of simple main effects revealed that the effect of the presentation duration was significant for all grid luminance conditions—7 cd/m^2: $F(7, 189) = 3.117$, $p < .005$; 13 cd/m^2: $F(7, 189) = 3.749$, $p < .001$; 28 cd/m^2: $F(7, 189) = 12.419$, $p < .0001$. The simple main effect of grid luminance was significant when the presentation duration was equal to or longer than 280 ms—40 ms: $F(2, 144) = 0.197$, $p = .822$; 133 ms: $F(2, 144) = 0.357$, $p = .7$; 280 ms: $F(2, 144) = 12.873$, $p < .0001$; 413 ms: $F(2, 144) = 28.425$, $p < .0001$; 693 ms: $F(2, 144) = 26.109$, $p < .0001$; 973 ms: $F(2, 144) = 40.463$, $p < .0001$, 1,400 ms: $F(2, 144) = 24.333$, $p < .0001$, 2,000 ms: $F(2, 144) = 20.143$, $p < .0001$.

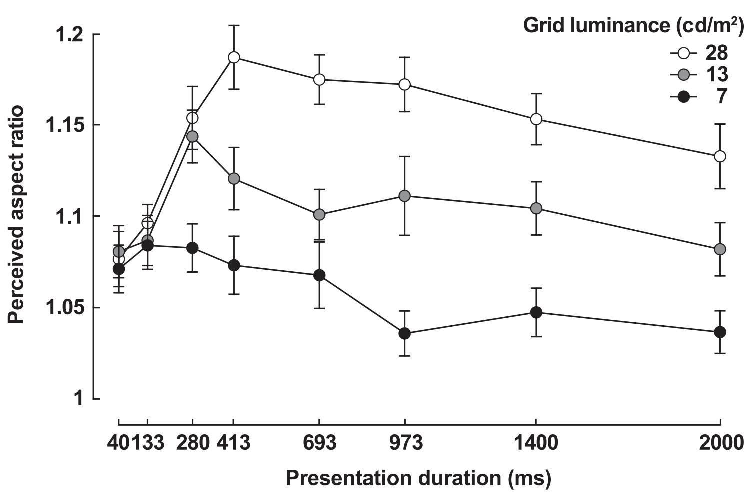

Figure 3. Results of Experiment 1a. The mean perceived aspect ratios of the patches, averaged over the 10 observers, are shown as a function of presentation duration. Error bars denote standard errors of the mean. A higher perceived aspect ratio indicates a stronger magnitude of the eggs illusion. *Note:* Please refer to the online version of the article to view the figures in colour.

Multiple comparisons with Ryan's method (Ryan, 1960) showed that perceived aspect ratios were significantly different for each pair of all grid-luminance combinations (*p*s < .001) and for seven pairs of presentation-duration combinations as follows: 40–280 ms, 40–413 ms, 40–693 ms, 133–280 ms, 133–413 ms, 280–2,000 ms, and 413–2,000 ms (*p*s < .05).

The present results found that both grid luminance and presentation duration affected the magnitude of the eggs illusion. The significant main effect of grid luminance is consistent with Qian and Mitsudo (2016), showing that a brighter grid made circular patches appear more elliptic. Furthermore, we found that the effect of grid luminance on the illusion interacted with presentation duration. For presentation durations equal to or shorter than 133 ms, no significant differences existed between the three levels of grid luminance. However, for presentation durations longer than 133 ms (i.e., 280–2,000 ms), the simple main effect of grid luminance was significant. The results of multiple comparisons suggest that the illusory deformation was almost saturated at a presentation duration of around 280 ms, because no significant differences were found between 280 ms and 413, 693, 973, or 1,400 ms. Under conditions with grid luminance values of 13 cd/m^2 and 28 cd/m^2, the illusory deformation was enhanced at short stimulus configurations (280 ms). A significant difference between 280 and 2,000 ms suggested that the illusion was weakened when the stimuli were presented for longer durations (a few seconds). Similar to the scintillating grid illusion, these results showed that the eggs illusion also occurs at brief presentations.

Furthermore, the values of perceived aspect ratio were evidently greater than 1, even at brief presentation durations of 40 and 133 ms. We questioned if the observers saw the illusion at short presentation durations of 40 and 133 ms. Our informal observations indicate that the illusion is imperceptible at very short presentations, and thus, we consider that the observers' settings obtained at 40 and 133 ms resulted from their common response bias against selecting the leftmost position of the response scale (i.e., a perfect circle). To address this issue, we conducted Experiment 1b using a cancellation method.

Experiment 1b: Cancellation of the Eggs Illusion Under Various Temporal Conditions

Based on the results of Experiment 1a, it was debatable whether the illusion disappeared under conditions of brief exposure ($\leq$133 ms) because the obtained values of the perceived aspect ratio were greater than 1. Therefore, to investigate whether such values were a result of a response bias, we used a cancellation method which has also been employed in Qian and Mitsudo (2016, Experiment 2). In this method, the perfectly circular small patches were replaced by ellipses with several aspect ratios relative to grid orientation. If the reported aspect ratios were related to a response bias, but not to the eggs illusion, the obtained aspect ratios will be less systematically influenced by the aspect ratio of the small patches in the test pattern.

Methods

The methods employed in Experiment 1a were used, except for those described here.

Observers. Sixteen observers participated in Experiment 1b (6 men and 10 women; mean age = 24.9 years; *SD* = 5.6 years). Of them, two took part in Experiment 1a as well.

Apparatus and stimuli. The luminance value of the grid was 28 cd/m^2, as it generated the strongest illusion in Experiment 1a. In the experiment, instead of manipulating the grid luminance, the aspect ratio of the white patches was altered as an experimental variable in

Experiment 1b. In addition to the perfect circle, elliptic patches were employed in Experiment 1b. The physical aspect ratio of the patches varied with respect to the local grid orientation, resulting in the following seven levels: 0.87, 0.91, 0.96, 1.00 (perfect circle), 1.05, 1.09, and 1.14. The diameter of the perfect circles was 39.8′. To control the patch size, the area of the patches was maintained constant across different patches as in Qian and Mitsudo (2016, Experiment 2). Regarding the elliptic patches, the lengths of the axis along the local grid orientation were 37.2′, 38.0′, 39.0′, 40.8′, 41.6′, and 42.5′, whereas the lengths of the other axis were 42.7′, 41.7′, 40.7′, 38.9′, 38.1′, and 37.4′, respectively. In addition to the patch shape, the presentation duration was also examined as the other experimental variable in Experiment 1b. Since the aim of Experiment 1b was to confirm the illusion under a brief stimulus exposure, we reduced the levels of presentation duration, yielding to the following three durations: 40, 280, and 693 ms.

For the response display, the nine-point scale used in Experiment 1a was changed to a 6-point scale. Under each point of the scale, there was a pair of sample patches with the same aspect ratio. Although the sample patches at the leftmost point of the scale were two perfect circles with a diameter of 39.8′, two ellipses with the same aspect ratio but with different orientations (longer vertical axis or longer horizontal axis) were located under each scale point between the second and the sixth scale points from the left end. The sizes (shorter × longer axes) of the five pairs of ellipses were 39.0′ × 40.8′, 38.0′ × 41.6′, 37.2′ × 42.5′, 36.4′ × 43.4′, and 35.4′ × 44.3′. Consequently, the corresponding aspect ratios of the sample patches were 1.00, 0.96, 0.91, 0.88, 0.84, and 0.80, respectively.

Procedure. Observers were asked to choose one of the six alternatives that was closest to the patches they perceived in the test stimulus. No feedback on response accuracy was provided. Three conditions of presentation durations were varied across blocks with five repetitions in a randomized order. Each block consisted of 21 trials (7 patch shapes × 3 repetitions), a total of 315 experimental trials (21 trials × 15 blocks) were tested for each observer.

Data analysis. To analyze how perceived patch shape is related to local grid orientation, we fitted data from different aspect ratios with a three-parameter Gaussian curve (mean, *SD*, and peak amplitude). The fitting procedure was the same as that used in Experiment 2 of Qian and Mitsudo (2016).

Results and Discussion

Figure 4 shows the perceived aspect ratios averaged over the 16 observers. A two-way within-participant ANOVA was conducted on the mean perceived aspect ratios with factors of presentation duration and patch aspect ratio. The results of ANOVA revealed significant main effects of presentation duration—$F(2, 30) = 62.442$, $p < .0001$, $\eta_p^2 = .806$—and patch aspect ratio—$F(6, 90) = 63.474$, $p < .0001$, $\eta_p^2 = .809$—and a significant interaction—$F(12, 180) = 16.995$, $p < .0001$, $\eta_p^2 = .531$. Tests of simple main effects showed that the effect of presentation duration was significant for all patch aspect ratios—0.87 aspect ratio: $F(2, 210) = 39.053$, $p < .0001$; 0.91 aspect ratio: $F(2, 210) = 16.391$, $p < .0001$; 0.96 aspect ratio: $F(2, 210) = 11.222$, $p < .0001$; 1.00 aspect ratio (perfect circle): $F(2, 210) = 28.897$, $p < .0001$; 1.05 aspect ratio: $F(2, 210) = 50.912$, $p < .0001$; 1.09 aspect ratio: $F(2, 210) = 70.713$, $p < .0001$; 1.14 aspect ratio: $F(2, 210) = 95.099$, $p < .0001$. The simple main effect of patch aspect ratio was significant for all presentation duration conditions—40 ms: $F(6, 270) = 3.427$, $p < .005$; 280 ms: $F(6, 270) = 46.541$, $p < .0001$; 693 ms: $F(6, 270) = 70.246$, $p < .0001$.

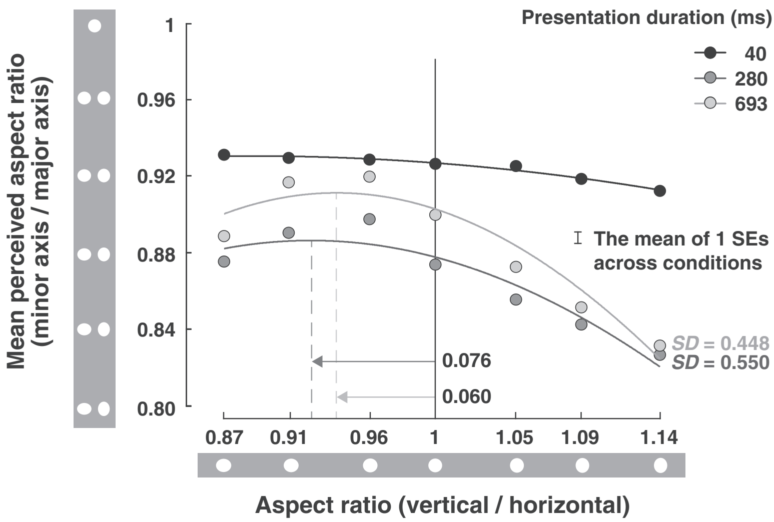

Figure 4. Results of Experiment 1b. The mean perceived aspect ratios averaged over the 16 observers are shown as a function of physical aspect ratio. Corresponding patch shapes are illustrated along the graph axes. Best-fitting Gaussian curves and amplitude peaks of each fitting curve are displayed in the graph.

To examine how the obtained aspect ratios were systematically related to the patch aspect ratio, a Gaussian function with three free parameters (i.e., the mean, *SD*, and peak amplitude) was fitted to the perceived aspect ratios. Because fitting was unstable or impossible for six observers in the 40-ms condition, we estimated the three parameters of the Gaussian curve for the 14 observers at presentation durations of 280 and 693 ms (fitting for data from two observers were excluded because of their unreliable fitting results). As shown in Figure 4, the mean values of the fitted Gaussian curve were shifted to smaller aspect ratios at presentation durations of 280 and 693 ms, suggesting that somewhat elongated patches were required to cancel or weaken the illusory eggs effect. The *SD* values of the Gaussian curve were comparable to those of Qian and Mitsudo (2016). These results generally replicated the results obtained at the 1-second presentation duration in Experiment 2 of Qian and Mitsudo (2016). In contrast to presentation durations of 280 and 693 ms, the results obtained at a presentation duration of 40 ms were almost flat and were relatively closer to the aspect ratio of 1.0 than those of 280 and 693 ms. This suggested that the observers provided almost a similar response, regardless of the different physical patch shapes. These results indicated that no eggs illusion occurred when the stimulus was presented for 40 ms, perhaps because the stimulus was almost invisible. Furthermore, a series of t tests with independent samples were performed to compare the best-fit values of amplitude, mean, and *SD* between durations of 280 and 693 ms. The results of t tests revealed a significant difference on amplitude—$t(26) = 3.48$, $p < .01$, Cohen's $d = 1.316$—and *SD*—$t(26) = 2.07$, $p < .05$, Cohen's $d = 0.781$. The mean values were not significantly different—$t(26) = 1.07$, $p = .29$, Cohen's $d = 0.404$, which is consistent with the results of multiple comparisons in Experiment 1a.

The significant interaction between grid luminance and presentation duration found in Experiments 1a and 1b suggested a possible interrelationship between spatial and temporal properties. To investigate the interaction further, and to thoroughly discuss orientation processing, we manipulated spatial configuration and presentation duration in the following experiments.

Experiment 2: The Eggs Illusion Produced by Bars

To determine the role of the orientation information provided by the grid and bars, in Experiment 2, we removed either horizontal or vertical bars in the grid configuration of the eggs pattern. Instead of grid luminance, we employed spatial configuration as an experimental factor. We tested three spatial configurations: horizontal bars only, vertical bars only, and both horizontal and vertical bars (i.e., the grid used in Experiment 1). We predicted that because orientation information is weakened in the horizontal-bars-only and vertical-bars-only configurations, the eggs illusion would be reduced in these conditions compared with the grid condition.

Methods

The methods were the same as those in Experiment 1a, except the following.

Observers. Ten observers participated in Experiment 2 (five men and five women; mean age = 30.3 years; $SD = 6.7$ years). Three of them also participated in Experiment 1a.

Apparatus and stimuli. For the test stimulus, the luminance value of the grid was 28 cd/m^2, which generated the strongest illusion in Experiment 1a. There were two experimental variables in Experiment 2: stimulus configuration and presentation duration. The stimulus configuration varied in three conditions: grid, horizontal, and vertical. In the grid condition, stimuli were identical to those used in Experiment 1a. In the horizontal condition, the 11 horizontal bars of the original grid and circular patches located on horizontal bars were presented. Similarly, in the vertical condition, the 11 vertical bars of the original grid and circular patches were presented. The numbers of bars and circular patches in the horizontal and vertical conditions were half of those in the grid condition. The presentation duration varied in eight conditions: 40, 67, 133, 213, 347, 493, 693, and 1,000 ms. Except for 40 ms, the values of the presentation durations were almost half of those in Experiment 1a, in an attempt to investigate the time course of the eggs illusion in more detail.

Procedure. In addition to the blank interval, the fixation cross remained on the screen during the time that the test stimulus was presented. To make the fixation cross salient in the test stimulus, the color of the fixation cross was changed from white to red. Observers were asked to view the fixation cross when it was presented, regardless of the presentation of the test stimulus. For each observer, a total of 120 experimental trials were conducted (3 stimulus configurations × 8 presentation durations × 5 repetitions).

Results and Discussion

Figure 5 shows the perceived aspect ratios as a function of presentation duration, averaged over the 10 observers in Experiment 2. We conducted a two-way within-participant ANOVA on the mean perceived aspect ratios, with factors of stimulus configuration and presentation duration. We found significant main effects of stimulus configuration—$F(2, 18) = 18.691$, $p < .0001$, $\eta_p^2 = .675$—and presentation duration—$F(7, 63) = 5.049$, $p < .001$, $\eta_p^2 = .359$—and a significant interaction—$F(14, 126) = 8.472$, $p < .0001$, $\eta_p^2 = .485$. Tests of simple main effects showed that the effect of presentation duration was significant for each stimulus configuration—grid: $F(7, 189) = 12.68$, $p < .0001$; horizontal: $F(7, 189) = 3.745$, $p < .001$; vertical: $F(7, 189) = 3.287$, $p < .005$. The simple main effect of stimulus configuration was significant when the presentation duration was equal to or longer than

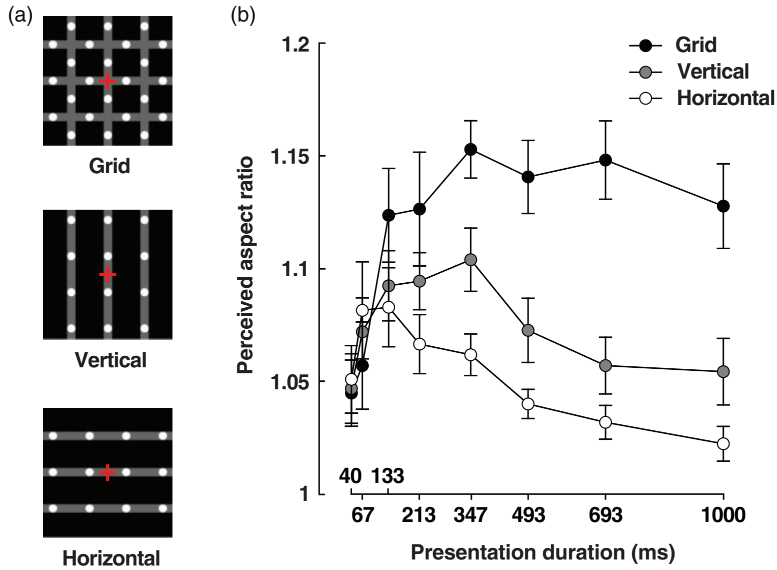

Figure 5. Stimuli and results for Experiment 2. (a) Schematic illustrations of test stimuli used in the grid, vertical, and horizontal conditions. (b) Results of Experiment 2. Mean perceived aspect ratios, averaged over the 10 observers, are shown as a function of presentation duration. Error bars denote standard errors of the mean.

133 ms—40 ms: $F(2, 144) = 0.075$, $p = .927$; 67 ms: $F(2, 144) = 1.182$, $p = .310$; 133 ms: $F(2, 144) = 3.537$, $p < .05$; 213 ms: $F(2, 144) = 6.96$, $p < .005$; 347 ms: $F(2, 144) = 16.143$, $p < .0001$; 493 ms: $F(2, 144) = 20.464$, $p < .0001$; 693 ms: $F(2, 144) = 29.053$, $p < .0001$, 1,000 ms: $F(2, 144) = 22.672$, $p < .0001$. Multiple comparisons showed that perceived aspect ratios were significantly different between the horizontal and grid conditions ($p < .0001$) and between the vertical and grid conditions ($p < .001$). There was no significant difference between the horizontal and vertical conditions ($p = .07$). Three pairs of presentation-duration combinations showed significant differences as follows: 40–133 ms, 40–213 ms, and 40–347 ms ($ps < .001$). Figure 5(b) shows that the illusion became weaker when stimuli were presented for more than 347 ms in the horizontal and vertical conditions. Results of multiple comparisons revealed that for the horizontal condition, the illusion significantly declined when the stimuli were presented for 1 s compared with stimulus presentations of 133 and 213 ms ($ps < .05$). A similar decline during the longer presentation was not significant in the vertical condition ($p > .05$). In contrast to the case of the grid condition, where the illusion was evident even at longer presentations, the illusory deformation generated by horizontal bars is likely to be more easily weakened by a prolonged presentation.

Figure 5(b) suggests that vertical bars might produce a stronger illusion than horizontal bars across long presentation durations. However, the multiple comparisons between the vertical and horizontal conditions revealed a significant difference between the two, only at a presentation duration of 347 ms ($p < .05$).

The results of Experiment 2 showed that horizontal or vertical bars could generate the illusory deformation under conditions of short stimulus presentations. A similar tendency of the reduced illusory effect at longer presentation durations was obtained in the 13-cd/m^2 grid condition of Experiment 1a, supporting the idea that the eggs illusion can be generated by a brief presentation. The illusory deformation generated by the horizontal or vertical bars was significantly weaker than that generated by a grid (containing both horizontal and vertical bars) at long presentation durations. However, this might be a result of the reduction of the number of the stimulus elements in both the horizontal and vertical conditions (i.e., half the number of gray bars and white patches). In Experiment 3, we controlled orientation information by keeping the number of the stimulus elements as constant as possible.

Experiment 3: Manipulating Bar Orientation

In Experiment 2, the illusory deformation generated by either the horizontal or vertical bars was found to be significantly weaker than that resulting from the original grid pattern. However, this reduction might not be associated with the orientation information itself because the number of the stimulus elements (i.e., patches and bars) in both the horizontal and vertical conditions was halved compared with that in the grid condition. In Experiment 3, we employed new stimulus patterns to manipulate orientation information quantitatively.

Methods

The methods employed in Experiment 1a were used, except the following.

Observers. Fifteen observers (six men and nine women; mean age = 25.1 years; SD = 5.7 years), who were recruited from Experiment 1b, participated in Experiment 3.

Stimuli and procedure. The luminance value of the grid was set at 28 cd/m^2, as this value generated the strongest illusion in Experiment 1a. To examine the illusory deformation at relatively short presentations, we used five levels of presentation duration: 40, 133, 280, 413, and 693 ms. The stimulus configuration was the other experimental variable, for which the following seven conditions were used: (a) grid, the same as that used in Experiment 1a with both horizontal and vertical bars; (b) horizontal, circular patches on horizontally oriented bars with the patch density and bar density virtually identical to those of the grid condition; (c) vertical, the pattern in which the horizontal condition was oriented 90°; (d) H60, horizontal bars and oblique bars oriented 60° relative to the horizontal bars; (e) H30, horizontal bars and oblique bars oriented 30° relative to the horizontal bars; (f) V60, vertical bars and oblique bars oriented 60° relative to the vertical bars; (g) V30, vertical bars and oblique bars oriented 30° relative to the vertical bars (see Figure 6).

With regard to the H60, H30, V60, and V30 conditions, the orientation of the oblique bars (clockwise or counterclockwise) was counterbalanced across trials. Each stimulus was presented through a circular aperture with a diameter of 12.4° to ensure the consistency of both the size and number of the stimulus elements constant across the seven stimulus configurations.

Each observer completed 140 experimental trials in a randomized order (7 stimulus configurations × 5 presentation durations × 4 repetitions).

Results and Discussion

Figure 6 shows the perceived aspect ratios separately for the seven stimulus configurations, averaged over the 15 observers. A two-way within-participant ANOVA was conducted on the mean perceived aspect ratios, with both the stimulus configuration and presentation duration as independent variables. We found significant main effects of stimulus

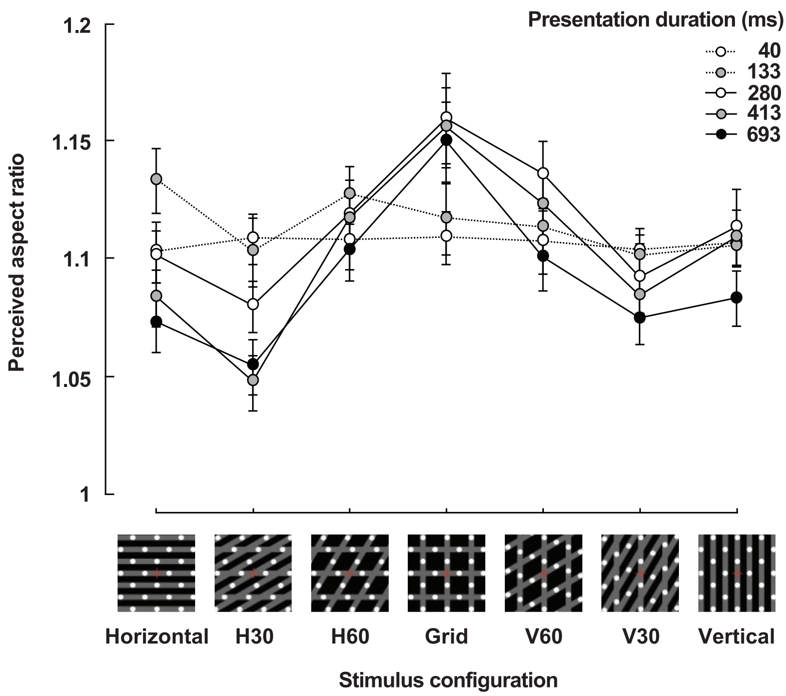

Figure 6. Schematic illustrations of the seven stimulus configurations and the results of Experiment 3. Mean perceived aspect ratios, averaged over the 15 observers, are shown separately for the seven stimulus configurations. The error bars denote the standard errors of the mean. *Note:* Please refer to the online version of the article to view the figures in colour.

configuration—$F(6, 84) = 7.290$, $p < .0001$, $\eta_p^2 = .342$—and presentation duration—$F(4, 56) = 4.489$, $p < .005$, $\eta_p^2 = .243$—and a significant interaction between the two factors—$F(24, 336) = 3.439$, $p < .0001$, $\eta_p^2 = .197$. The simple main effects of presentation duration was significant for the grid, horizontal, and H30 conditions—grid: $F(4, 392) = 5.866$, $p < .001$; horizontal: $F(4, 392) = 5.071$, $p < .001$; vertical: $F(4, 392) = 1.504$, $p = .200$; H60: $F(4, 392) = 0.935$, $p = .444$; H30: $F(4, 392) = 8.083$, $p < .0001$; V60: $F(4, 392) = 2.038$, $p = .088$; V30: $F(4, 392) = 1.559$, $p = .184$. The simple main effect of stimulus configuration was significant when the presentation duration was equal to or longer than 280 ms—40 ms: $F(6, 420) = 0.047$, $p = 1.000$; 133 ms: $F(6, 420) = 1.282$, $p = .264$; 280 ms: $F(6, 420) = 6.099$, $p < .0001$; 413 ms: $F(6, 420) = 10.058$, $p < .0001$; 693 ms: $F(6, 420) = 7.974$, $p < .0001$.

As described earlier, the simple main effect of presentation duration was significant in both the horizontal and H30 conditions, although the same was not found for the vertical or V30 condition. Considering that these conditions had almost the same configuration except for the orientation, it was implied that the presentation of the horizontal bars plays an important role in inducing the eggs illusion. However, multiple comparisons based on Ryan's method (Ryan, 1960) showed slightly inconsistent evidence, in that a lack of significant differences was found between the following conditions: horizontal versus vertical, H60 versus V60, and H30 versus V30 ($ps > .05$). These results suggest that perceived deformation is similar between the horizontal and vertical configurations when taking into account for presentation duration.

Multiple comparisons for the main effect of stimulus configuration with Ryan's method revealed a significant difference for pairs of grid-horizontal, grid-vertical, grid-H30, grid-V30, H30-V60, and H30-H60 (*p*s < .05). They were as follows: (a) pairs of grid-horizontal, grid-vertical, grid-H30, grid-V30, and H30-V60 at a presentation duration of 280 ms (*p*s < .05); (b) pairs of grid-horizontal, grid-vertical, grid-H30, grid-V30, H30-V60, H30-vertical, and H30-H60 at a presentation duration of 413 ms (*p*s < .05); and (c) pairs of grid and all other conditions, and the H30-V60 and H30-H60 pairs, at a presentation duration of 693 ms (*p*s < .05). These results suggested that the differences between the grid and H30/V30 conditions and between the grid and horizontal/vertical conditions were more evident than those between the grid and H60/V60 conditions. These findings provided evidence of a gradual decrease of the illusory effect in the following order: grid (orthogonal), H60/V60, H30/V30, and horizontal/vertical conditions.

Similar to Experiment 2, Figure 6 suggests that the illusion generated by the vertical condition might be stronger than that generated by the horizontal condition. However, the multiple comparisons between the horizontal and vertical conditions did not reveal any significant difference between the two at each presentation duration.

In Experiment 3, we replicated the differential illusory magnitude found between the grid and bar conditions of Experiment 2 and further clarified that the difference resulted from the change in orientation information, but not from the density and number of stimulus elements.

General Discussion

This study examined the role of orientation information in the eggs illusion, by manipulating various spatiotemporal stimulus parameters. In Experiment 1a, we replicated Qian and Mitsudo's (2016) results, which showed that the eggs illusion was affected by grid luminance, and found a significant effect of presentation duration on this illusion. In Experiment 1b, by using a cancellation method, we found that the illusion occurred when presentation duration was equal to or longer than 280 ms. In Experiment 2, we clarified the significant effect of spatial configuration in the eggs illusion and significant interaction between spatial configuration and presentation duration. In Experiment 3, we systematically explored the orientation information and demonstrated the significant interaction between orientation information and presentation duration. Orientation information was demonstrated as an important factor that influenced the magnitude of the eggs illusion.

Roles of Relative Orientation Information and Local Orientation Information

To explain the results of the three experiments, we introduce two types of orientation information. We define the orientation signals provided by orthogonally arranged bars as *relative* orientation information. Relative orientation information is typically provided by the grid and does not exist in the horizontal or vertical condition in Experiments 2 and 3, because all bars in these conditions were parallel to each other. The other type of orientation information is *local* orientation information, which refers to the orientation information around and close to the white patches. Local orientation information exists in all conditions used in this study.

Although the local orientation information was previously proposed as an important factor for the generation of the eggs illusion (Qian & Mitsudo, 2016), the function of relative orientation information was revealed in this study for the first time. In Experiment 2, long stimulus presentations ($\geq$347 ms) weakened the illusion when the grid was replaced by either horizontal or vertical bars. Because Experiment 3 demonstrated that the results were the same as those of the horizontal and vertical conditions while the numbers of patches and bars were controlled, we speculate that a decline in the illusion under the horizontal and vertical conditions of Experiment 2 is because of a lack of relative orientation information. Considering that the relative orientation is important for the illusion, the illusory deformation would not be reduced by changing the number and density of stimulus elements. This idea coincides with the results obtained in all the three experiments in this study: Stimulus configurations in which sufficient relative orientation information was presented, such as in those of Experiment 1 and in the grid condition of Experiments 2 and 3, produced a strong illusory effect when the presentation duration was relatively long. The systematic manipulation of the relative orientation in Experiment 3 provided more conclusive evidence on the importance of relative orientation information. That is, when changing the relative angle between horizontal and vertical bars from 90° (orthogonal, i.e., the grid condition) to 60°, 30°, and 0° (parallel to each other, i.e., the horizontal and vertical conditions), we found a somewhat nonlinear change in the strength of the eggs illusion (Figure 6). Consequently, it was found that both relative and local orientation information contribute to the eggs illusion.

A reviewer asked us to consider the relation between the eggs illusion and the Helmholtz (1867) irradiation illusion. In the irradiation illusion, a white object on a black background is perceived as larger than a black object on a white background. There are two features in the irradiation illusion. First, the white and black objects differ in contrast polarity along their edges. However, in the eggs illusion, each white patch (perceived to be deformed) has no polarity reversal relative to the gray bar and black background. Therefore, the eggs illusion seems to differ from the irradiation illusion in terms of contrast polarity. Second, the two objects in the irradiation pattern differ in luminance contrast. In a later study, van Erning et al. (1988) systematically investigated the effect of edge contrast on perceived size and found that an object is perceived larger as the contrast increases. The eggs illusion might be partly due to the irradiation illusion, because each white patch in the eggs pattern is surrounded by four areas with different luminance values (gray and black). The contrast between the white patch and black background is higher than that between the white patch and gray bar. Accordingly, the white patches might be perceived to expand in the direction orthogonal to the gray bars. If the eggs illusion occurs entirely on the basis of the irradiation illusion, perceived deformation would be similar between both grid and bar conditions. However, as demonstrated in Experiments 2 and 3, the illusory deformation was much larger in the grid condition than in the bar conditions. A larger magnitude of the eggs illusion in the grid condition can be well explained by the contribution of the relative orientation information. Therefore, the present data support Qian and Mitsudo's (2016) view that the eggs illusion is distinguished from the Helmholtz irradiation illusion.

Temporal Properties of the Eggs Illusion

By exploring the orientation processing, temporal properties of the eggs illusion have also been clarified. The results of duration manipulations in the present research revealed two temporal characteristics of the eggs illusion. Across all the experiments, the illusion occurred under conditions of brief stimulus presentations (approximately 200–300 ms), steeply increasing in conditions of very brief duration (approximately 200 ms). Such a steep increase was observed in all the conditions across the three experiments and was considered as a representation of the deformed shape under conditions of brief presentation. In contrast, at longer presentation durations (approximately 1,000–2,000 ms), the strength of the illusion remained high, without a significant reduction from the steep increase, for most configurations across the three experiments, except for the horizontal and vertical conditions in

Experiment 2, in which the illusion was significantly weakened at long presentation durations. To explain why the illusory effects generated by horizontal or vertical bars could not be maintained at longer presentation durations, we noticed the lack of relative orientation in the horizontal and vertical conditions. The relative orientation information provided by orthogonal bars seems to be indispensable for the eggs illusion under longer presentations. This is important evidence that the interaction between processing of spatial and temporal information is effective in modulating the eggs illusion.

Comparing the Eggs Illusion With the Scintillating Grid Illusion

As mentioned in the Introduction section, the eggs illusion and scintillating grid illusion are influenced by both grid luminance and patch size. In this study, we found three new common features shared by the two illusions.

First, the magnitude of the illusions varied as a function of presentation duration in a similar way. Neither the eggs illusion nor the scintillating grid illusion was evident when the presentation duration was less than 100 ms; it then increased steeply and became strongest at presentation durations of around 200 to 300 ms. Schrauf et al. (2000) and the results of the 28-cd/m^2 grid condition of Experiment 1 suggest that the illusions occur until the presentation duration was increased up to 1 second. Based on these similarities, we propose that the eggs and scintillating grid illusions shared features in the temporal domain.

Second, horizontal or vertical bars placed parallel to each other produced both illusory effects in some conditions; however, the effect was significantly weaker in the parallel bar configurations than in the original grid configuration (Qian et al., 2010 and this study). A reduction in relative orientation information was considered a reason for a decrease in the scintillating grid illusion with parallel bar configurations (Qian et al., 2010). Nevertheless, distinguishing the local orientation information from the relative one was difficult in the scintillating grid illusion because both were located at the intersections in the grid. In contrast, we were able to separately assess the two types of information in the eggs illusion, as the circular patches were not located at the intersection of the grid. The results of Experiment 3 showed that the decline in the parallel bar conditions resulted from the lack of relative orientation, not from the reduction of the number and density of stimulus elements.

In Experiments 2 and 3, we noted a subtle anisotropic effect with regard to the bar orientation on the eggs illusion, in which vertical bars tended to produce a stronger deformation than horizontal bars. Interestingly, a similar vertical superiority effect was also observed in the scintillating grid illusion, since Qian et al. (2010) reported that vertical bars generated a slightly stronger scintillating effect than horizontal bars (their results were also not statistically significant). Although the exact reason for these anisotropic effects remains unclear, these data appear to highlight another common feature between the eggs and scintillating grid illusions.

Third, relative orientation information seems to play a role in both the eggs and scintillating grid illusions. Qian et al. (2012) showed that the magnitude of the scintillating grid illusion was stable if the relative orientation around an intersection of the grid was unchanged, even when the relative positions of the intersections were randomly displaced with respect to each other. As discussed in this section, the magnitude of the eggs illusion remained constant around long presentation durations ($\geq$347 ms) as long as the orthogonal bars were presented. Altogether, these results provide further evidence for the similarities between the eggs illusion and scintillating grid illusion.

Future Directions

Further investigation is necessary to resolve several unsettled issues. First, the interaction between processing of spatial and temporal information on the eggs illusion should be investigated in detail, with prospects for a possible neurophysiological mechanism of the eggs illusion. Second, the similarities between the eggs illusion and scintillating grid illusion should be investigated in more detail, to determine the possible common mechanism underlying both illusions. Referring to previous research on the scintillating grid illusion, the relationship between the retinal position (foveal and peripheral) and magnitude of the illusion should be systematically examined in future.

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