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The bumpy circle illusion: apparent shape-distortion of filled circles placed on a checkered pattern

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Abstract

A new visual illusion in which circles placed on the checkered-pattern background appear to be polygons is reported. In this article, we first demonstrated that the apparent distortion of circles in this 'bumpy circle illusion (BCI)' depends on the luminance difference between the circles and the components of the background. Then, with the aim of clarifying the mechanism that causes this phenomenon, the 'low-pass filtering theory' the 'segmentation theory', the 'corner effect theory', and the 'completion theory' were investigated. As a result, the low-pass filtering theory and the completion theory were rejected because they predicted the occurrence of the illusion in some modulated BCI figures that produced no illusion. The 'segmentation theory', which postulated that the same mechanism as in the curvature blindness illusion produces BCI, was also rejected because the same luminance assignment as for BCI image components does not produce the curvature blindness illusion. In addition, the curvature of lines appears to deform in the curvature blindness illusion, whereas the BCI does not produce an illusion of line circles, which also shows the difference between the two phenomena. The 'corner effect theory' is the most promising because it correctly predicts (1) how the apparent distortion of the circles appears and (2) the presence/absence of illusion with the outline circles depending on the checkerboard luminance alteration cycles inside and outside of the circles. However, the corner effect theory can only be justified if it is assumed that the strength of the effect is different depending on whether the checkered pattern is applied to the inside or outside of the circles. Whether such asymmetry does exist and the reason why the asymmetry occurs needs further investigation.

Keywords: *curvature*; *luminance difference*; *shape perception*; *perceptual organization*; *convexity bias*

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Many visual illusions of shape deformation (i.e. apparent changes in line orientation and contour shape) are triggered by the difference in luminance between the figure and its background. Classically, the café wall illusion (Fraser, 1908; Gregory & Heard, 1979) may be the best-known example of this type of phenomenon, and new discoveries have been continued over the past ten years or so. For example, the jaggy diamond illusion (Kawabe et al., 2010) is a phenomenon in which diamonds placed at the intersections of grids appear to have jaggy illusory 'thorns'; the eggs illusion (Qian & Mitsudo, 2016, 2019, 2020) is a phenomenon in which white circles located at the midpoint of the intersection of grids on a black background appears to be deformed into ellipses; the curvature blindness illusion (Takahashi, 2017) is a phenomenon in which smooth sinusoidal curves, which have abrupt luminance change at the peak of the curve, appear to be triangular corrugated zig-zag lines; Kite mesh illusion is an illusion in which the edges of kite-like rhombus appears to bend inward depending on the luminance of the figure outlines and their background (Bertamini & Kitaoka, 2018; Oppel, 1855). Although these illusions are similar in terms of their phenomenological appearance, their mechanisms have been considered to be the function of different levels of visual information processing. Studying illusions that span these multiple mechanisms will

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contribute to our understanding of how the hierarchical shape perception mechanisms are integrated.

This article reports a new illusion that also appears to be caused by the difference in luminance between the figure and its background. This illusion consists of a checkered pattern of dark grey and light-grey colour, on which the apparent shapes of equally spaced circles are deformed, typically appearing to be polygons with rounded corners with their vertices pointing in various directions (Fig. 1). This illusion was discovered when one of the authors (MI), who is a filmmaker, was creating materials to be used in video production on Adobe Illustrator (3rd prize in the 10th visual illusion and auditory illusion contest in Japan http://www.psy.ritsumei.ac.jp/~akitaoka/sakkon/sakkon2018.html). This phenomenon is henceforth referred to as the 'bumpy circle illusion (BCI)'.

Illusory effect of the bumpy circle illusion

The shape of circles in Fig. 1 may seem to be randomly deformed; for example, the vertex of 'polygons' is oriented in various directions. Careful observation, however, reveals that the distortion of the circles is not random and depends on the luminance difference between circles and adjacent background regions. Let us focus on the uppermost eight circles in Fig. 2a. To most people, the leftmost circle in this figure looks like a hexagon with its top vertex slightly tilted counterclockwise, while the rightmost circle looks like a hexagon with its top vertex slightly tilted clockwise. You may notice that the alternation of lightness and darkness of the checked pattern under the outline of the left circle and the right circle is shifted by half a cycle. The distortion of the asymmetric shape of the two circles can be attributed to the asymmetry of the luminance variation around the circles. In other words, the apparent randomness of the distortion in Fig. 1 is probably due to the irregular overlapping of the circles and their background pattern. This view is supported by the fact that the orientation of all the 'hexagons' appear to be reversed when the alternating cycles of light and dark in the background are inverted to that of Fig. 2a (Fig. 2b) or when all the circles are painted with white instead of black (Fig. 2c). Furthermore, when circles are aligned to cover the checkered pattern in the same way (for instance, in Fig. 2d, we modified the space between the circles so that the pattern covered by each circle is identical), those circles will distort into the

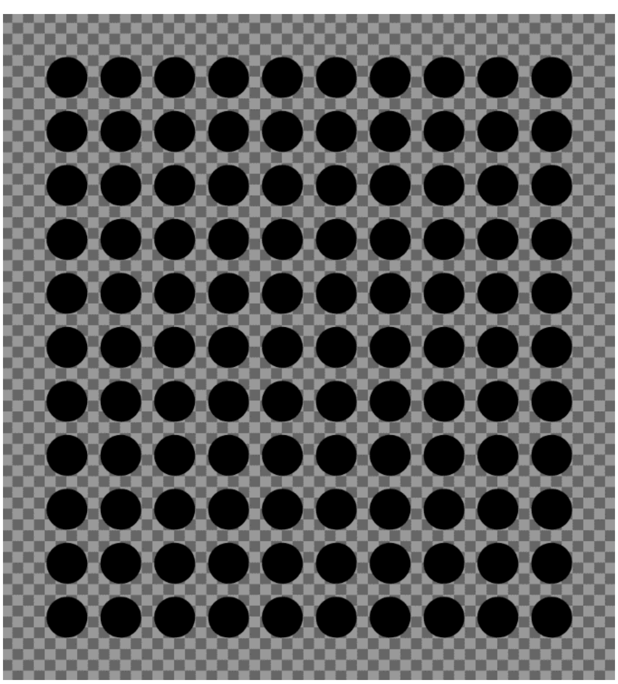

Fig. 1. The *bumpy circle illusion* (Ishikawa, 2018). The shapes of the equally spaced filled black circles on the checkered pattern appear deformed, typically as polygons with vertices pointing in various directions.

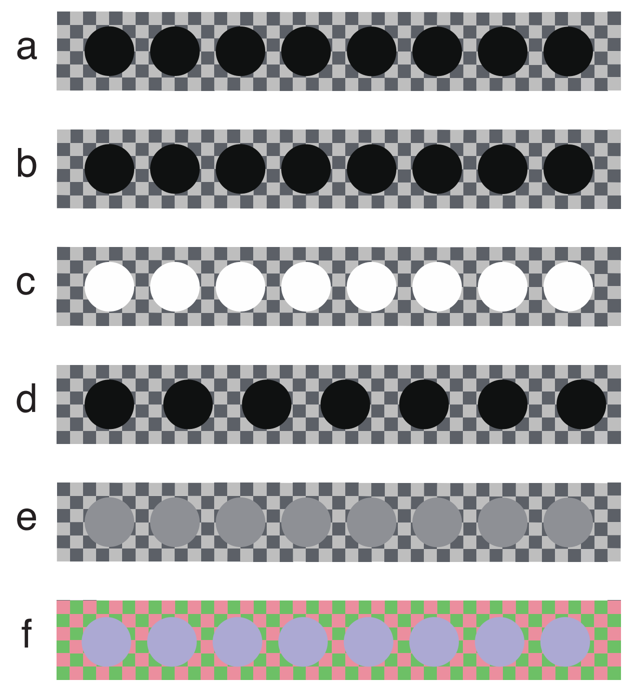

Fig. 2. Effect of the luminance difference between the circles and background on the apparent shape deformation. (a) and (b) The BCI basic figure. It can be seen that reversing the light-dark alternation cycle of the background checkered-pattern reverses the apparent tilt of the 'hexagons'. (c) The colour of the circle in Fig. 2a is replaced by white. The apparent distortion of the circle (the direction of the apparent hexagonal tilt) is opposite to that of Fig. 2a. (d) Figure with circles arranged so that the background light-dark alternating cycle is equal for all circles. In this case, all circles appear to transform into 'hexagons' of the same shape. The illusion disappeared (e) when disks are coloured grey with a luminance level in between the two grey levels of the background, or (f) if the circles and background checker pattern are drawn with equal luminance (the equiluminant figure was made with the online tool http://www.psy.ritsumei.ac.jp/~akitaoka/JavaScript-paint_color01L.html).

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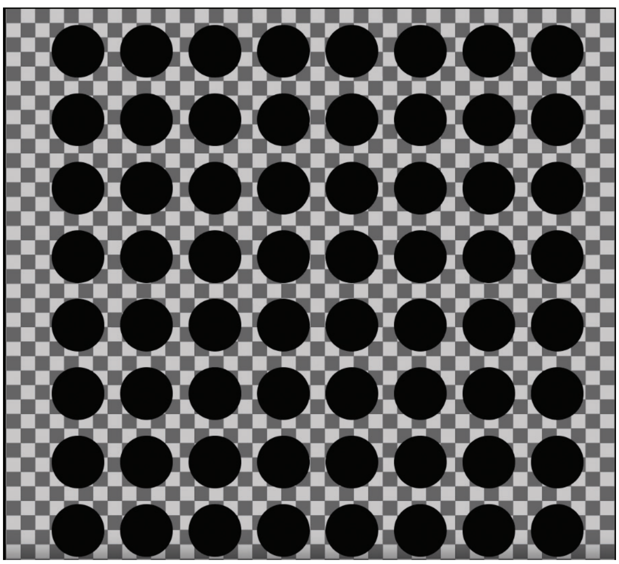
same shape. The illusion does not appear when disks are coloured grey with a level in between the two grey levels of the background (Fig. 2e) or in the figure with equal luminance (Fig. 2f), supporting the view that the luminance difference between the circles and background elements determines the way of apparent shape distortion. In addition, when the background checkerboard is rotated with respect to the stationary circle elements, the contours of the circles themselves appear to undulate while changing their shape, again suggesting that the luminance difference determines the appearance of the circle shape (Movie 1).



Movie 1. When the background checker pattern is rotated, the contours of the circles transform into polygons that appear to wiggle.

The BCI is effective enough even in the central vision. For example, in Figs 2a–d, the distorted shape will be seen no matter which of the circles is fixated. However, the effect of the illusion seems affected by the visual angle size. If you look at a closer distance, it becomes clear that the angular-looking shape is a circle.

Visual angle size interacts with retinal eccentricity in the occurrence of illusion. This interaction is demonstrated in Fig. 3. For example, fixate the leftmost circle in the top row in this figure. At the certain viewing distance where the illusion clearly appears in this circle, there seems to be no difference in the strength of the illusion between the foveal and peripheral circles. However, when the leftmost circle in the middle or bottom row is viewed in the central vision at the same viewing distance, the illusion will be weakened or disappear, while the illusion is observed in the peripheral circles.

The aforementioned is based on the observations of several observers including the authors and it is expected that there are individual differences in the effect. The interaction between visual angle size and presentation position (retinal eccentricity) will need to be quantitatively confirmed.

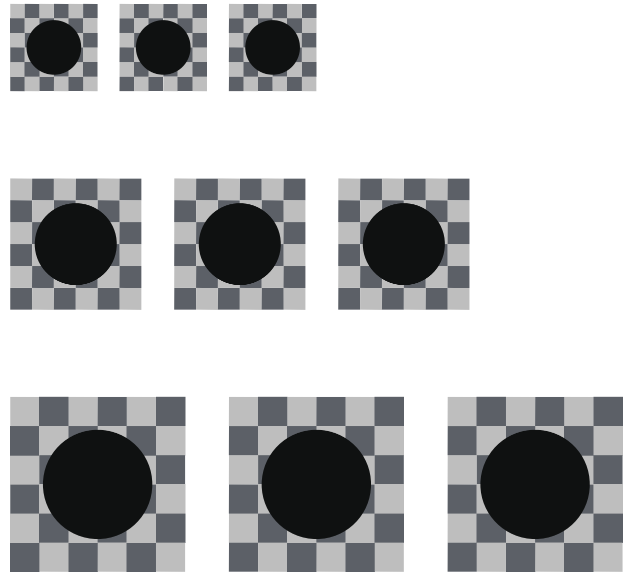


Fig. 3. Effect of the retinal image size and eccentricity on the apparent shape deformation. When the upper leftmost image is observed at an appropriate viewing distance, the illusion is clearly visible even in the central vision, and the illusion strength is not different between the central and peripheral vision. When the leftmost image in the lower row is observed in the central vision at the same viewing distance, the illusion is significantly weakened. With the larger figures, the illusion seems to be more apparent in the peripheral vision.

This article will henceforth discuss the mechanisms of BCI on the basis of previous studies that also consider the shape illusion caused by the luminance arrangement of the visual images. The four specific mechanisms examined are (1) the lower spatial-frequency-components (Ginsburg, 1986; Ginsburg & Evans, 1979), (2) the segmentation of the figure caused by the luminance difference (Anderson & Burr, 2018), (3) the 'corner effect' which has been considered to be responsible for the Café wall illusion and related phenomena (Kitaoka, 1998), and (4) the visual completion.

Examination of the explanation based on low-pass filtering

Perhaps the most straightforward and naïve explanation of BCI is that the illusion is caused by the circle's colour intruding into the background where the colour (luminance) difference between the circle and background elements is small. The idea is that, for example, the boundary between the circle and the background elements is ambiguous where the difference in luminance between them is small, whereas their boundary is clear where the difference

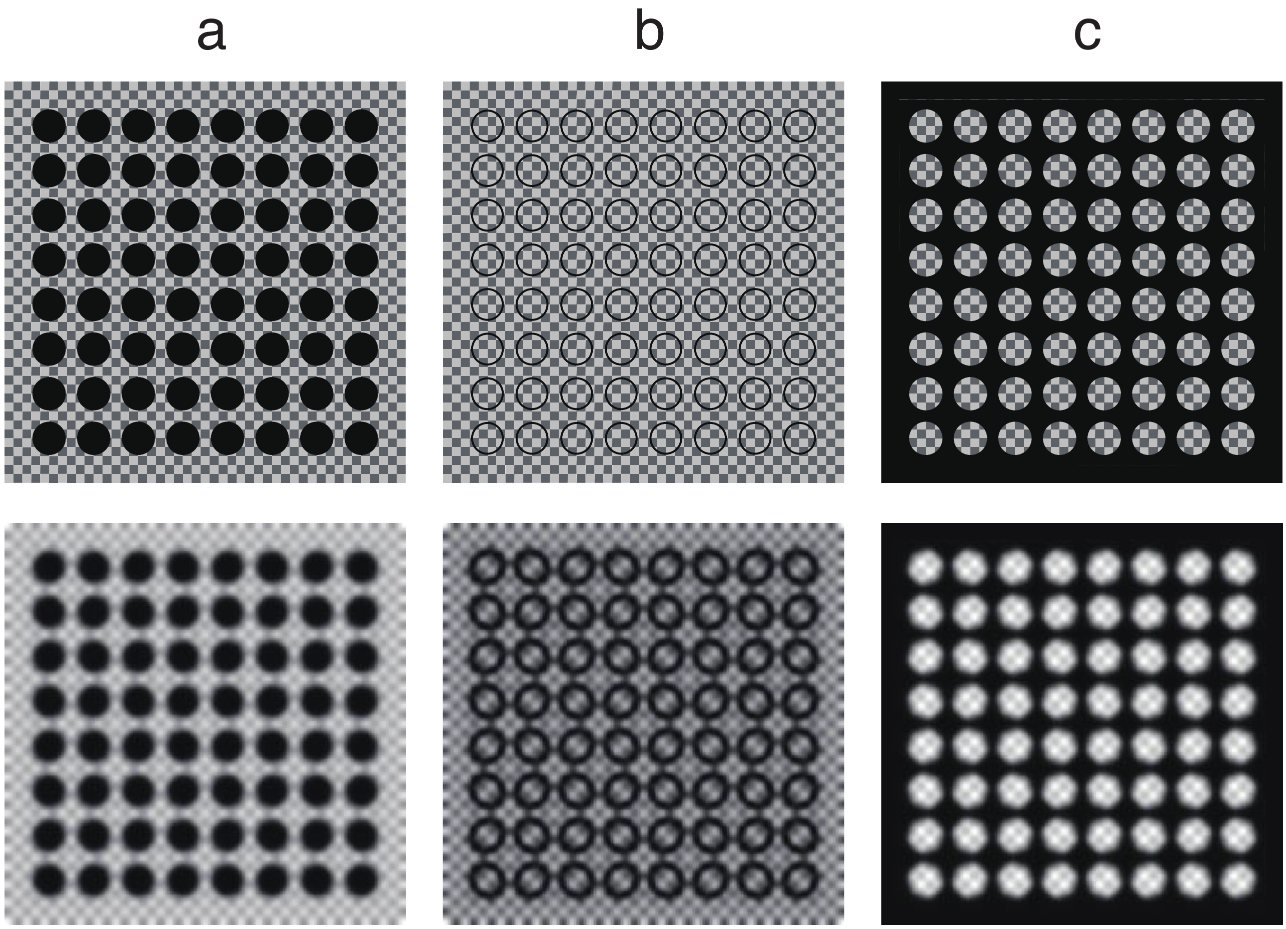


Fig. 4. Upper row: (a) original figure of BCI, (b) filled circles replaced by line circles in the original figure. (c) 'checkered-circles' variation. Lower row: (a)–(c) with the same low pass filter applied. Circle distortion is observed in all low-pass filtered figures in a–c, but such distortion (illusory effect) is not seen in the unfiltered (top) images in column b and column c.

in luminance between them is large, resulting in the contours of the circles appearing bumpy.

The possible mechanism that could produce such an appearance may be optical blur (e.g. Coren et al., 1978; Ward & Coren, 1976) or perception that depends on the lower-spatial-frequency channel (Carrasco et al., 1986; Ginsburg, 1986; Ginsburg & Evans, 1979, but see also Carlson et al., 1984), both of which have been applied to explain several visual illusions. The explanation based on such mechanisms assumes that some kind of illusion is due primarily to lower spatial-frequency components of the retinal image. To evaluate this explanation, a low-pass filter[1] was applied to the basic figure of the BCI (Fig. 4a).

We found that the low-pass filter theory is insufficient as an explanatory principle for BCI, as it does not predict the disappearance of the illusion after a certain manipulation is applied to the basic illusion figure. The low-pass filtered figure (bottom of Fig. 4a) does show deformed circles, but the filtered deformations do not match with the appearance of the illusion (top of Fig. 4a); that is, the apparent orientation of the illusory hexagon's vertices is opposite to the blurry hexagons in the filtered image. In addition, as shown in Figs 4b and 4c, the illusory shape deformation of circles disappears when the filled circles are replaced by outline circles (top of Fig. 4b) or redrawn with the circles having a checkered pattern and the background painted with a uniform luminance (top of Fig. 4c). However, when the low-pass filter was applied to these images, the resulting blurred images showed deformed shapes of circles (bottom of Fig. 4b and 4c). That means optical blur or perception based on a low spatial frequency component would predict that both the outline circles figure (Fig. 4b) and the 'checkered circles' versions of a figure (Fig. 4c) would also produce the illusion, which is not the case. The absence of illusion in these figures cannot be

[1]Low-pass filtering was performed using the R script provided by Dr Hiroyuki Tsuda (https://htsuda.net/archives/2096). A low-pass filter of the same intensity was applied to all figures, filtering out the frequency component higher than around ten cycle per image (all images were set at 512 × 512 pixels). The specific parameter settings are as follows: freqFilter(img, scheme = "lowpass", cyclePerImage = 10, smoothing = T).

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explained by optical blur or the output of low spatial frequency channels.

Comparison with the curvature blindness illusion

The phenomenon apparently most similar to BCI might be the curvature blindness illusion (Takahashi, 2017), in the sense that physically smooth curvy lines appear to be non-smooth zigzag lines. At first glance, the curvature blindness and BCI have the following major differences: In the original figure of the curvature blindness illusion (Fig. 5a), curvy lines themselves have a luminance change, whereas in the BCI the luminance change is happening on the background, not on the figures with curvy contour (i.e. circles are uniform black). However, we found that the curvature blindness can be observed by the background luminance change instead of the luminance change in curved lines per se (Fig. 5b; As far as we know, this variation of the curvature blindness illusion has not been published anywhere). It would be, therefore, worth considering whether the common mechanism produces the curvature blindness illusion and BCI.

Takahashi explains the curvature blindness illusion by assuming the function of a lower curvature detector that depends on the luminance contrast polarity. This explanation is based on the ordinal view of visual curvature detection (e.g. Loffler, 2008); that is, the local orientation detection is first performed by neurons in the small receptive field (e.g. in V1), and the curve is perceived by integrating their outputs by the higher 'curvature detector' (e.g. in V2~V4). Takahashi suggested that the integration of local orientation is disrupted by the abrupt changes of the contrast polarity in the curvy lines and that induces the appearance of angular lines. This explanation is consistent with reports that the mechanisms involved in the perception of curvature are sensitive to the luminance contrast polarity (e.g. Bell et al., 2011; Gheorghiu & Kingdom, 2006). However, since in the BCI figure there is no abrupt change in contrast polarity between the circles and their background (i.e. the luminance of the circles is always lower than the luminance of the background), Takahashi's explanation of curvature blindness illusion is not applicable to BCI.

Anderson and Burr (2018) later suggested that the segmentation of the curved line by the luminance change, not contrast polarity, produces the curvature blindness illusion. According to their explanation, the illusion is caused by the segmentation process induced by the abrupt luminance change along the sine curve. Suppose the line is segmented between the peak and the trough of the sine wave. In that case, the segment will be treated as a straight line, and the junction neighbouring those two 'straight lines' is perceived as an angular corner (i.e. the curvature blindness illusion occurs). In contrast, if the segment includes a curvy part of the sine wave, that appears to be an arc of a circle (i.e. no illusion is produced). If their theory is correct, changes in contrast polarity are not essential for the occurrence of curvature blindness. Indeed, they have shown that curvature blindness also occurs in curves with no change in contrast polarity relative to the background (i.e. line luminance is always high or low relative to the background; Figure 2B in Anderson & Burr, 2018).

The 'segmentation hypothesis' is also applicable to a variant of the curvature blindness illusion we devised (Fig. 5b); that is, if the difference of background luminance indirectly segments part of the curved line and if the segmentation occurs between the peak and the trough of the sinusoid (i.e. the segment can be approximated as the straight line), the illusion is produced; conversely, if the segment includes the curvy part of the sine wave, the illusion is not produced. A similar explanation seems to be applicable to BCI. That is, the segmentation of the circle contour by the background luminance change may give the circle an angular appearance.

So, would the segmentation hypothesis explain BCI? An essential part of this theory seems to be whether the image components have enough luminance difference that sufficiently causes image segmentation. Thus, if the two illusions are caused by the same 'segmentation' mechanism, the curvy lines in Fig. 5b should be sufficiently segmented by the same luminance difference as the BCI original figure (Fig 1) to produce curvature blindness. Figure 5c shows the variant of Fig. 5b, where stimuli and background luminance are aligned with those of the BCI;

a

b

c

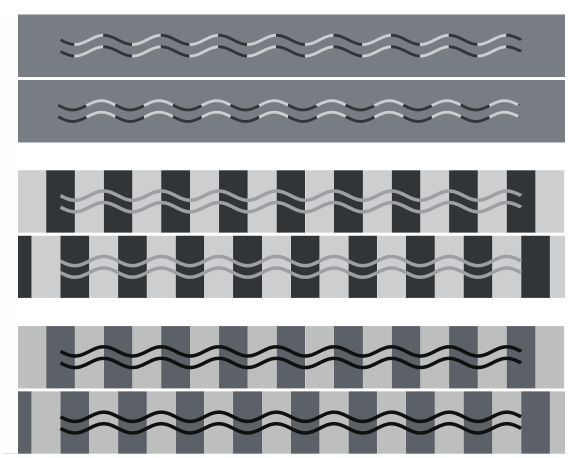

Fig. 5. The curvature blindness illusion (Takahashi, 2017) and its variations. (a) The original curvature blindness illusion. (b) The luminance change is added to the background instead of curved lines per se. This variant also produces the same strength illusion as the original figure. (c) The variation of Fig. 4b, in which stimuli and background luminance are aligned with those of the BCI original figure; that is, the luminance of the lines is the same black as the circles in BCI, and the luminance of the background is aligned with the elements of the checkered pattern in BCI, respectively. The illusion disappears in this figure.

that is, the luminance of the lines is the same black as the circles in BCI, and the luminance of the background is aligned with the elements of the checkered pattern in BCI, respectively. This figure clearly shows no illusion.

This demonstration may have made the difference between BCI and the curvature blindness illusion more evident. Luminance arrangements that produce BCI, that is, when the luminance of the curvy line is lower than the background luminance levels, do not produce curvature blindness. Conversely, it was also confirmed that luminance arrangements that produce curvature blindness do not produce BCI: in the figure shown in Fig. 2e, where the luminance of the circle matches the curvy line in Fig. 5b, and the luminance of the background checkerboard matches the background in Fig. 5b, where curvature blindness was observed. We have already seen that no BCI is observed in this figure. Thus, it is highly possible that the mechanisms producing BCI and the curvature blindness illusion are different, although they are similar at first glance.

Examination of the explanation by the 'corner effect'

In terms of the luminance difference between adjacent regions determining the direction of the perceived distortion, BCI is similar to the Café Wall illusion (Gregory & Heard, 1979). In addition, the 'checkered illusion', which was derived from a deliberation of the mechanism of Café Wall illusion (Kitaoka, 1998; Wade, 1982), seems to be closely related to BCI, because in this illusion, the luminance of small squares adjacent to relatively larger squares distorts the shape of the larger squares. In this section, we will discuss the possibility that the mechanism that produces the Café Wall illusion (and thus produces the checkered illusion) also produces the BCI.

Most existing explanations of the Café Wall illusion, such as the border-locking theory (Gregory & Heard, 1979), the luminance induction theory (McCourt, 1982), and the Fraser illusion reduction theory (Morgan & Moulden, 1986), pre-request the existence of straight lines flanked by rectangles, and thus cannot be directly applied to the explanation of BCI, which does not have straight lines. It has also been pointed out that these theories have limitations in explaining the Café Wall illusion (Kitaoka, 1998).

Among the existing explanations of the Café Wall illusion, the 'corner effect' (Kitaoka, 1998; Moulden & Renshaw, 1979; Pierce, 1898) is one that does not require the existence of straight lines and thus has the potential to explain BCI. The corner effect is a phenomenon in which the angle of a corner composed of planes or line segments appears to be smaller than it actually is. If we consider that angles formed by the circle contour and background elements with small luminance differences (e.g. dark-grey surfaces in a checkered pattern when the circle is black) are underestimated in the BCI figure, the circle contour in that area could be distorted. This may explain why the shapes of circles are deformed, as if they have obtuse corners (Fig. 6).

The function of the corner effect also explains the absence of the illusion in outline circles (Fig. 4b top). In the figure where filled circles are replaced with outline circles, the line of circle contour is often flanked with the same luminance background squares (Fig. 7a). In this case, the corner effects generated outside and inside the circle may work to cancel each other, and then circular shapes would not be distorted. In support of this explanation, when the luminance alteration of the checkered pattern is reversed between the inside and the outside of outline circles (i.e. the corner effect would not be cancelled, Fig. 7b), an apparent distortion of the circle outline can be observed (Fig. 8a). So far, so good; the corner effect looks promising as an explanation for BCI. However, as shown in Fig. 8b, no illusion is produced when the outside of the outlined checker circles are painted with uniform grey, although the corner effect would not be cancelled in this case (Fig. 7c). Considering all of the aforesaid, it can be summarized as follows.

1. No illusion is observed by simply replacing filled circles with line circles (Fig. 4b top), whereas the illusion is observed when reversing the period of luminance alternation between the inside and outside of a line circle (Fig. 8b). Thus, it is natural to be assumed that the corner effect is also worked inside the circle (otherwise it cannot 'cancel' the illusory effect as predicted in Fig. 7a).
2. However, the illusion does not occur in figures where the corner effect can be considered to work only on the inner side of line circles (Fig. 4c top and Fig. 8b).
3. The illusion seems to be observed only when the corner effect worked from both the inside and the outside of circles. Therefore, the corner effect acting

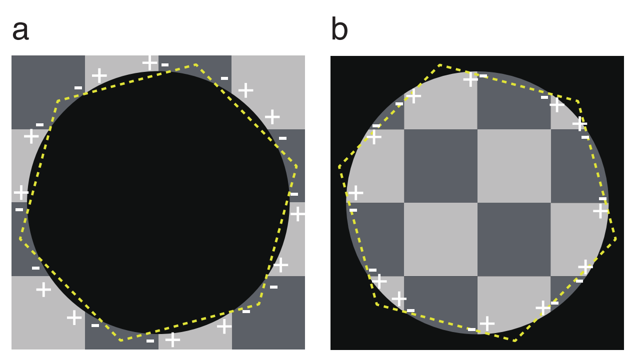

Fig. 6. Predicted distortion of the circle shape based on the 'corner effect'. The '-' symbols indicate that the corner effect underestimates the angle between the outline of the circle and one side of the background square, while the '+' symbols indicate that the angle would be overestimated. The predicted shape distortion (shown in a yellow dashed line) agrees well with the appearance of illusion in the original BCI figure (a) but not in the 'checkered circle' type figure (b).

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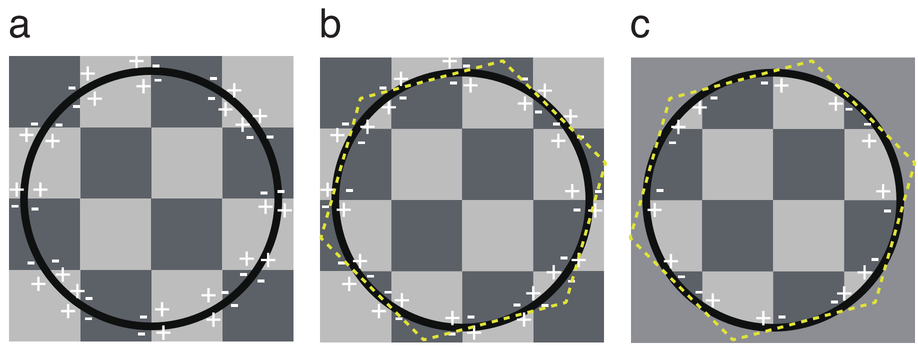

Fig. 7. Predicted effect of the corner effect on the line circles. As in Fig. 6, '-' and '+' symbols indicate that the corner effect underestimates/overestimates the angle between the outline of the circle and the square elements in the background. (a) If we simply replace the filled circle with a line circle, we could expect the corner effect acting inside and outside the circle to cancel each other out (thus, no illusion is predicted). (b) If the period of the checkered-pattern luminance change is reversed between the inside and outside of the circle, the shape distortion of the circle caused by the corner effect can be predicted (the predicted distortion is shown in the yellow dashed line). (c) If the checkered-pattern is applied only inside the circle and the outside of the circle is uniformly grey, the shape distortion of the circle should be expected by the corner effect. Of the above, (a) and (b) correspond well with the perception of actual figures (see Fig. 4b top and Fig. 8a). However, the circle distortion predicted in (c) is not observed (Fig. 8b).

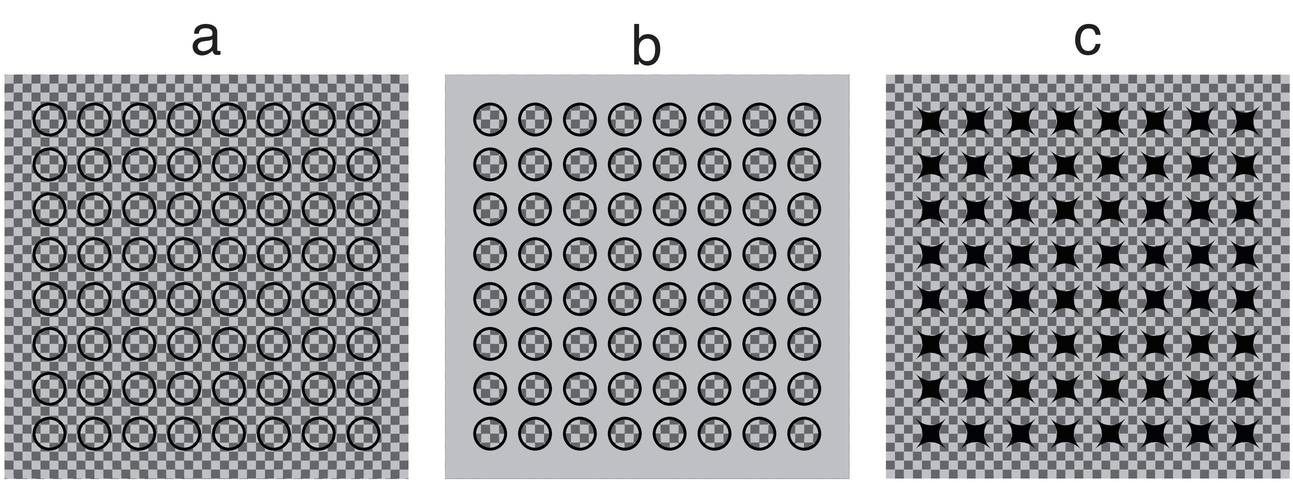

Fig. 8. (a) The illusion is observed even with outline circles when the cycles of luminance change of the checkerboard are reversed between the inside and outside of the circles. The occurrence of illusion is consistent with the prediction based on the corner effect (shown in Fig. 7b). (b) No illusion is observed when the outside of the outlined checkered circles is painted with uniform grey, although the corner effect is expected to work from the inner side of the circle in this figure (shown in Fig. 7c). (c) No illusion in concave contours.

inside the circles is considered to have only a weak effect in generating the illusion by itself.

The explanation based on the visual completion

One reviewer pointed out that visual completion may play an important role in BCI. This 'completion theory' assumes that the circle contour is subjectively complemented in the areas where the luminance contrast between the circle and the adjacent background area is low, because the edges are not clearly visible. The illusory angular corners are created by the edges of the area with high luminance contrast, which intrude into the areas with weaker luminance contrast and cross each other at the area.

However, the completion theory, like the filter theory, fails to explain the absence of illusion with line circles (Fig. 4b top). Since, in the line circle figure, the outline of the circle is sandwiched between areas of equal luminance, the completion theory predicts a rather stronger illusion with line circles than in filled circles. This is clearly not the case, as already mentioned. In addition, under the figure where the illusion occurs with line circles (i.e. when the luminance alternation cycle is reversed inside and outside the circle, Fig. 8a), the completion theory predicts that the illusion disappears due to the opposite contrast between inside and outside of the line circle, but in fact the opposite is true; the illusion occurs in the figure.

In addition to this, the completion theory assumes that the completion connects edges less smoothly than the actual contour. However, it is not obvious that the contour completion leads angular appearance. A previous study has reported, rather to the contrary, that in visual completion (especially modal completion, which this theory assumes), the arc is smoothly complemented (Singh, 2004). For these reasons, the corner effect theory is still considered more convincing than the completion theory at present.

General discussion

The discussion so far can be summarized as follows: Firstly, it was found that the way the circle shape deforms in BCI depends on the difference in luminance between the circle and the background elements. Four possible mechanisms that could produce this illusion – low-pass filtering, contour segmentation, visual completion, and the corner effect – were investigated. Of these, the low-pass filtering or visual completion predicts that illusions are produced in the modified BCI figures in which the filled circles are replaced by outline circles (top of Fig. 4b) or redrawn with the circles having a checkered pattern and the background painted with a uniform luminance (top of Fig. 4c). However, since the illusion is not observed in these figures, it was concluded that the explanation relying on the low spatial frequency component or visual completion alone is insufficient to explain the BCI. The contour segmentation, which assumes BCI is a variant of the curvature blindness illusion, was also rejected because the luminance assignment in the BCI figure components does not induce the curvature blindness illusion. This was interpreted as the luminance difference in the BCI figure being insufficient to cause the segmentation. The corner effect might be the most promising of the four theories examined, as it correctly predicts how the circle shape would be deformed (Fig. 6a) and that the occurrence of the illusion in the figure in which the luminance alternation cycle of the checkered pattern is reversed between the inside and outside of the line circle.

Here, we would also like to compare BCI with other phenomena in which the shape of the circle appears distorted. Firstly, the eggs illusion (Qian & Mitsudo, 2016) is a phenomenon in which the contour of the circle appears to extend in a direction of high contrast with the background. Since the contour of the circle appears to erode in the direction of a low contrast area in BCI, these two illusions are clearly caused by a different mechanism. Secondly, there is a known phenomenon in which prolonged fixation of circles produced afterimages of polygonal shapes (Ito, 2012). Although BCI is not a phenomenon that appears in aftereffects, there are similarities in that the visual information input of circles produces the perception of polygons, thus the responsible mechanism can be common. However, the mechanism of this shape deformation aftereffect is unclear, although the presence of interocular transitions of the aftereffects suggests the involvement of post-V1 mechanisms.

Shape perception is thought to be established by hierarchical processing (Loffler, 2008). Specifically, small neurons in the receptive field first detect the direction of local edges in an early processing stage (e.g. V1), and then the detected fine line segments are integrated into progressively more complex global shapes in subsequent processing (e.g. V2 ~ V4) (Dumoulin & Hess, 2007; Ito & Komatsu, 2004; Kramer & Fahle, 1996; Pasupathy & Connor, 1999). Considering the orientation component of local elements influences the shape perception of circles (Day & Loffer, 2009; Levi & Klein, 2000), it may be straightforward to take the path that the local orientations detected at the V1 are biased by the corner effect, resulting in a distortion of the shape as a consequence of the integration of local components. What is assumed here is nicely illustrated in the previous article by Day and Loffer (2009, Fig. 1); if the individual orientation components of Gabor patches are set so that they represent a pentagon, but they are arranged on the circumference of a circle, the overall shape of the figure is not perceived as a circle but as a pentagon. In this demonstration, the local orientation components of the individual Gabor patches are physically manipulated to deviate from the local directional components of the circle's contour, whereas in the BCI, this deviation might be caused by the corner effect and results in a similar distortion of the overall shape.

In the given scenario, we suggest that disruption of local edge orientation detected in the early stage is responsible for the polygonal visibility. However, the lack of illusion in the 'checkered circles' version of the figure (Figs 4c and 8b) complicates the explanation solely based on the disruption of detected orientation at an early stage. As revealed by demonstrations presented so far, the occurrence of BCI is restricted to cases where the checkered pattern is placed outside the circles, while no illusion seems to occur when the checkered pattern is placed only inside the circles. This can be interpreted as the corner effect seeming to be weaker inside the circles and stronger outside the circles. This asymmetry may be explained by considering that the processing of the edge integration process after the local orientation modulation has occurred is also involved in BCI. One such possible mechanism is the 'convexity bias' of the visual system. It is well known that in figure-ground judgements, a surface with convex contours is more likely to be judged as a figure (Kanizsa & Gerbino, 1976). In addition, convex features are more determinative than concave features while judging figure similarity (Subirana-Vilanova & Richards, 1996). The convexity bias may lead the visual system to be more sensitive to local orientation disruption of convex contours outside the circle than to local orientation

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disruption of concave contours inside the circle. Figure 8c verifies this explanation. This figure shows a circle replaced by a super ellipse with concave contours, but the individual shapes will appear uniformly concave curve contours and will not appear angular.

In addition to this, the assignment of border ownership may also be responsible for whether the curved outline belongs to the circles or not. The 'checkered circles' version of the figure looks like a checkerboard viewed through the circular holes in the black frontal surface. In this case, the curve contour belongs to the black frontal surface, not the circles. This may reduce the influence of the luminance difference between the checkerboard and the black surface on the local orientation detection of circler contours.

In summary, we here suggest that there might be a disruption of orientation detection in the earlier stage, possibly due to the corner effect, and the sensitivity to the disruption of local orientation depends on the judgement of whether the contour is convex/concave or figure/ground at the mid-level processing (V2 to V4). The neurons involved in border ownership and figure-ground segregation are mostly found in V2-V4 (Zhou et al., 2000), and most of the cells responding to moderately complex shapes in V4 are biased towards convex contours (Pasupathy & Conner, 1999), is consistent with the given explanation.

This explanation is only a posteriori speculation and requires further study, but in any case, the asymmetry of the BCI occurrence when the checkered pattern is attached to the background or to the circles may be an interesting subject to explore how the mechanism of figure-ground segregation and local edge integration are interacted, as past studies have considered them in separate contexts. BCI could be an effective tool for a comprehensive understanding of the hierarchical mechanism of shape perception.

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