

# Illusory object motion in the centre of a radial pattern: The Pursuit–Pursuing illusion

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**Abstract.** A circular object placed in the centre of a radial pattern consisting of thin sectors was found to cause a robust motion illusion. During eye-movement pursuit of a moving target, the presently described stimulus produced illusory background-object motion in the same direction as that of the eye movement. In addition, the display induced illusory stationary perception of a moving object against the whole display motion. In seven experiments, the characteristics of the illusion were examined in terms of luminance relationships and figural characteristics of the radial pattern. Some potential explanations for these findings are discussed.

**Keywords:** Visual illusion, motion perception, smooth pursuit, equiluminance, radial pattern, illusory motion.

## 1 Introduction

Generally, the visual system is very sensitive to object motion. However, because of high sensitivity, several kinds of motion are misdetected and perceived as motion illusions. This paper introduces a new motion illusion with a unique feature. The illusion arises with a disk placed in the centre of radially arranged thin sectors (see [Figure 1](#)). When the eyes pursue a moving object, the disk looks as if it moves in the same direction as the pursuit. Here, this illusion is called the Pursuit–Pursuing illusion. In this section, motion illusions reported to date are summarized, and a description of the configuration and features of the Pursuit–Pursuing illusion follows.

### 1.1 Previously reported motion illusions

Kitaoka and Ashida (2007) reviewed and classified previously reported motion illusions in their paper from the point of phenomenology. They divided the illusions into two types: motion perception from a static image (called “automatic type”) and misperception of a (retinally) moving visual object (called “motion-dependent type”). Here, we will not discuss this grouping, but instead we will group the illusions from a different point of view, based on features that are shared by the phenomena. The following subsections describe such groups of motion illusions. The motion illusion presented in this paper and described later needs almost all of the featured keywords in the description, ie, motion contrast, radial stimulus configuration, eye movement, and an object on high-contrast stripes.

#### 1.1.1 *Motion illusions as a basic principle in vision*

Some motion illusions exhibit principles that are common among visual properties. Contrast and assimilation are illusory effects that are also observed in other visual properties, eg, brightness, colour, orientation, and size. Induced motion (Duncker 1929; Gogel and Griffin 1982), which is considered as motion contrast, is a phenomenon in which a stationary object is seen to move in a direction that is opposite to the background or the nearby motion direction. In the case of motion capture (Ramachandran 1987), as motion assimilation, a stationary coloured object is perceived to move in the same direction as that of the overlapping high-contrast dots. Another study (Ramachandran and Cavanagh 1987) demonstrated that motion of a low-frequency component captured apparent motion of sparse random dots.

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Both motion-capture cases indicate that clear motion of a salient object captures ambiguous motion of an object with weak motion signals.

### 1.1.2 *Circular or radial stimulus configurations*

In the point of figural configurations, motion illusions often appear in a circularly repeated or radially arranged pattern. For example, the MacKay Ray figure (MacKay 1957) is a radial “ray” pattern with strong luminance contrast, which induces perceptual waver and a concentric afterimage with illusory rapid rotation. When rings are placed on a MacKay Ray figure, the configuration becomes consistent with “Enigma” by Leviant (1982, 1996). The static figure produces an illusory stream of something whitish within the ring areas when one views the centre of the figure. Several studies have proposed causes of the illusion. Zeki et al (1993) proposed a cortical-level explanation with positron emission tomography image data, which showed differential activation in the V5 complex. Gregory (1993) criticized the explanation and suggested that the fluctuation of accommodation and small eye movement produced motion signals. On the other hand, Mon-Williams and Wann (1996) proposed that fixational eye movements induced the illusion. Hamburger (2007) suggested that microsaccades only enhance the illusion but are not the cause of the illusion, thus showing that a positive afterimage of an Enigma stimulus induced the illusory stream. (However, it should be noted that the appearance of the illusory motion seemed much different from the usual Enigma stream.) Gori et al (2006) showed a clear regularity in the stream-direction reversals, suggesting cortical-level saturation and an effect of motion adaptation in determining the illusory stream directions, suggesting an interaction between real and illusory motions. Kumar and Glaser (2006) also suggested a cortical origin. Troncoso et al (2008) proposed that microsaccades triggered the illusory stream. Recently, Ruzzoli et al (2011) demonstrated a causal role of V5/MT in the Enigma illusion (and not of V1) using repetitive transcranial magnetic stimulation. From the point of computational analysis, Fermüller et al (1997) proposed that both fixational eye movements and higher-level interpretation of the motion signals could be crucial for the illusion. Thus, the cause of Enigma is still debated and not yet resolved. Pinna and Dasara (2005) reported another illusion using a stimulus configuration that is similar to Enigma, ie, the Windmill illusion. A grey ring was placed on a high-contrast windmill pattern, just as in Enigma. When the transparency of the ring was increased/decreased, an illusory stream in the ring area was perceived. When the “windmill” rotates, the illusory stream is seen to rotate in the opposite direction.

In the Fraser and Wilcox (1979) illusion, repeated luminance gradations in a circular configuration create an impression of slow rotation. The direction of the illusion is considered to be in the dark-to-light direction (Faubert and Herbert 1999). The illusion is stronger with a stimulus with higher contrast and/or larger eccentricity (Naor-Raz and Sekuler 2000). The “Rotating Snakes” illusion (an optimized Fraser–Wilcox illusion) (Kitaoka 2003) produces a similar (but stronger) effect. The Rotating Snakes illusion consists of a circularly arranged specific order of four steps of luminances (black, dark grey, white, and light grey; Kitaoka and Ashida 2003). The illusory motion direction is observed in a direction from black to dark grey or white to light grey. The origin of the illusion has been debated from different viewpoints. Conway et al (2005) reported that the combination of differences in response latencies to different luminance contrasts and reversed phi (Anstis 1970) produced the illusion. Backus and Oruç (2005) proposed that the progress in luminance and contrast adaptations shifted the perceived gravities of the pattern. Murakami et al (2006) measured fixational eye movements and found that the amount of drift movements and the illusion strength showed a correlation (also see Murakami 2006). Later, Beer et al (2008) replicated the results. Using fMRI, Kuriki et al (2008) recorded the increase in neural activity in the

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motion sensitive area of the human visual cortex during the observation of Rotating Snakes. Recently, Tomimatsu et al (2011) showed a similarity in the time course of the strength of the Fraser–Wilcox and Rotating-Snakes illusions, and suggested that adaptation is a crucial factor to induce or attenuate the illusions.

The Pinna–Brelstaff illusion (Pinna and Brelstaff 2000) and the Rotating Tilted Line illusion (Gori and Hamburger 2006; Gori and Yazdanbakhsh 2008) also consist of circularly arranged elements, ie, squares or tilted lines. Both illusions produce illusory circular motion against physical image expansion or contraction on the retina.

Almost all of these illusions use repeated patterns in circular or radial configurations to induce strong effects through the accumulation of local illusory motion components or weakening perceived motion–position conflict. Even the Enigma illusion can be arranged in a non-radial version (Gori et al 2006; Kumar and Glaser 2006; MacKay 1957; Troncoso et al 2008). The key factor of the Pinna–Brelstaff illusion and the Rotating Tilted Line illusion is the inconsistency between the smooth retinal motion in a radial direction and the detected motion direction that is oblique to the radial direction due to the aperture problem for motion. Thus, there is some uncertainty as to whether circular or radial configurations themselves are the essence of the illusions noted in this subsection.

### 1.1.3 *Object on high-contrast stripes*

The Ouchi illusion (Ouchi 1977; Spillmann and Werner 1990) arises from a checkered circle placed on a checkered background. Both areas are filled with high-contrast check patterns of rectangular elements, although the orientations of the rectangles are orthogonal. The direction of signaling motion in each area is biased to the direction that is orthogonal to each rectangle orientation. Thus, when retinal motion arises, predominantly detected motions in the two areas may be inconsistent, resulting in a perceived slide of the illusory circle (Fermüller et al 2000; Mather 2000). Ashida et al (2005) demonstrated that the relative amplitude of the relevant Fourier fundamentals and harmonics leads to a quantitative prediction of the illusion, regarding the checker pattern as a plaid. On the other hand, Pinna and Spillmann (2005) devised a variety of sliding motion stimuli that did not have any directional bias. Thus, it is possible to argue that the two orthogonal stripes in the Ouchi illusion are not the cause of the illusion but only the cause of the directional bias produced through the failure in integrating local motion vectors.

One type of sliding motion produced by Pinna and Spillmann (2005; Figure 9) arises in a striped circle placed on a striped background. Both high-contrast stripes are in the same orientation, but the phases are opposite. This gives an interesting motion illusion; that is, the perceived motion direction is opposite to the actual motion direction. No explanation has been given for this illusion. The Pursuit–Pursuing illusion described later is phenomenally similar to this illusion.

Generally, high-contrast stripes enhance motion detection in a specific direction, ie, orthogonal to the stripe orientation. However, high-contrast stripes could also indirectly affect motion perception of an object on the stripes. Anstis et al (2006) showed that the perceived speed of a rotating bar changes according to the relative orientation between the bar and background stripes. They suggested that perceived motion of phantom stripes within the bar induced by the background stripes modulated the perceived speed of the bar rotation. The Footsteps illusion (Anstis 2001, 2004) is produced by yellow and blue rectangles moving smoothly on black and white stripes. The footsteps-like perceived speed change of the rectangles is considered as reflecting the luminance-contrast and perceived-speed relationship, although some static factors have been proposed (Sunaga et al 2008). The Enigma illusion (Leviant 1982, 1996) and the Windmill illusion (Pinna and Dasara 2005)

noted above also arise in a ring area placed on background radial stripes or sectors with strong luminance contrast.

#### 1.1.4 *Ambiguous motion*

Directional ambiguity of local motion components caused by the aperture problem produces motion illusions. The well-known Barberpole illusion (Lidén and Mingolla 1998; Shimojo et al 1989; Wallach 1935) is a typical example. The Oblique Line illusion (Bressan and Vezzani 1995) shows a simple illusory figure producing the aperture problem for motion. The Rotating Tilted Line illusion seems to be caused by local motion that is detected in the middle of the tilted lines causing the aperture problem for motion (Gori and Yazdanbakhsh 2008) or by tilted lines that are longer than the receptive field size of cortical motion detectors (Yazdanbakhsh and Gori 2008). The same principle can be applied to the Accordion Grating Illusion (Gori et al 2011; Yazdanbakhsh and Gori no date) where a striped pattern is seen to expand/shrink in a direction perpendicular to the stripes during back-and-forth head movements, similar to the Bulging Grid illusion (Foster and Altschuler 2001). The Pinna–Brelstaff illusion may be related implicitly to the aperture problem (Gurnsey et al 2002) just as in the Rotating Tilted Line illusion.

Ito (1993) showed that ambiguity in local motion directions in translational sine waves created ambiguous motion perception between two-dimensional translation and three-dimensional rotation. The figure–ground reversals that result in changes in edge ownerships can create a similar ambiguity between two-dimensional translation and three-dimensional rotation in a motion display (Ito and Kawabata 1998).

#### 1.1.5 *Involvement of eye or head movement*

Sometimes motion illusions are associated with eye or head movements. The Filehne illusion (Filehne 1922) is a phenomenon arising when eyes pursue a moving target in a dark room. A stationary background object is seen to move in a direction that is opposite to the pursuit direction. The Swinging Motion illusion (Khang and Essock 2000) also produces a motion illusion in a direction that is opposite to the smooth-pursuit eye movement. The stimulus was stripes that were parallel to the eye-movement direction. They explained the illusion by hysteresis of contrast changes according to the smooth pursuit. Autokinesis is an illusion where a small static luminous object in the dark appears to move. This phenomenon is related to drift eye movement (Poletti et al 2010).

Smooth pursuits not only produce misperception of motion along the pursuit directions but also produce illusory motion components in the orthogonal directions. When an object surrounded by oblique edges with repeated high-contrast local structure is viewed during smooth eye movement, the object shape is seen to expand or shrink (Fantoni and Pinna 2008; Ito et al 2009, figure 1). This kind of illusory motion probably comes from the inconsistency between the direction of the physical motion and the direction of the misdetected strong motion component. The Boogie-Woogie illusion from Cavanagh and Anstis (2002) showed clear contrast between the well-detected first-order motion along the striped contour and poorly detected second-order motion that is perpendicular to the contour. These illusions in this paragraph, however, do not need to be related to eye movement. Smooth retinal motion is all that is needed.

Some motion illusions disable observers in tracking a target by smooth eye movements. The Chopsticks illusion and the Rotating Rings illusion (Anstis 2003) change the perceptual property of the intersections, resulting in a failure to track the intersection visually, although induced motion did not affect the tracking motion in spite of the perceived distortion of the

motion path (Anstis and Ito 2010). Conversely, Tomimatsu et al (2010) showed that smooth pursuit eye movement greatly reduces the effect of the Rotating Snakes illusion.

The illusions noted above in this subsection are not caused by saccades. However, saccades sometimes cause other types of motion illusions. Ito (2005) found that saccades cause motion perception of colour-defined objects in a direction that is opposite to the saccade direction. After analyzing the characteristics of the illusion, he suggested that delayed rod activities are involved in the illusion (Ito 2008). Takahashi et al (2010) reported a similar illusion.

The Pinna–Brelstaff illusion and the Rotating Tilted Line illusion are sometimes related to to-and-fro head movement. The Bulging Grid illusion (Foster and Altschuler 2001) produces an illusory spherical bulge on a checkerboard pattern when one approaches it. The Accordion Grating illusion (Gori et al 2011) noted above produces perception of asymmetrical expansion and curvature of the stripes during approaching head movement. In the Breathing Light illusion (Gori and Stubb 2006), a blurred white spot appears wider and brighter when one approaches it. However, these illusions remain the same when the figures are smoothly magnified. Therefore, the to-and-fro head movement is not essential for these illusions.

#### 1.1.6 *Delay of motion*

The Fluttering-Heart illusion (Nguyen-Tri and Faubert 2003; von Grünau 1975a, 1975b, 1976; von Helmholtz 1867/1962; von Kries 1896/1962) causes anomalous motion impression along the object motion path, where object motion perception is delayed relative to background motion perception, causing apparent phase lags between them when they are swinging. This illusion is favored by mesopic vision and a combination of saturated colours (especially a blue object on a red background). von Grünau concluded that the Fluttering Heart illusion was caused by the suppressed rod signals by activities of long-wavelength cones. Nguyen-Tri and Faubert (2003) proposed that the time delay was caused by the response latency of colour-defined motion relative to luminance-defined motion. On the other hand, Kitaoka and Ashida (2007) showed that the delay of motion signals from low-contrast random dots could produce the Fluttering-Heart illusion and that such apparent motion delay produced apparent depth, just as in the Pulfrich effect (Pulfrich 1922) when dark stimuli with high and low contrasts were binocularly fused. Carlson et al (2006) placed a small square filled with static noise on a larger square filled with dynamic noise. When the two moved, the small square appeared to lag behind the larger one, creating apparent spatial offset (Floating Square illusion). Thus, there seem to be several factors that could delay motion onset detection or slow the perceived speed. When the degraded motion signals are combined with strong motion signals, these motion illusions arise.

#### 1.2 A new motion illusion

The present study reports a new motion illusion where a visual object is seen to move in the same direction as that of pursuit eye movement. Figure 1a shows a typical example of the stimuli used to induce this illusion. A yellow disk is placed on a radial pattern consisting of 30 thin dark-grey sectors on a light-grey field. The structures of the stimuli used here share some features with a figure produced by Pinna et al (2002), as shown in Figure 1b. They developed a ‘Scintillating Luster’ illusion, using a grey disk located in the centre of 18 radial lines (the optimal induction condition), in a modified version of the Ehrenstein figure (Ehrenstein 1941). In the current study, the lines in the Pinna–Spillmann–Ehrenstein figure were replaced by ‘sectors’ (although, strictly speaking, the sectors were not true sectors on the screen because they were partially occluded by a disk). The area of dark sectors was the same as that of the light background, ie, a 50% duty ratio of the luminance along a circular path around the centre disk. Equiluminance between the disk and the surroundings (i.e.,

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sectors and the background) was used to optimize the figure for the motion illusion. When the stimulus was placed in a peripheral visual field, pursuit tracking of another moving object induced illusory motion perception of the yellow disk in the same direction as the pursuit direction on the stationary radial pattern, as shown in [Figure 2a](#). Thus, this illusion is referred to as the “Pursuit–Pursuing illusion”. On the other hand, if a printed copy of the figure was rotated by hand while fixating on the centre point, as shown in [Figure 2b](#), the yellow disks would not rotate with the sheet but appeared to remain stationary or even to rotate in the opposite direction detaching from the sheet. Thus, this illusion not only produced illusory motion perception of a stationary object but also produced illusory stable perception of a moving object against its physical motion. Although the appearance of the illusion changes greatly, depending on whether the retinal motion is caused by eye movement or by stimulus movement, the underlying mechanism may be the same.

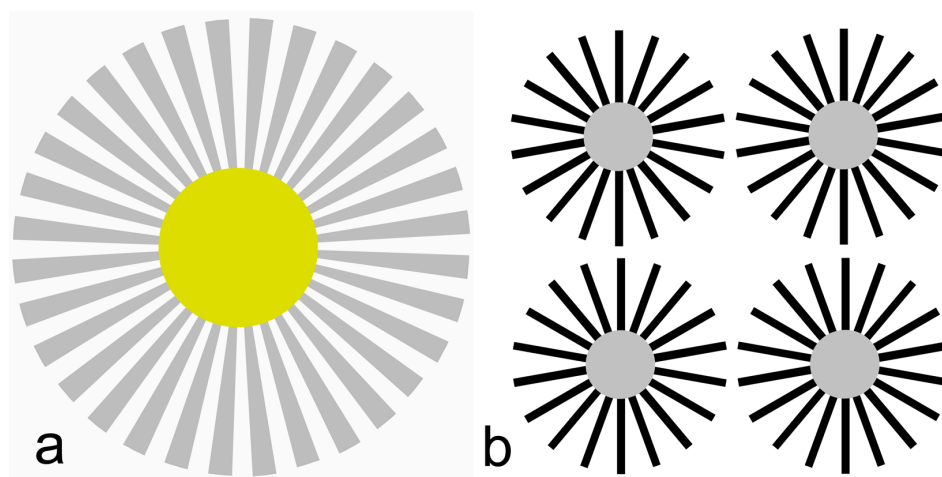
The Pursuit–Pursuing illusion has definitive features that are rarely observed in other motion illusions. The first is that the illusory motion arises in an opposite direction to the retinal motion direction. Several illusions producing the perception of motion components at right angles to the retinal-motion direction have been previously reported (eg, Gori and Hamburger 2006; Ito et al 2009; Pinna and Brelstaff 2000; ie, “illusory motion in a direction different from the retinal-image motion”; Kitaoka and Ashida 2007). However, the Pursuit–Pursuing illusion does not produce illusory right-angle motion components but produces those components in the direction that is opposite to the retinal motion. Although this is an “illusory motion in the direction parallel to the retinal-image motion” (Kitaoka and Ashida 2007), the direction is the opposite of that of the Swinging-Motion illusion (Khang and Essock 2000) or the Fhirene illusion, which produces illusory motion in a direction that is opposite to the pursuit direction. Reversed phi (Anstis 1970) and a kind of sliding motion illusion (Pinna and Spillmann 2005), as noted in Section 1.1.3, are rare examples of illusory motion produced in the reversed motion direction.

The second feature is that the centre disk does not move when the sheet of the radial patterns is moved. To my knowledge, an illusion of being stationary against physical motion has not been reported. [Figure 9](#) in Pinna and Spillmann (2005) could be an exception, although they did not discuss this. However, illusory stationary perception is difficult to measure. Therefore, in the present paper, illusory motion by pursuit eye movement was measured.

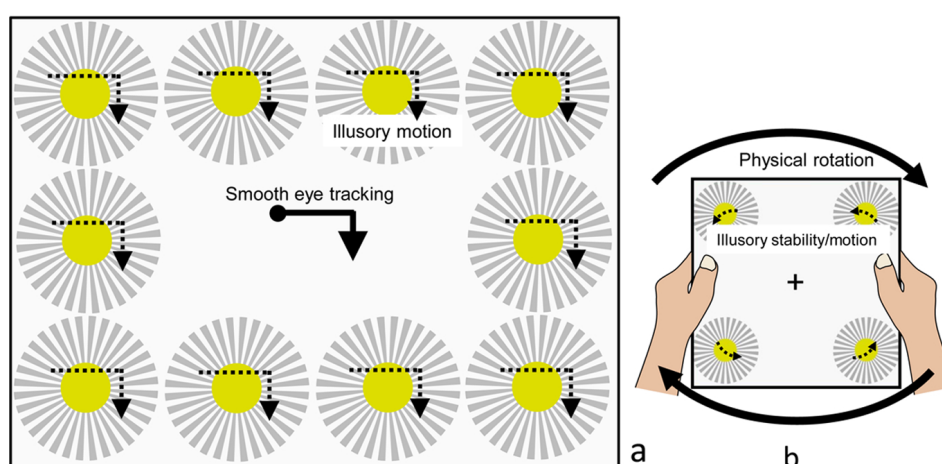
The third feature is that there is no anisotropy in the effect. The effects in almost all of the motion illusions caused by smooth retinal motion depend on the angles between the retinal motion direction and the detected motion direction (Bressan and Vezzani 1995; Fantoni and Pinna 2008; Gori and Yazdanbakhsh 2008; Ito et al 2009; Pinna and Brelstaff 2000). Some depend on the angles between the retinal motion direction and the orientation of the stimulus elements, eg, parallel (Khang and Essock 2000) or orthogonal (Pinna and Spillmann 2005, figure 9; Ito et al 2009, figure 5). The Pursuit–Pursuing illusion uses a radial pattern that has virtually no orientation in shape. Thus, retinal motion in any direction could produce the same illusory effect (although pursuit eye movement itself may be smoother in a horizontal direction). It is also unique in that, in spite of the radial stimulus configuration, this illusion needs one-dimensional retinal motion, not expansion/contraction of the stimulus pattern or fixation in the stimulus centre.

On the other hand, the Pursuit–Pursuing illusion has similar features to some of the visual illusions reported previously. The illusory figure includes a radial pattern, which can be seen in the MacKay ray figure, Enigma, and Pinna–Spillmann–Ehrenstein figure. There is a strong contrast stripe along the contour of the centre disk in the figure. This is a similar structure to the Fantoni–Pinna illusion and Enigma.

The current study sought to introduce the new phenomenon (ie, the Pursuit–Pursuing illusion), describe its characteristics, and explore the optimum conditions for inducing the illusory motion to elucidate the underlying mechanisms involved. Experiments 1 and 2 varied the luminance of the stimulus disks while the sector and background luminance remained constant. Experiment 3 varied the luminances of the sectors and the background. Experiment 4 tested the effect of changes in contrast between the sector and background luminances. Experiments 5 and 6 explored the optimum conditions in terms of the number and length of sectors. Experiment 7 quantitatively measured the illusory effect. The variables used in the experiments were chosen mainly to determine the best condition for the illusion and thus were rather exploratory. However, I discuss some of the provisional hypotheses for the illusion based on the data acquired here, eg, a combination between strongly detected motion signals in the surround and poorly detected motion signals from the disk produces perceived motion contrast.



**Figure 1.** Typical stimulus figures producing illusions. (a) Example of the stimulus figure tested here. (b) Example of the illusory scintillating figure used by Pinna et al (2002).



**Figure 2.** Illusions produced by Figure 1a. (a) Illusory motion perception during smooth eye-movement tracking of a moving object (the Pursuit–Pursuing illusion). (b) Illusory stable perception during physical movement of the sheet. When one rotates the stimulus sheet while fixating on the central cross, the yellow disks can be seen to be stationary against the sheet rotation, or even to rotate in the opposite direction to the physical rotation direction. Please refer to the PowerPoint demonstration (<http://www.design.kyushu-u.ac.jp/~ito/IOM.ppt>).

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## 2 Experiment 1

In Experiment 1, the luminance of the centre disk was varied to explore the optimum luminance relationship between the disk luminance and the surrounding luminance for the Pursuit–Pursuing illusion. The luminance contrast of stimuli is one of the factors affecting motion detection or perceived motion speed (Anstis 2003; Stone and Thompson 1992; Thompson 1982). When the disk luminance is near the average of the surrounding luminance, the disk motion on the retina is considered as second-order motion. It is suggested that poor motion detection of the disk is one reason why the disk is seen to move with the eyes or why the disk appears stationary against its physical motion.

### 2.1 Method

#### 2.1.1 Participants

In total, 39 naïve graduate students and the author participated in Experiments 1–7. Before formal data collection, participants observed a typical stimulus that was considered to induce the effect robustly. An experimenter asked each participant whether they perceived illusory motion. Three of 40 participants did not perceive the illusion at all and so were excluded from formal data collection. Of the 37 participants who perceived the motion illusion, an experimenter asked in which direction they perceived the yellow disks to move: (1) the same direction as that of eye tracking, (2) the opposite direction, or (3) a random or uncorrelated direction. All 37 participants reported that the yellow disks appeared to move in the same direction as that of the pursuit eye movement. These participants were assigned to each experiment.

Eighteen naïve participants served as observers for Experiment 1. All participants had normal or corrected-to-normal visual acuity and gave informed consent before taking part in the experiments, which were approved by the local ethics committee.

#### 2.1.2 Apparatus and stimuli

The stimulus displays were produced by a computer (Dell, Inspiron Mini 12) and projected on a screen with an LCD video projector (Sony, VPL-PX31). The screen size was 204 cm (horizontal) × 153 cm (vertical), treated as a 1024 × 768 pixel matrix. The screen subtended 72.2 (horizontal) × 57.3 (vertical) deg of visual angle at a viewing distance of 140 cm. As shown in Figure 2a, we used 10 disks, each of which was placed at the centre of 30 radial sectors on a light-grey background. The thickness of the sectors was lower in the central regions, maintaining the duty ratio at 50% along centric paths (see Figure 1a). The disks were coloured yellow. The diameters of the disk and the radial pattern were 7.0 deg and 20.2 deg of visual angle, respectively, when they were placed in the centre of the screen. The disk luminance was varied as an experimental variable, ie, 24.1 cd/m<sup>2</sup>, 31.5 cd/m<sup>2</sup>, 43.1 cd/m<sup>2</sup>, 54.0 cd/m<sup>2</sup>, 65.1 cd/m<sup>2</sup>, 76.0 cd/m<sup>2</sup>, and 83.0 cd/m<sup>2</sup>. The sector and background luminances were 31.8 cd/m<sup>2</sup> and 76.2 cd/m<sup>2</sup>, respectively.

#### 2.1.3 Procedure

A stimulus figure was presented with a black dot to be tracked (1.4 deg in diameter). As shown in Figure 2a, 1 s later, the fixation dot moved along a square path (7.4 deg × 7.4 deg) in a clockwise direction at a speed of 9.9 deg/s. The corners of the square path were rounded to enable participants to maintain smooth pursuit. After 9 s (three times revolution), the spot stopped, and participants evaluated the strength of the illusory motion in an 11-deg scale (0–10), where 0 indicated that no motion was perceived, and 10 indicated vivid motion perception. Two or three participants stood in front of the screen at a distance of 140 cm



and completed the trials in parallel. Due to height differences, not all participants observed the stimuli in the centre of the screen. For example, shorter participants had to look slightly upwards to view the screen. However, on the large screen, the phenomenon was robust enough to produce a strong motion illusion, even if the viewing position deviated markedly from the centre of the screen in the horizontal, vertical, or depth dimensions. After each stimulus presentation, participants individually recorded a rating on an evaluation sheet without showing it to the other participants. Each session included the seven disk-luminance conditions presented in a random order. Two sessions were conducted for each participant.

## 2.2 Results and discussion

Figure 3 shows the results of Experiment 1. As shown clearly in the figure, the rated illusion strength was highest when the disk luminance was  $54.0 \text{ cd/m}^2$ , which was the average (or middle) of the sector and background luminances. In particular, when the disk luminance was lower than the sector luminance, the illusion was very weak. Figure 3 also shows the Michelson contrast between the disk luminance and the surrounding luminance (ie, the average of the sector and background luminances) as a function of disk luminance. The results clearly showed that the illusion-strength ratings and the contrasts exhibited an inverse relationship. Although there were large individual differences in the illusion-strength ratings, a similar tendency to perceive a strong illusion when disk luminance was set to the average (ie, the middle value) between the sector and background luminances was exhibited by almost all participants. Individual differences in rated illusion strength may reflect a difference in the smoothness of the pursuit eye movement or a difference in the rating strategy used.

The results were submitted to a one-way analysis of variance (ANOVA). The main effect of disk luminance was found to be significant,  $F(6, 102) = 19.89, p < .0001$ . The results of a multiple-comparison analysis (Ryan's method) revealed no significant differences between the  $54.0 \text{ cd/m}^2$  and  $65.1 \text{ cd/m}^2$  conditions ( $p > .05$ ), but the two conditions exhibited significantly higher ratings compared to the other conditions ( $p < .05$ ). One possible reason why no differences between the  $54.0 \text{ cd/m}^2$  and  $65.1 \text{ cd/m}^2$  conditions were found may be that the effectively equiluminant point between yellow and grey shifted slightly due to peripheral viewing, as shown in Experiment 3.

## 3 Experiment 2

Experiment 1 showed that the illusion was strongest when the disk luminance was around the average (or middle) between the sector and background luminances. These results might suggest that poorly detected motion of the centre disks is an important factor to induce the effect. However, it was not clear which was actually important for inducing the illusion; that is, the average or the middle value in the luminance of the disk. In Experiment 2, the area proportion of the sectors was varied, and the average and middle values of luminance were isolated to test thoroughly whether the equiluminance was or was not crucial for the Pursuit–Pursuing illusion.

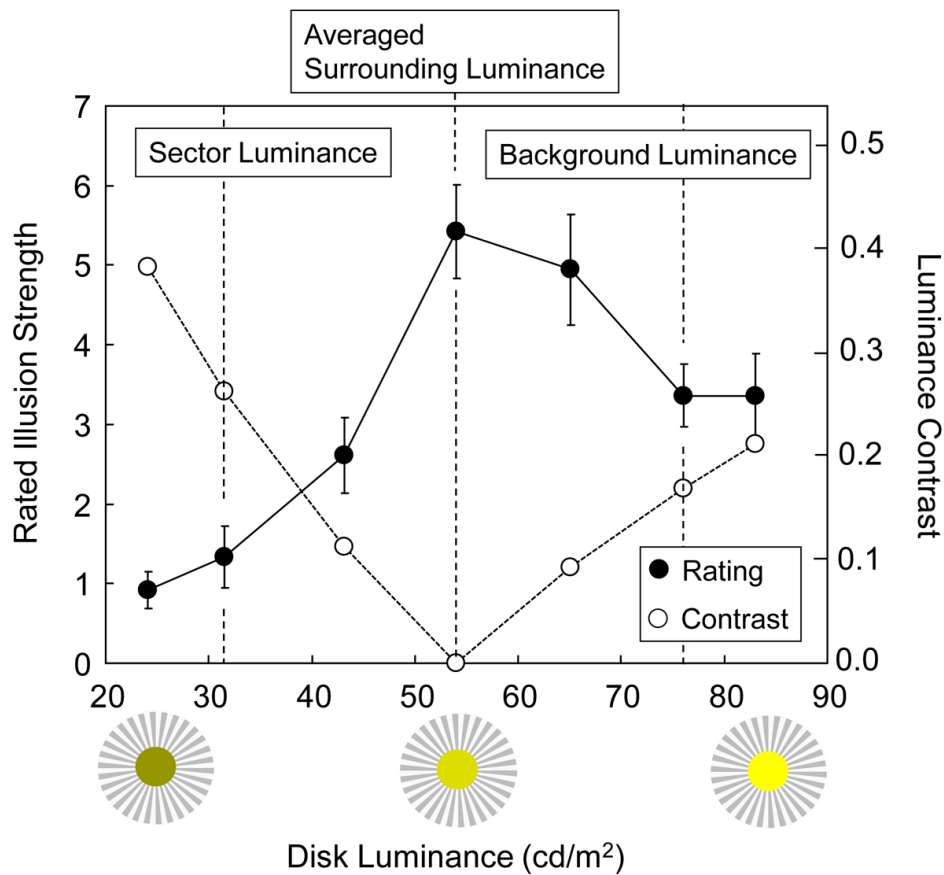
### 3.1 Method

#### 3.1.1 Participants

The same 18 participants from Experiment 1 participated in Experiment 2.

#### 3.1.2 Apparatus and stimuli

The area proportion between the sectors ( $31.8 \text{ cd/m}^2$ ) and the background ( $76.2 \text{ cd/m}^2$ ) was varied in two conditions without changing the number of sectors or the luminance, as shown in Figure 4. The darker stimulus included thicker sectors, ie, consisting of a 75% sector area



**Figure 3.** Results of Experiment 1. Filled circles indicate rated illusion strength as a function of disk luminance. Error bars indicate *SE*. Open circles indicated Michelson contrasts between the disk luminance and the averaged surrounding (sector and background) luminance.

and a 25% background area, respectively. On the other hand, the lighter stimulus included thinner sectors, ie, consisting of a 25% sector area and a 75% background area, respectively. In these stimulus conditions, the middle value in the luminance constant ( $54.0 \text{ cd/m}^2$ ) was maintained, but the average luminance of the surroundings was changed to  $42.9 \text{ cd/m}^2$  (darker condition) or  $65.1 \text{ cd/m}^2$  (lighter condition). The disk luminance was varied in seven conditions, as in Experiment 1. The other details were the same as in Experiment 1.

### 3.1.3 Procedure

One session included 14 trials (7 disk-luminance conditions  $\times$  lighter/darker conditions). Two sessions were conducted. The order of the trials was randomized within each session. The other procedure was the same as in Experiment 1.

## 3.2 Results and discussion

Figure 5 shows the results of Experiment 2. The curves clearly show that the darker (lighter) stimulus condition caused a shift in the most appropriate disk luminance for inducing the illusion to a darker (lighter) direction, compared to the results from Experiment 1. The most effective luminance for inducing the illusion was consistent with the average (not the middle) luminance of the surroundings, in both the darker and lighter stimulus conditions.

A one-way ANOVA was conducted on the results of the lighter stimulus conditions. The main effect of disk luminance was found to be significant,  $F(6, 102) = 42.99$ ,  $p < .0001$ . The results of multiple comparisons analysis revealed no significant difference



**Figure 4.** Stimuli used in Experiment 2. The left panel shows the radial pattern in the darker stimulus condition, while the right panel shows the lighter stimulus condition. See details in the text.

between the strength of illusion induced in the  $65.1 \text{ cd/m}^2$  and  $76.0 \text{ cd/m}^2$  disk-luminance conditions ( $p > .05$ ) but revealed that the two conditions were associated with significantly higher ratings compared to the other conditions ( $p < .05$ ). A one-way ANOVA was also conducted for the darker stimulus conditions. The main effect of disk luminance was found to be significant,  $F(6, 102) = 37.53$ ,  $p < .0001$ . A multiple-comparison analysis revealed no significant differences between the strength of illusion induced in the  $43.1 \text{ cd/m}^2$  and  $54.0 \text{ cd/m}^2$  disk-luminance conditions ( $p > .05$ ) but revealed that the two conditions were associated with significantly higher ratings than the other conditions ( $p < .05$ ). One possible reason for the failure to find any statistically significant difference between the best two luminance conditions for both darker and lighter stimuli may be a small shift in the effective equiluminance point by peripheral viewing, as noted earlier. This problem is tested further in Experiment 3.

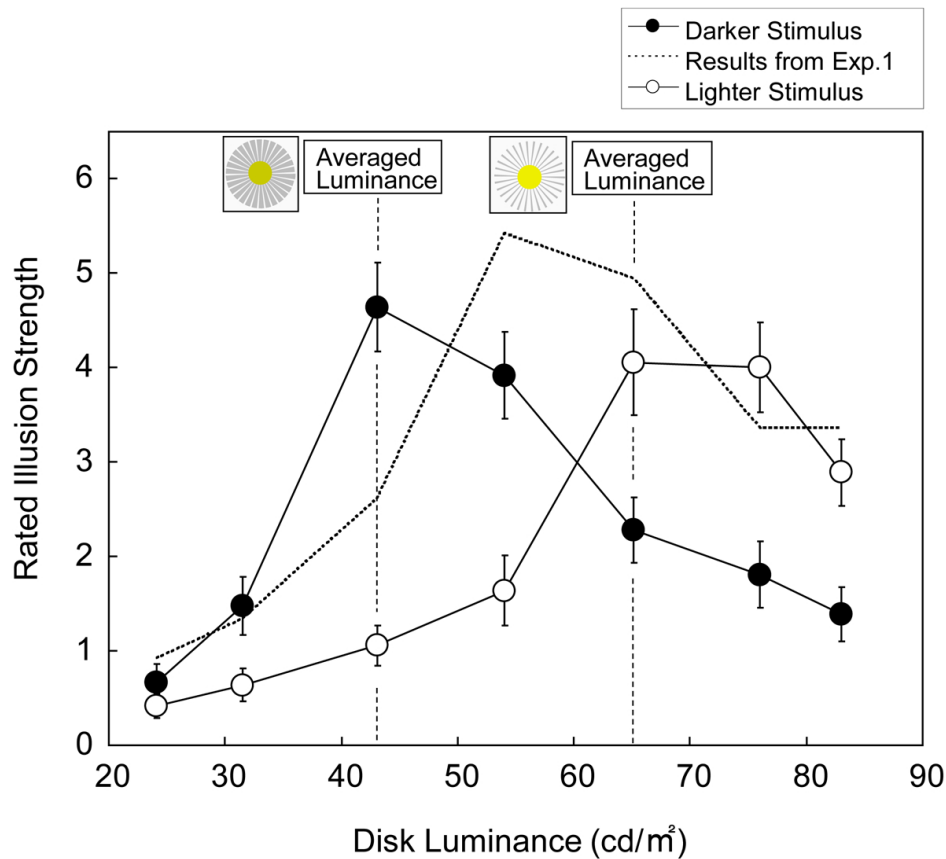
The disk luminance at which the illusion was the strongest corresponded to the average luminance between the sector and the background luminance in Experiments 1 and 2. Thus, the illusion was found to be strongest when the disk and the average of the surroundings (sector and background) were equiluminant. Figure 6 shows the relationship between the rated illusion strength and the Michelson contrast between the disk luminance and the surrounding luminance averaged over the sector and the background areas, obtained from Experiments 1 and 2. The results clearly indicated that when the luminance contrast was low, the illusion was strongly induced. These results could be indicate that poor motion detection of the central disks is critical for the illusion.

## 4 Experiment 3

Experiments 1 and 2 showed that the Pursuit–Pursuing illusion was strongest when the yellow disk luminance was at the average of the sector and background luminances. However, it has not yet been shown that any change in luminance of the surroundings changes the disk luminance that produces the best illusion according to the change in the averaged luminance of the surroundings. Experiment 3 further measured the best luminance condition with changing surrounding luminances but without changing the luminance contrast used here. In Experiment 3, the point of each participant's individual equiluminance between yellow and grey was also measured to analyze the results precisely.

### 4.1 Method

#### 4.1.1 Participants



**Figure 5.** Results from Experiment 2. The left broken line indicates the averaged luminance of the surroundings in a darker stimulus, while the right broken line indicates that in a lighter stimulus. Error bars indicate *SE*.

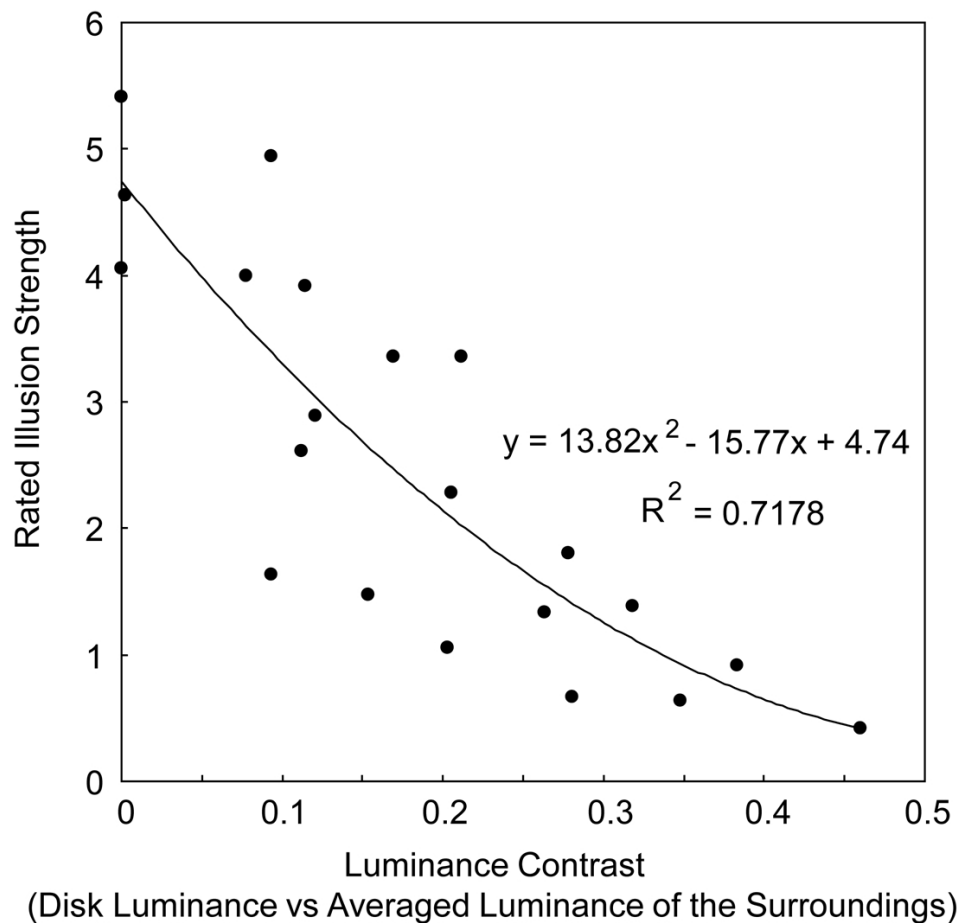
The author and two naïve graduate students participated.

#### 4.1.2 Apparatus and stimuli

The stimulus was produced by a computer (Dell, XPS-502X) presented on a 24-inch LCD display (Mitsubishi, RDT233WX-3D) and viewed from a distance of 35 cm. The luminances of the background and the sectors were 100 cd/m<sup>2</sup> and 50 cd/m<sup>2</sup> in the high-luminance condition. In the middle-luminance condition, the luminances were set at 80 cd/m<sup>2</sup> and 40 cd/m<sup>2</sup> for the background and sector luminances, respectively. In the low-luminance condition, 60 cd/m<sup>2</sup> and 30 cd/m<sup>2</sup> were used. The subjects sat on a chair with a chin rest and tracked a black dot with their eyes as in Experiment 1. Only one stimulus figure was presented to the bottom left of the display. The size of the stimulus figure was 14.4 deg in diameter, and the size of the disk was 4.9 deg in diameter. The centre of the disk was 20.6 deg apart from the centre of the tracked dot path. Other stimulus properties were the same as those in Experiment 1.

#### 4.1.3 Procedure

There were two experimental sessions. In the first session, the yellow-disk luminance to produce the best illusion was measured. The participant's task was to adjust the disk luminance to maximize the effect. They could control the disk luminance by pressing a



**Figure 6.** Rated illusion strength as a function of Michelson contrast between the luminance of the disk and the surrounding areas.

button from  $5 \text{ cd/m}^2$  to  $125 \text{ cd/m}^2$  in steps of  $5 \text{ cd/m}^2$ . The participants performed six trials for each of the three surrounding luminance conditions in a randomized order.

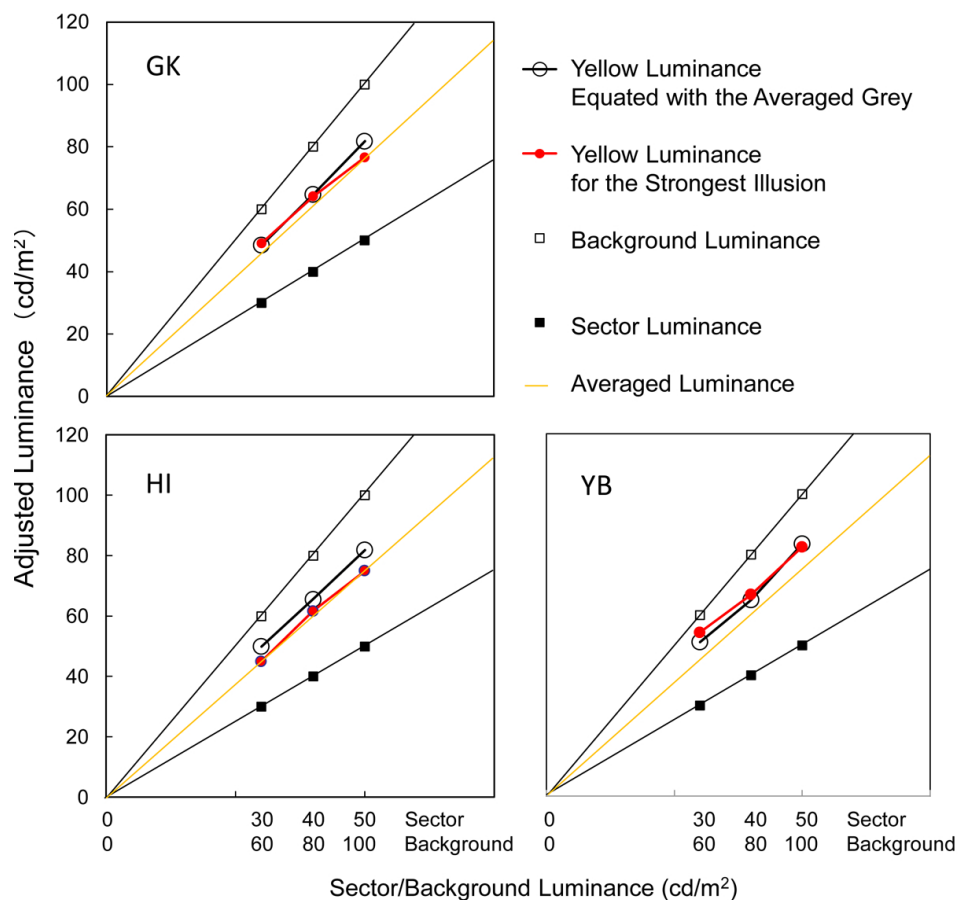
In the other sessions, an individual equiluminance was measured where the yellow disk luminance was effectively equated to the averaged luminances of the surrounding grey (ie,  $75 \text{ cd/m}^2$ ,  $60 \text{ cd/m}^2$ , and  $45 \text{ cd/m}^2$  for high-, middle-, and low-luminance conditions, respectively) by heterochromatic flicker photometry. Participants fixated on a cross presented at the centre of the dot motion path to be tracked. The yellow and grey squares were alternated at 10 Hz in the screen position where the stimulus was presented. The participants adjusted the yellow luminance by pressing a button to minimize the perceived flicker. Six measurements were conducted.

#### 4.2 Results and discussion

Figure 7 shows the results. The adjusted luminances for the best illusory effect and the individual equiluminance points acquired from three participants were plotted. The participants' adjustments were quite precise, ie, exhibiting very little variance. Even if the surrounding luminances changed, the best luminances were always between the sector and background luminances, and often slightly above the average of the surrounding luminances. The yellow luminances that were effectively equiluminant to the average of the surrounding grey luminances were also slightly above the averaged photometrical luminance. This trend was the same for the results from the three participants. Data from two participants showed that the luminances for the best illusion were almost equal to the yellow luminances that

were effectively equiluminant to the averaged surrounding luminance, rather than the yellow luminances that were simple averages of the photometric surrounding luminances. This inversely demonstrated the importance of the equiluminant yellow. The result from the other participant showed that the disk luminance for the best illusion was similar to the photometric average luminance. This is possibly due to an individual difference in the strategy for judging the best illusion. These results also explain why the resulted curves acquired in Experiments 1 and 2 (as shown in figures 3 and 5) were not keen at the photometric equiluminance.

Together with the results from Experiments 1 and 2, it can be clearly shown that the disk luminance in the averaged surrounding luminance is a determinant of the illusion strength.



**Figure 7.** Disk luminance to maximize the illusory effect. Under all the combinations of sector and background luminances, the Michelson contrast was the same (33%). The adjusted yellow-disk luminance for the strongest illusion was almost always between the yellow luminance in the average of the photometric sector and background luminances and the yellow luminance that was effectively equated with the averaged grey luminance by flicker photometry.

## 5 Experiment 4

The results from Experiments 1–3 may suggest that the illusion was strong when motion signals from the disk were weak. However, if the low luminance contrast between the disk and the surroundings (ie, unclear motion signals) was the only factor affecting the illusion, a grey equiluminant background without sectors would be expected to induce an illusion of the same strength. Thus, Experiment 4 investigated the effects of the luminance contrast between the sectors and the background, including the zero-contrast (homogenous

grey) condition. This stimulus manipulation is considered as changing the strength of the detected surrounding motion without changing the strength of the detected disk motion or as changing the visibility of the radial pattern surrounding the disk.

### 5.1 Method

The same 18 participants who took part in Experiments 1 and 2 participated in Experiment 4. The luminance of the disk was held constant at  $54.0 \text{ cd/m}^2$ . However, the luminance contrast between the sectors and the background was varied in four conditions, while the average luminance remained almost constant. The sector and background luminances were paired as follows: (1)  $54.5 \text{ cd/m}^2$  and  $54.5 \text{ cd/m}^2$ , (2)  $65.2 \text{ cd/m}^2$  and  $42.8 \text{ cd/m}^2$ , (3)  $76.2 \text{ cd/m}^2$  and  $31.8 \text{ cd/m}^2$ , and (4)  $84.1 \text{ cd/m}^2$  and  $24.4 \text{ cd/m}^2$ , for sector and background luminances, respectively. The Michelson contrasts of these four pairs of luminances corresponded to 0, 0.21, 0.41, and 0.55, respectively. When the contrast was 0, no sectors (and thus no radial patterns) were perceived. The other methods were the same as those in Experiments 1 and 2.

### 5.2 Results and discussion

Figure 8 shows the results from Experiment 4. The linear relationship between the rated illusion strength and the luminance contrast of the radial pattern is evident from the graph. When the luminance contrast of the radial pattern was high, the rated illusion strength was high within the contrast range tested. When the contrast was 0 (ie, when there was no radial pattern), the illusion was still induced, but weakly so. A one-way ANOVA revealed a significant main effect of contrast,  $F(3, 51) = 33.33$ ,  $p < .0001$ . Multiple comparisons revealed significant differences between every pair of conditions ( $p < .05$ )

It is possible that the yellow disk luminance and the plain grey background luminance were not effectively equiluminant for some people, and that the residual luminance difference between the disk and the plain grey background caused by individual differences in equiluminance or peripheral viewing could have weakened the illusion. However, two factors indicate the importance of the radial pattern in this illusion. First, when the radial pattern was visible, a relatively strong illusion was induced over a broad range of disk luminances, as shown in Figure 3. The range of disk luminances, which induced a much stronger illusion than the plain grey background condition, may thus be far broader than that of the individual differences in equiluminance between yellow and grey or that of equiluminance shift by peripheral vision. Second, the higher contrast between the sector and background luminances induced a stronger illusion, even though the averaged luminance of the surrounding area remained the same. The results revealed that even when the residual luminance difference between the disk and the average of the surrounding luminances weakened the illusion, the effect of the radial pattern became greater according to the increase in luminance contrast between the disk and the background.

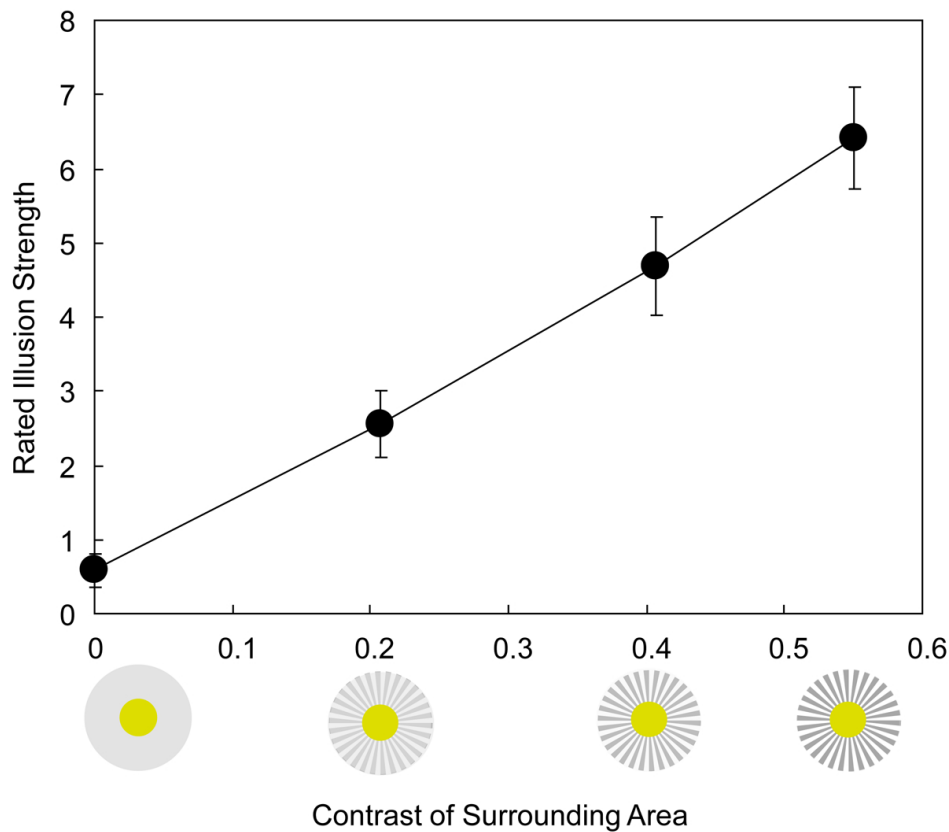
Informal observations were carried out to discern the illusory effect in the yellow disk without the surroundings after the equiluminance matching by flicker photometry in peripheral vision. The effect actually arose without a radial pattern, as shown in Figure 8, but was still much weaker than that with a radial pattern.

From the results so far, one possible hypothesis could be that well-detected motion of the surrounding high-contrast radial grating and poorly detected disk motion may cause motion contrast, resulting in a perceived disk-motion component in a direction opposite to the surrounding motion direction.

One may argue that when the contrast of the surroundings (ie, sectors and the background) changes, the contrast between the disk and the sectors, or between the disk and the background, also changes. The three contrasts were not independent but covariant. Thus, it is possible to interpret the results as showing that the luminance contrast at each point of the sector-disk contact had an effect on the illusion, even if the averaged luminance was the

same between the disk and the surroundings. This factor could not be excluded from the present results and should be tested in future by a minute stimulus manipulation.

When the contrast between the sector and background luminances was close to 1.0, the illusory motion became noisy by flicker impressions and assumed a dazzling appearance for some observers. This resulted in a degraded motion illusion in smoothness. Thus, the subjective ratings would not be suitable in the higher-contrast stimuli.



**Figure 8.** Rated illusion strength as a function of the Michelson contrast of the surroundings. Error bars indicate *SE*.

## 6 Experiment 5

In Experiment 4, the high contrast of the surrounding stimulus was shown to be important. When a visual object was surrounded by high-contrast striped edges, the edge part induced a motion illusion (Cavanagh and Anstis 2002), and such an illusion could induce perception of the object deformation (Fantoni and Pinna 2008). To confirm the importance of the radially arranged sectors in this illusion, and not the striped edge around the disk, Experiment 5 investigated the effect of the length of the sectors. If the striped edge was critical for the illusion, the sector length may not have been important (high-contrast dotted edges were sufficient).

### 6.1 Method

Fifteen naïve graduate students (none of whom participated in the previous experiments) participated in Experiment 5. Experiment 5 tested the effect of the length of the sectors (ie, the size of the radial surroundings) on the strength of the illusion. The length of the sectors from the inner edges touching the disk to the outer sector edges was varied in seven conditions; 0%, 10%, 20%, 30%, 40%, 60%, and 93% of the disk diameter. The number of



sectors was constant at 30. Each session included trials in the seven conditions, conducted once in a random order. Two sessions were conducted for each participant. All other methods were the same as those used in Experiment 4.

## 6.2 Results and discussion

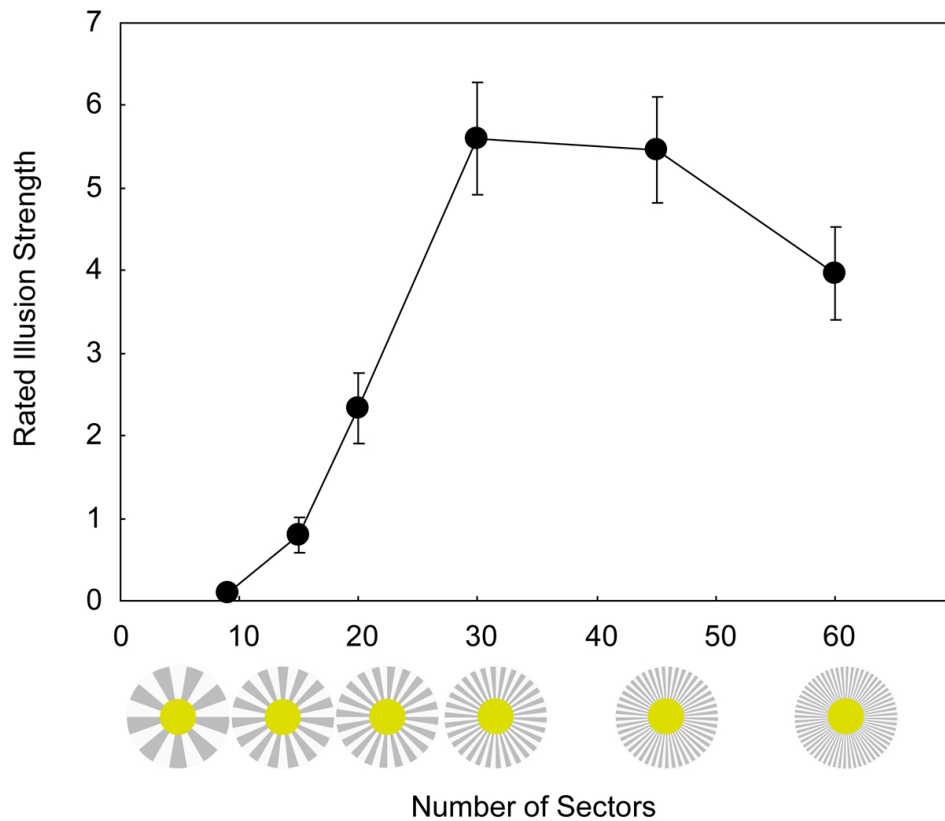
As shown in [Figure 9](#), the length of the sectors was also a critical factor when it was less than 60% of the sector diameter, which produced the highest-rated illusion strength. A one-way ANOVA revealed a significant main effect of the length of sectors,  $F(6, 84) = 22.99, p < .0001$ . Multiple comparisons revealed that the rated illusion strength in the 60% sector length condition was significantly different from that in the 0%, 10%, 20%, and 30% conditions ( $p < .05$ ), though the difference between the 60% condition and the 40% or 93% conditions did not reach significance ( $p > .05$ ). The results suggest that the Pursuit–Pursuing illusion needs sectors in a certain amount of length and that the striped edge around the disk was not sufficient.

The sector length is related to ambiguity in the detected motion directions of the surrounding stimulus. Gori and Yazdanbakhsh (2008) showed that a compromise between local motion signals from contour motion and those from line-end motion determines the perceived motion direction of the Rotating Tilted Line illusion. Yazdanbakhsh and Gori (2008) used the illusion to estimate the receptive field size of motion detectors. According to their theory, when the present sectors were shorter than the receptive field size, the perceived sector motion could become similar to the real motion. On the other hand, when the sectors were longer, the perceived sector motion could become more perpendicular to the sector orientation due to the aperture problem. As for the present stimulus, very short sectors (eg, 10%) could have produced a Boogie-Woogie illusion (Cavanagh and Anstis 2002) along the disk edge. However, possibly due to peripheral viewing, the illusion was not seen. As a dotted line biases its perceived motion direction to the line orientation (Ito et al 2009), detected motion directions in the shorter sector conditions may be circular along the disk edge. On the other hand, if the longer sector is misperceived in motion direction by the aperture problem, the perceived motion direction would also be circular around the disk. Thus, the possible misdetections of the surrounding motion were similar for the shorter and longer sector conditions. It is not appropriate to say that the difference in the magnitude of the illusion is explained by the difference in detected motion directions in the surrounding sectors. Instead, it is possible that the magnitude of the illusion is determined by the amount of detected motion signals in the surrounding area, which depends on the sector length.

From the point of the perceived structure of the stimulus figure, there is an important difference between the short and long sector conditions. The stimulus disk with short sectors appears to have dotted edges belonging to the disk. On the other hand, the disk with long sectors appears to be floating on the radially arranged sectors, ie, forming the figure–ground relationship. This perceived depth separation could arise from the illusory motion of the disk. However, it is also possible that the figure–ground relationship enhances the motion contrast between the disk and the radially arranged sectors.

## 7 Experiment 6

Some illusions with radial lines are sensitive to the number of lines. For example, Kumar and Glaser (2006) tested the effect of the number of lines in the Enigma illusion. They found that the strength of the illusory effect showed an inverted U curve according to the increasing number of lines and that 3.6 degrees of line spacing (ie, 100 radial lines in the figure) was best for the illusion. The scintillating luster effect in Pinna et al (2002) also revealed an inverted U curve for the number of lines. In their illusion, 18 radial lines in the figure were best for the illusory luster and brightness enhancement (see [Figure 1b](#)). The Windmill illusion (Pinna



**Figure 9.** Rated illusion strength as a function of the length of radial components. Error bars indicate SE.

and Dasara 2005) uses only eight sectors. Experiment 6 explored the best condition for the number of radially arranged sectors.

### 7.1 Method

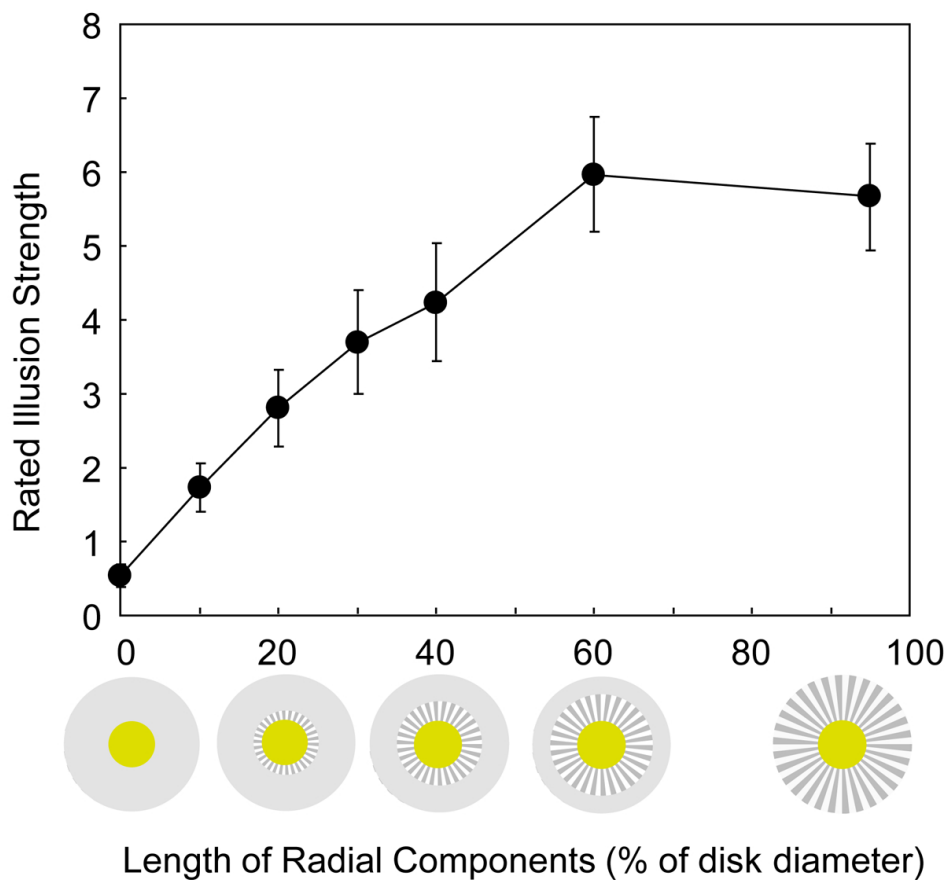
The same 15 naïve graduate students who participated in Experiment 5 participated in Experiment 6. In Experiment 6, as shown in Figure 10, the number of sectors was varied. To keep the duty ratio along the circular path around the disk at 50%, when the sectors decreased in number, the thickness of each sector increased counter-proportionally. The values used were 9, 15, 20, 30, 45, and 60, as shown in Figure 10. Each session included trials in six conditions, conducted once each in a random order. Two sessions were conducted for each participant. All other methods were the same as those used in Experiment 5.

### 7.2 Results and discussion

As shown in Figure 10, the results revealed that the number of sectors was a critical factor for inducing the illusion. The rated illusion strength was found to be highest when there were 30 sectors. A one-way ANOVA revealed a significant main effect for the number of sectors,  $F(5, 70) = 37.82, p < .0001$ . Multiple comparisons revealed that the rated illusion strength in the 30-sector condition was significantly different from that in the other conditions ( $p < .05$ ), except for the 45-sector condition ( $p > .05$ ).

Changes in the number of sectors also changed the number and width of the inner edges of the sectors touching the disk, spatial frequency of the surroundings, and homogeneity in locally averaged luminance. It is apparent that the numerosity of the sectors covaried with the spatial frequency and the density together. Density is considered to be a primary visual attribute (Durgin 1995). Burr and Ross (2008) and Ross and Burr (2010) showed that numerosity was also a primary sensory attribute independent from density. The result for

the filled area illusion by Giora and Gori (2010) showed that the spatial frequency and the number of elements had an effect independently on the perceived extension of the textured square. In the present experiment, it is also possible that the number of sectors (or edges touching the disk) and spatial frequency were independent factors. The results showed the inverted U-shaped curve of the illusory effect according to the increase in the number of the sectors. A larger number of sectors may increase the strength of the illusion, while a higher spatial frequency may decrease the visibility of the sectors due to the low resolution in peripheral vision. On the other hand, it is also possible to hypothesize that the density, not numerosity, is important here. A lower density of sectors increased the unevenness of the locally averaged luminance, violating equiluminance between the disk and the surroundings.



**Figure 10.** Rated illusion strength as a function of the number of sectors. Error bars indicate *SE*.

## 8 Experiment 7

Experiment 7 quantitatively measured the strength of the illusory effect. The experiments noted above mainly used a subjective estimation method to test the illusion. Therefore the illusory strength measured so far was limited to indicating the relative effectiveness among stimulus conditions. Here, the illusion strength was measured by matching between real and illusory motions to show quantitatively the amount of the illusion.

### 8.1 Method

#### 8.1.1 Participants

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The author and two graduate students, who all also participated in Experiment 3, participated in Experiment 7.

### 8.1.2 Apparatus and stimuli

The apparatus was the same as that used in Experiment 3. [Figure 11](#) shows the schematic illustration of the stimulus display. In the top centre of the screen, a circularly moving black dot was presented, which participants tracked with their eyes. The rotation speed was 0.5 rev/s. The diameter of the circular path was varied in three (3.3 deg, 4.9 deg, and 7.4 deg, corresponding to 67%, 100%, and 150% of the yellow disk diameter, respectively). In the lower-left part, a static illusory figure ([Figure 1a](#)) was presented. The diameter of the whole radial shape was 14.4 deg, and that of the central disk was 4.9 deg. The distance between the centre of the stimulus disk and the centre of the circular path of the dot motion was 28.0 deg. The sector and background luminances were 40 cd/m<sup>2</sup> and 140 cd/m<sup>2</sup>, respectively. The number of sectors was 30.

In the lower-right part, a circularly moving yellow disk was presented. The phase was matched with that of the tracking target. The diameter of the circular path of the physical motion of the matching disk could be changed from 0 deg to 8.3 deg in 0.49-deg steps (from 0% to 170% of the disk diameter with 10% steps). The diameter and the luminance of the physically moving matching disk were identical to those in the illusory figure. The distance between the stimulus disk and the centre of the physical motion path of the matching disk was 30.4 deg.

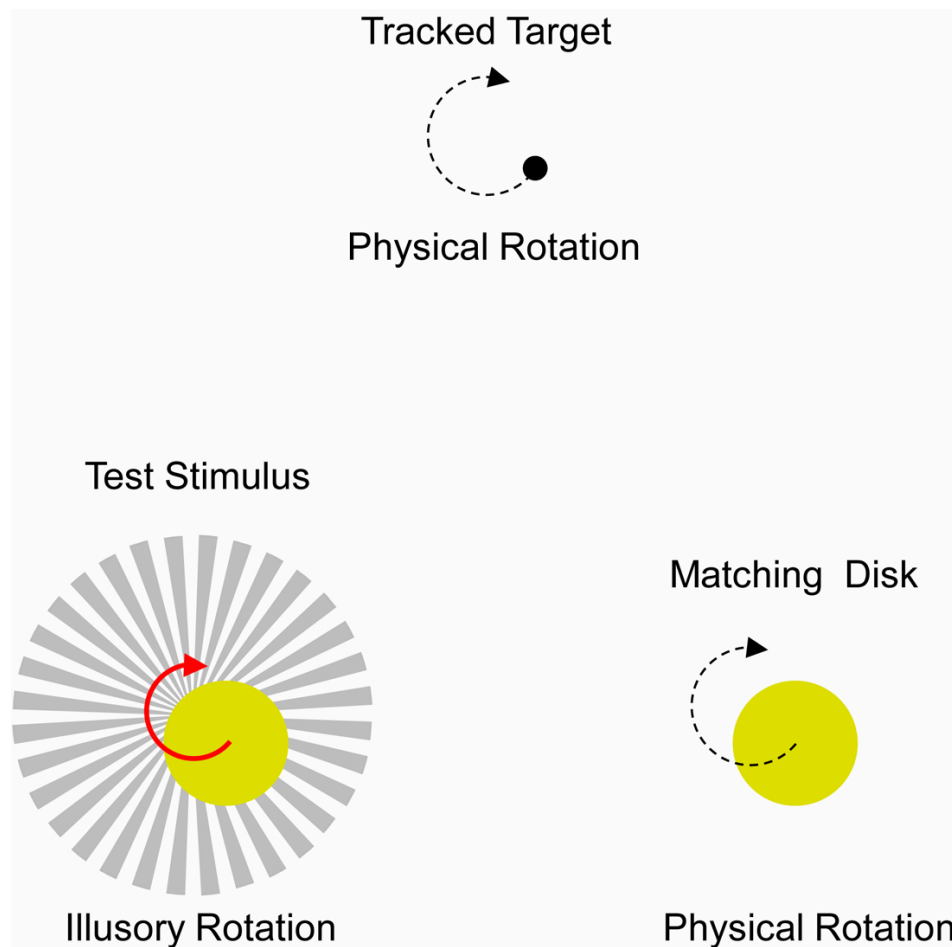
### 8.1.3 Procedure

Before measuring the illusion strength, the luminance of the yellow disk was individually equated with 90 cd/m<sup>2</sup> of grey, ie, the average of the surrounding luminances determined by flicker photometry. Participants fixated on a cross presented at the centre of the circular path of the dot motion. The yellow and grey squares were alternated at 10 Hz in the screen position where the stimulus was presented. The average luminance of six measurements was set to the yellow disk of the test stimulus and the yellow matching disk.

Participants matched the circular-path diameter of the physical motion of the matching disk with the diameter of the illusory circular motion path by pressing a button while tracking the physically rotating dot with the eyes, as shown in [Figure 11](#). In a randomized order, six measurements were conducted under the three tracking path diameter conditions for each participant.

## 8.2 Results and discussion

[Figure 12](#) shows the results for Experiment 7. For one participant, as the path diameter of the tracking target increased, the matched path diameter of the matching disk increased proportionally. However, the results from the other participants did not show the same trend. The matched path diameter almost equaled the diameter of the tracked-target path under the 3.3-deg path-diameter (67% of disk diameter) condition. This suggests that the illusory motion speed or path length corresponded to the eye movement speed or path length. This also suggests that the illusory motion produced an illusory position shift of the disk by 33% of the disk diameter. On the other hand, the 4.9-deg and 7.4-deg path-diameter conditions failed to produce a larger illusory effect for two participants. One factor that can suppress the large illusory motion is a motion–position conflict. Thirty-three percent of the disk diameter might be the ceiling of the illusory effect with this measuring method. Another factor that can decrease the illusory motion is the lower quality or the lower amount of eye movements. The smoothness of eye movements would be less with higher-speed tracking, and sometimes



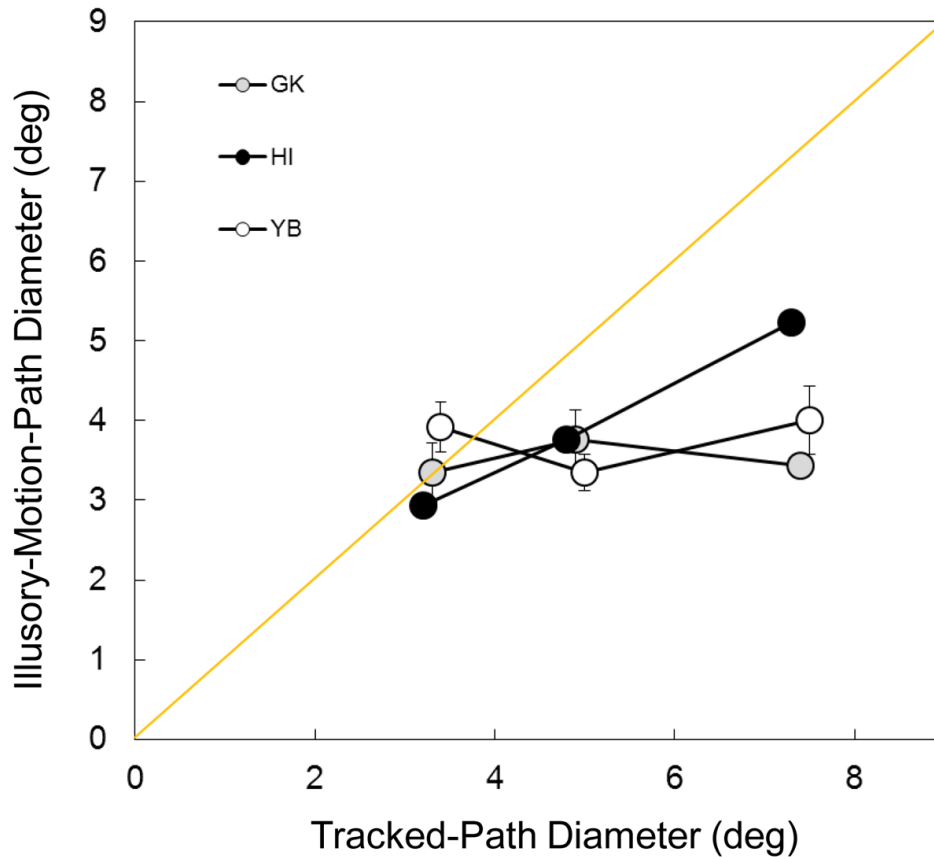
**Figure 11.** Schematic illustration of the measuring method in Experiment 7. Participants matched the diameter of the physical rotation path of the matching disk according to the impression of the illusory rotation path of the yellow disk in the test stimulus while tracking the physically rotating target. Note that the yellow disk in the test stimulus was physically static in the centre of the radially arranged sectors.

with small saccades. The diameter of an actually tracked path might be smaller than the diameter of the physical path of the tracking target when the target speed was high. From informal observations, tracking also by pointing a finger seemed to increase the illusory effect. This may be because observer-generated motion is easier for the observer to track with their eyes (Steinbach and Held 1968).

Although the present effect was very large, this result may not be the maximized performance because several factors are still left untested, eg, stimulus size, and eccentricity. In any case, the matching method could quantitatively measure the illusory effect. This method will be used for future research on this illusion.

One of the best procedures to describe the illusory effect quantitatively is a cancelling method. However, there were two reasons not to adopt the method here. First, it was problematic to move the stimulus disk because the disk had to be placed in the centre of a radial pattern to produce the illusion. Second, even when the disk was physically moved in a direction as far as possible, the real motion did not affect the illusory motion perception. That is, the real disk motion within the short distance was not sufficient to cancel the illusion in the present stimulus setting. To cancel the illusory motion, the disk had to move on a path largely off the centre of the radial pattern, which itself could weaken the illusion.

Another technical possibility to measure the effect quantitatively is to move the stimulus figure instead of moving the eyes. However, the fine radial sectors were not seen to move smoothly on a PC display. The artefact in wrong apparent motion, caused by the monitor refresh and afterimages on the display, reduced the quality of the illusion. More importantly, subjective standstill was more difficult to measure quantitatively than subjective motion.



**Figure 12.** Diameter of the illusory circular motion as a function of the diameter of the physical circular motion of the tracked target. The oblique line in the figure indicates a hypothetical illusory circular-motion diameter when the circular motion of the tracked target produced the illusory circular motion at an amount of 100% in diameter. Error bars indicate *SE*. Please note that each marker is horizontally slightly shifted to avoid overlap.

## 9 General discussion

Through the seven experiments, the characteristics of the Pursuit–Pursuing illusion have been described. Experiments 1–3 revealed that illusory motion was perceived most strongly when the disk was at the same luminance as that of its surroundings (the average of the sector and background luminances). This equiluminant condition may allow perceptual positional shifts of the disk in the radial pattern. Experiment 4 indicated that the radial pattern should be in high luminance contrast for inducing a strong illusory motion. This finding confirms that the radial pattern plays an important role in producing the illusion, in addition to equiluminance between the disk and the surroundings. Experiments 5 and 6 also revealed that the length and number of the surrounding sectors were critical factors to determine the illusion strength. Taken together, the experiments described in the current study clarified the characteristics of the new motion illusion, ie, the Pursuit–Pursuing illusion, and indicated the optimum conditions for inducing illusory motion in this paradigm. Finally,

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Experiment 7 demonstrated the possibility of quantitatively measuring the illusion, which will be used in future research or in comparing the effect with other motion illusions.

This phenomenon differs from the Fluttering-Heart illusion (Grünau 1975a, 1975b, 1976; Nguyen-Tri and Faubert 2003), where object motion perception is delayed relative to background motion perception, causing apparent phase lags between them resulting in the perception of the stimulus moving back and forth. The presently described phenomenon differs in that it always causes object-motion perception in the direction that is opposite to the surrounding motion, whereas the Fluttering Heart illusion causes this effect for a very short period around the stimulus–motion–direction reversal. This is the case even when the Fluttering Heart illusion is caused by the difference between luminance-defined and colour-defined motions (Nguyen-Tri and Faubert 2003) or by high-contrast and low-contrast motions (Kitaoka and Ashida 2007). In addition, the present illusion (Figure 2b) arises even when viewed in sunlight, whereas the Fluttering-Heart illusion is strongest when viewed under conditions of mesopic vision. In addition, the classic Fluttering-Heart illusion requires saturated colours and is especially strong with a combination of a blue target on a red background. In contrast, the present illusion arises even with grey-scale images, although a coloured disk produces a more conspicuous effect.

The present effect may be related to the motion-capture effect reported by Ramachandran (1987), which shares common stimulus characteristics. The stimuli in both effects consist of unclear motion of a low-contrast object and clear motion of a high-contrast object. However, an important difference between the two phenomena is in the direction of illusory motion. In the case of motion capture, a stationary coloured object is perceived to move in the same direction as high-contrast objects. On the other hand, in the present effect, a disk is perceived to move in the same direction as that of the participant's eye movement, which is opposite to the motion direction of the surrounding high-contrast pattern. Although the disk actually moves on the retina in the same direction as the surrounding motion, the two motion directions are perceived to be dissociated. In addition, as shown in Figure 2b, when one rotates the stimulus sheet while fixating at the centre, the radial patterns are seen to move as they do, while the disk appears to be stationary or to move in the opposite direction to the radial pattern motion. Thus, the weak motion of the disk is not captured by the strong motion of the radial pattern. As such, the Pursuit–Pursuing illusion presented here and the motion capture phenomena appear to be caused by different mechanisms.

In a previous study, the Pinna–Spillmann–Ehrenstein figure was investigated to explore the optimum conditions for inducing the scintillating luster effect (Pinna et al 2002). The optimum conditions reported by Pinna et al (2002) appear to differ from the optimum conditions for inducing illusory motion found in the present study. Two factors may account for this difference: first, the difference between lines and sectors; and second, the difference in illusory effects. The scintillating luster effect was investigated in terms of luster, while the present effect was investigated in terms of illusory motion. Pinna et al (2002) also reported illusory motion arising in their figure. However, the observed motion was proposed to be similar to that in the Ouchi illusion or the Fluttering Heart illusion (Pinna et al 2004). The researchers did not present a detailed analysis of the impression of illusory motion arising in their figure. As such, it is unclear whether the present illusion and the illusory motion observed by Pinna et al (2002, 2004) share the same or different mechanisms. On the other hand, it is difficult to control the present illusion with radial lines (instead of sectors) because it is difficult to define the equiluminance between the centre disk and the surroundings, which is critical for the illusion. The sectors had a constant average luminance over the surrounding areas, enabling the illusory motion effect to be maximized by setting the disk luminance at the same luminance as the averaged surrounding luminance. The sectors

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covering 50% of the surrounding area may contribute to motion detection in peripheral vision due to a strong effective luminance contrast, while lines around the centre disk would not be optimal in terms of motion detection in peripheral vision.

As a provisional hypothesis, the present effect may be explained by the functioning of centre-surround relative motion detectors (Loomis and Nakayama 1973; Murakami and Shimojo 1995; Tynan and Sekuler 1975). When the retinal image moves according to eye movement, the retinal motion of the radial pattern would be expected to be strongly detected, whereas the centre disk motion would be poorly detected. Thus, relative motion detectors could be activated, resulting in pseudo-opposite motion signals in the centre disk area (ie, motion contrast or induced motion). This hypothesis provides a good explanation for the results of Experiments 1–6 in four ways: (1) the disk would be expected to exhibit the same luminance as the averaged luminance over the surroundings to minimize motion detection of the disk; (2) the surrounding area consisting of sectors would be expected to exhibit a strong luminance contrast to produce strong motion signals in the surroundings; (3) the length and number of sectors would be critical in detecting surrounding motion; and (4) a sufficient number of sectors would be needed to homogenize the local averaged luminance.

An alternative explanation is that the disk and the surroundings are processed by somewhat different processes. Pinna et al (2004) suggested that the luster effect resulted from rivalry, possibly between activity in the magnocellular and parvocellular pathways. The outer parts of the sectors causing the Pursuit–Pursuing illusion are wider than the inner parts and have lower-spatial-frequency components. This could be an advantage for the motion-detection system. On the other hand, the inner parts of the sectors have a higher spatial frequency, which is a disadvantage for the motion system. This could lead to the combination of the poorly detected motion in the centre and the well-detected motion in the surround.

Generally, when stimuli for motion illusions are reproduced by isoluminant colours, most motion illusions vanish, eg, in the Bulging Grid illusion (Foster and Altschuler 2001), except in Ito (2005). This indicates that most motion illusions arise in the magnocellular pathway, or at least the magnocellular pathway plays an important role. However, in the Pursuit–Pursuing illusion, an equiluminant disk without sectors still works, although the effect is weak. This may indicate that the ineffectiveness in motion perception in the parvocellular pathway is one component of the Pursuit–Pursuing illusion. On the other hand, the spatial frequency components that the radial pattern shows are too high to be processed effectively by the magnocellular stream. Thus, the role of the magnocellular pathway in this illusion is not clear.

It is also possible that a radial shape produces an illusory component in the centre, which is only represented in the brain and not detected by motion-detection systems (cf Pinna et al 2002). Thus, when the eyes move smoothly, the disk would be seen to move with the eyes. Similarly, when the pattern moves, as in Figure 2b, the disk would be perceived as stationary, because the disk motion would not be detected. The typical radiation of a figural construction is also critical for the induction of other types of illusions, as found in Pinna et al (2002, 2003, 2004). This hypothesis also provides a good explanation for the results. Both Experiments 5 and 6 revealed that optimal figural features of a radial pattern exist, in terms of inducing the strongest illusory motion. Experiment 4 showed that higher-contrast surroundings induced a stronger illusion. High-contrast radially arranged sectors might produce firmer illusory shape components, such as the subjective contour seen in the Ehrenstein figure (Ehrenstein 1941). From the results of Experiments 4–6, around 30 high-contrast sectors at 60% (or more) length of the disk diameter may be the optimal radial figure within the range tested here.



However, it remains unclear how and where in the brain the illusory component in the centre of the radial pattern is produced.

Another candidate for a motion-undetectable image is afterimages. Generally speaking, afterimages may arise in the retina. Negative afterimages are thought to be caused by bleaching of retinal photoreceptors and, thus, should move with the eye. Petrov and Popple (2002) proposed a model to explain some types of motion illusions by afterimages. Anstis et al (2007) suggested that afterimages added to the present scene produce a motion-induced brightness illusion, ie, the Breathing Light illusion (Gori and Stubb 2006). This hypothesis was confirmed experimentally by Gori et al (2010). However, to produce the Pursuit–Pursuing illusion, sector length is critical, as shown in Experiment 5. The Pursuit–Pursuing illusion arises, even during slow or small eye movement. Thus, there is no reason why the sector length modulates the effect of the afterimage of the disk. In the Breathing Light illusion, adaptation for several seconds before the start of motion enhances the effect. However, the Pursuit–Pursuing illusion arises immediately with adequate strength, thus suggesting no need for adaptation for the illusion to occur. On the other hand, unexpectedly, it has been revealed that afterimages are not a simple retinal product but reflect visual processing in the brain (Ito *in press*; MacKay 1957; Shimojo et al 2001). Some contribution of afterimages produced in the brain to illusions might be found in future.

The effect of the present illusion is isotropic because it consists of a radial pattern. However, it may be possible to produce an illusory pattern that is optimized for a certain direction using a non-radial shape. Such a stimulus manipulation will be useful in further testing of the necessity of the illusory shape component produced by the Ehrenstein figure (Ehrenstein 1941) or the importance of motion detection in the surrounding. We are planning the next series of experiments along this line.

Some stimulus properties have been left untested, eg, the colour combination, displayed eccentricity, and the size of the stimuli. The colour of the disk, beside its brightness, seems not to be solely critical for the illusion. A reddish, bluish, greenish, or pinkish disk is also seen to move, while a small difference in the effect might exist. Generally, the illusion is enhanced in peripheral vision. However, it is hasty to draw conclusions, because the best stimulus eccentricity and the best stimulus size for the optimized illusion could be covariant. Thus, detailed experiments on the combined effect of the stimulus size, spatial frequency, and eccentricity are needed in the future just as conducted by Ashida (2002) testing the Ouchi illusion.

This paper has reported a novel motion illusion. Only reversed phi (Anstis 1970) and one type of sliding motion (Pinna and Spillmann 2005) have been reported previously to produce illusory motion in a direction that is opposite to retinal motion. The presently described phenomenon is a new example of such a motion illusion. On the other hand, when the present figure is rotated as shown in Figure 2b, the centre circles can be seen to be stationary, ie, the phenomenon appears as the illusory standstill against physical motion. This may be the first example of a “stillness” illusion.

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