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PHENOMENAL REPORT

Variations and extensions of the kinetic Orbison illusion

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Abstract

When a dot moves along a square trajectory on concentric circles, the trajectory appears to bend toward the center of the circles (the kinetic Orbison illusion). This report demonstrates new illusions that are variations or extensions of the kinetic Orbison illusion. We found that some of them produced an illusory effect that was larger than the original version of the kinetic Orbison illusion (up to 1.8 times larger than the original). The illusion became even stronger when a dot moved along a triangular trajectory, reaching 1.4 times the strength as that of the strongest illusion with the square trajectory. The implications of these illusions for the kinetic Orbison illusion and the relationship to previously reported motion illusions are discussed.

Keywords: *the kinetic Orbison illusion*; *geometrical illusion*; *relative motion*; *aperture problem for motion*; *induced motion*

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Orbison (1939) reported a geometrical illusion in which a circle or square appears to be distorted when placed on various geometrical patterns. A square placed on concentric circles is a typical example: the sides of the square appearing to bend inward (Fig. 1a). Matsunaga et al. (2023) found that when a dot moves on a square trajectory on concentric circles, the sides of the trajectory appear to bend inward (the kinetic Orbison illusion, see Fig. 1b). It has been shown that replacing a line segment that forms a geometrical illusion with the trajectory of a moving dot produces an illusion of the direction of motion or trajectory of the dot, for example, the Zöllner illusion (Khuu, 2012; Swanston, 1984; Zöllner, 1860) and the Hering illusion (Hering, 1861; Swanston, 1984). In these illusions, the motion streaks of the dot or subjective contours caused by dot motion were thought to interact with the background line segments to produce the geometrical illusions that could inversely change the apparent direction of motion of the dot (Khuu, 2012). Besides the traditional geometrical illusions, the trajectory of a moving object can be perceptually altered by the background lines (e.g. Anstis, 2012; Cesàro & Agostini, 1998; Cormack et al., 1992; Gheorghes et al., 2020; Ito & Yang, 2013).

Matsunaga et al. (2023) found that the magnitude of the kinetic Orbison illusion was twice that of the static Orbison illusion. The amount of the illusion greatly increased when the eyes tracked the moving dot, the illusion became stronger as the dot moved slower, and the illusion occurred even when the dot's trajectory did not cross the circles. These results contradict the hypothesis based on motion streaks. They proposed that a relative motion component between the dot and the circles contributes to the illusion when the dot is tracked by the eyes (Fig. 1c). Accordingly, the kinetic Orbison illusion may have two aspects: One is a static/traditional Orbison illusion that appears on the perceived motion trajectory. The other is an illusion of motion direction of a moving dot on a specific background. The present study focused on the latter.

The possible factor of relative motion in the kinetic Orbison illusion motivated us to produce new illusion demonstrations. The purpose of this report is to present the movies that can be considered as variations or extensions of the kinetic Orbison illusion. We have found that some of

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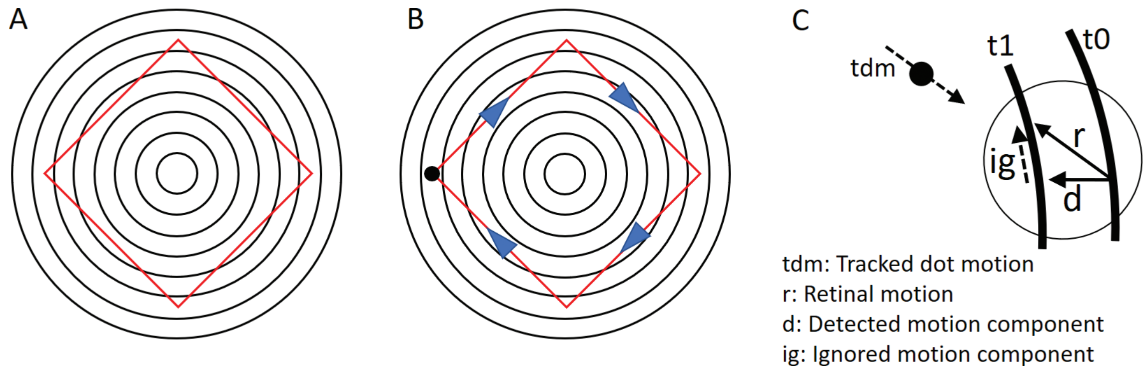

Fig. 1. The kinetic Orbison illusion. (a) shows an Orbison illusion figure. The sides of the square are perceived to bend inward. (b) shows a schematic illustration of the kinetic Orbison illusion. A dot moves along a square trajectory, and the sides of which are perceived to be curved inward. (c) shows the motion components and the aperture problem in the kinetic Orbison illusion at the right corner of the square trajectory (redrawn from Matsunaga et al., 2023). See details in text.

them have a much greater effect than the original version of the kinetic Orbison illusion. First, we produced a series of rotating dashed circle movies that are directly related to the kinetic Orbison illusion. Second, we produced a series of rotating radial line movies that eliminated circular contours but retained the rotational motion component of the background. Third, we produced triangular versions of the movies, which we found to be more impressive. We discuss the demonstrations in relation to the kinetic Orbison illusion and to previously reported motion illusions.

The trajectory and speed of the dot are always the same in the following demonstration movies, except for those using a triangular trajectory. The dot moves on a square trajectory rotated by 45 degrees because the kinetic Orbison illusion is stronger in the rotated square trajectory than in the upright trajectory (Matsunaga et al, 2023).

Rotating dashed circles

In this section, we demonstrate a new illusion of motion direction (or trajectory) of a dot on dashed circles. As shown in Fig. 1c, when the eyes track a dot moving on concentric circles (*tdm*), the circular contours on the retina move in the opposite direction to the dot's motion (*r*). Locally, however, the direction of motion of the smooth contours may be ambiguous due to the aperture problem (Adelson & Movshon, 1982; Wallach, 1935). When motion in a direction orthogonal to the circular contours is detected (*d*) and motion along the contours (*ig*) is ignored, the perceived motion direction of the dot can be biased toward the direction opposite to the detected circular contour motion (Matsunaga et al., 2023). This effect is thought to be greatest at the corners of the square trajectory and least at the midpoints of the sides. This may perceptually sharpen the corners of the square trajectory and conversely create a bending impression of the sides. According to this explanation, we produced a movie to reduce the effect of the aperture problem by using dashed circles (Fig. 2a). When the eyes track a dot that moves (*tdm*) on static-dashed concentric circles, the retinal motion (*d*) arises in a direction that is opposite to the dot's motion. Unlike Fig. 1c, in the configuration shown in Fig. 2a, the aperture problem does not arise, and the retinal motion can be correctly captured. We also produced a movie that adds a motion component along the circular contour by rotating the dashed circles to mimic the typical kinetic Orbison illusion (Fig. 2b). *tr* is the translational motion component that is opposite to the motion of the tracked dot. However, as the dashed circle rotates, the rotational motion component (*rot*) is added to *tr*. As a result, the actual retinal motion becomes the summed motion *d*. The retinal motion detected in Fig. 2b should be similar to that in Fig. 1c. However, the motion component *d* in Fig. 2b should be clearer than *d* of Fig. 1c. Thus, a stronger effect would be expected compared to the original kinetic Orbison illusion stimulus. Figure 2c shows a diagram indicating retinal motion when the dashed circles rotate in a direction opposite to the dot's revolution. The motion component of dashed circle rotation (*rot*) combines with *tr*, resulting in fast retinal motion *d*.

Measurements

We measured the amount of illusion to compare the effects with the original version of the kinetic Orbison illusion. Ten university students including two authors watched the movies, following the dot with their eyes. It took 8 s for the dot to make a clockwise or anticlockwise revolution along the square trajectory. They drew the perceived shape of the trajectory on a computer screen using a stylus pen (Fig. 3). They were instructed to draw a line through the four dots (Fig. 3a) according to the perceived shape of the dot's trajectory. The six movies described later were presented twice in random order, half of which reversed the direction of dot revolution and dashed circle rotation. In each movie, data were taken from four sides (Fig. 3c). Figure 3b shows a sample of the trajectory shapes drawn by the observers. The degree of perceived curvature, defined by the most radially inward

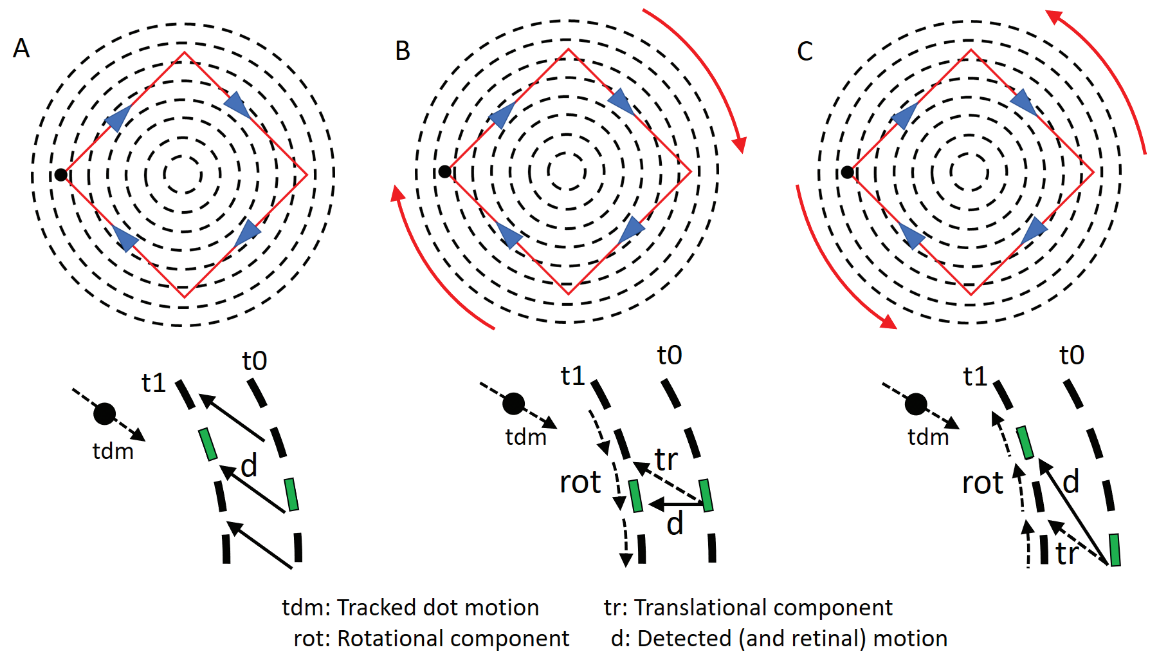

Fig. 2. Rotation of dashed circles. (a) shows the static-dashed circles. (b) shows the dashed circles rotating in the same direction as the dot revolution. (c) shows the dashed circles rotating in the opposite direction to the dot revolution.

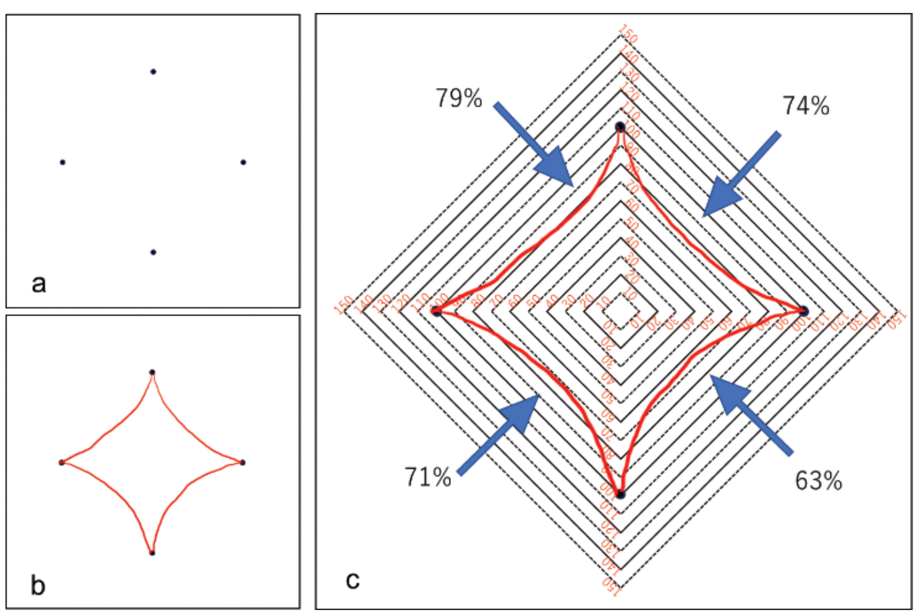

Fig. 3. Observer response and its measurement. (a) shows the response screen. (b) shows an example of the shapes drawn. (c) An example of the measurement. The percentages in the figure indicate the most radially inward positions.

(or outward) position, was read for each of the four sides using an overlapping scale (Fig. 3c). '100%' indicated the true square shape of the dot's trajectory passing through the four dots indicating the corners of the square in Fig. 3a. We define the amount of illusion as the most inward position in percent subtracted from 100%. Thus, when the most inward position was 85.0%, the amount of illusion for the movie was 15.0%. Note that the drawn trajectory only expressed the perceived trajectory shapes, and that even when the sides of the drawn trajectory appeared to bend inward, it was also possible for the vertices to stick out.

Demonstration movies (Movies 1 – 7, shown in Fig.4)

Movie 1 (Control)

A dot moving on a square trajectory is presented. There is almost no illusion.

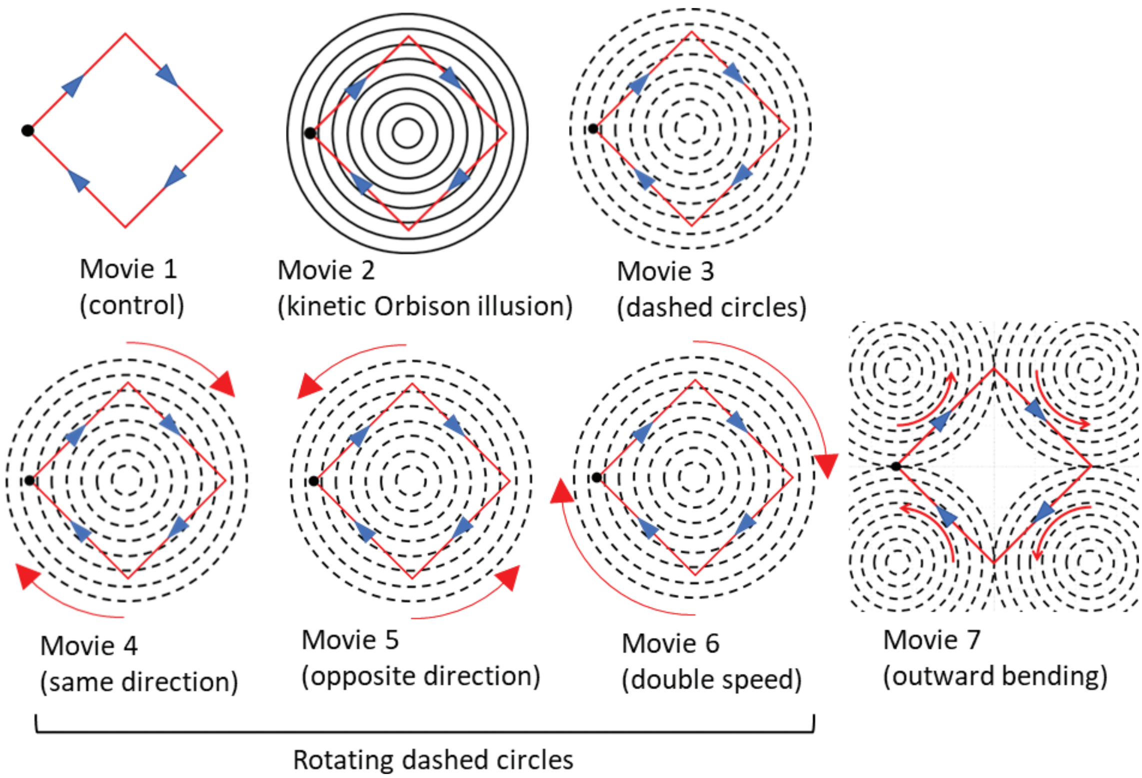

Fig. 4. Schematic illustrations of *Movies 1–7*. Each movie in this paper is in the MPEG4 format with a refresh rate of 60 frame/second.

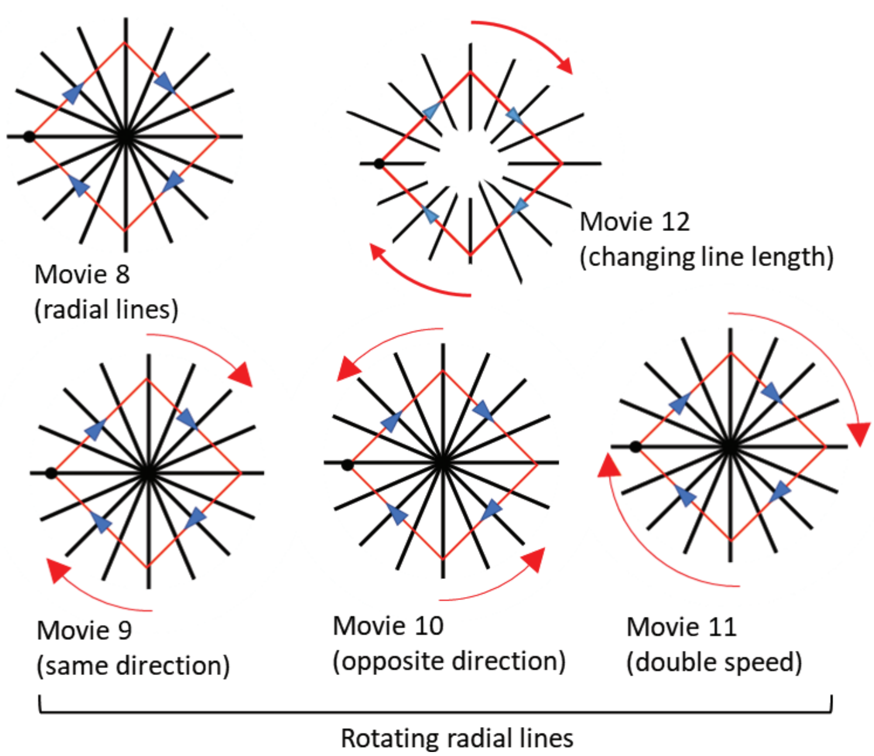

Fig. 5. Schematic illustrations of *Movies 8–12*.

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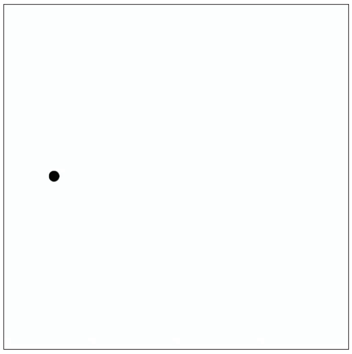
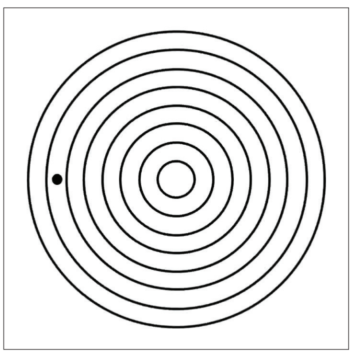
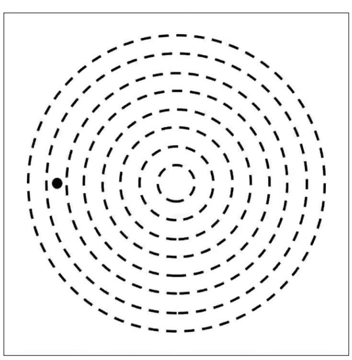


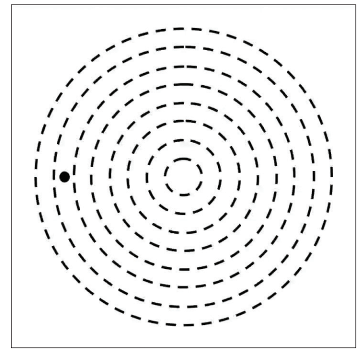
Movie 1



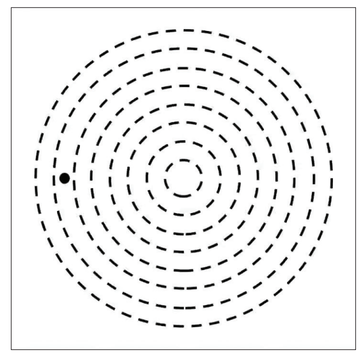
Movie 2



Movie 3



Movie 4



Movie 5

Movie 2 (Kinetic Orbison illusion with solid circles)

This movie shows an original version of the kinetic Orbison illusion. The sides of the trajectory were drawn to bend inward to a position of 83.4%, that is, the amount of illusion was 16.6%.

Movie 3 (Dashed circles)

This movie shows the kinetic Orbison illusion with dashed circles, avoiding the aperture problem for motion as shown in Fig. 2a. The amount of illusion measured was 6.8%. This reduction in the effect may be due to the clearer direction of retinal motion of the circular contours (and the dot), while the remaining effect may be due to the curved contours of the dashed circles creating a static Orbison illusion.

Movie 4 (Rotating dashed circles [same direction])

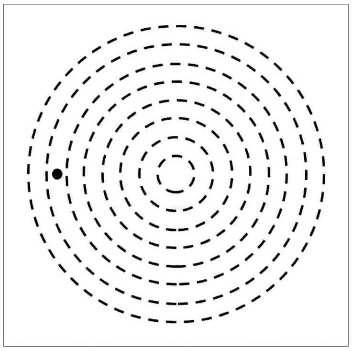
By rotating the dashed circles in the same direction as the dot's revolution, the motion component ignored due to the aperture problem in Fig. 1c (*ig*) is explicitly indicated as a motion component along the circular contour that mimics the situation of the kinetic Orbison illusion. That is, rotating dashed circles cancel the retinal motion component along the circular contours caused by the pursuit eye movement. The rotation speed was 45 deg/s, the average angular velocity of the dot's revolution. The relative motion between the dot and the circles should be similar to *Movie 2* (see Fig. 1c and 2b). *Movie 4* produced a surprising effect of perceptual 'bending' of the dot's trajectory. The amount of the illusion reached 30.0%, that is 1.8 times that of the original version of the kinetic Orbison illusion (*Movie 2*).

Movie 5 (Rotating dashed circles [opposite direction])

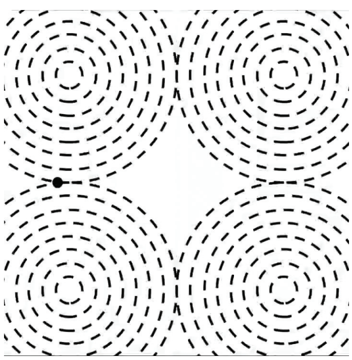
In this movie, the dashed circles rotated in the opposite direction to the revolution of the dot. The illusion was greatly reduced (4.9%). We discuss the reason for this later.

Movie 6 (Rotating dashed circles [double speed])

The dashed circles rotated in the same direction as the dot's revolution, but at twice the speed. The trajectory was



Movie 6



Movie 7

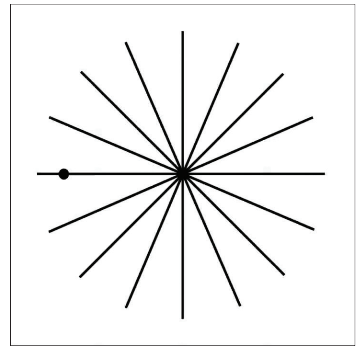
perceived as largely curved (27.3%), just as in *Movie 4*. We think that the illusory effect was saturated in this movie.

Statistical analysis

A one-way repeated measures analysis of variance (ANOVA) was performed on the six movies. The main effect was significant (F (5,45) = 35.6816, p < 0.0001, [η_p^2 = 0.7986]). Shaffer's modified sequential rejective Bonferroni procedure was used for multiple comparisons ($p < 0.05$). The amounts of illusion in *Movie 4* and *Movie 6* were significantly greater than those in the other movies. The amount of illusion in *Movie 3* was significantly smaller than in *Movie 2*. There was no significant difference between *Movie 5* and *Movie 1* and between *Movie 4* and *Movie 6*.

Discussion

Rotating the dashed circles in the same direction as the dot's revolution (*Movie 4*) most effectively produced the illusion. In *Movie 4*, the relative motion component between the dot and the circular contours, that is, the radial motion component, is clearly perceived because the circular motion component in the dot's revolution is common to the background rotation on average, reducing the relative motion along the circular contours. In *Movie 2*, however, there was some ambiguity in the relative direction of motion between the dot



Movie 8

and the circular contours due to the smoothly curved contours (compare *d* in Fig. 1c and *d* in Fig. 2b).

In *Movie 5* (i.e. *Rotating Dashed Circles [opposite direction]*), we might expect an illusion of an outward curved trajectory. However, the amount of illusion measured was close to zero. The loss of illusion may be partly due to the fact that the dot and the circles were perceived as moving independently or in two different depth planes, that is, as independent events in the perceptual organization of motion. Another possibility is that the hypothetical outward 'bending' effect and the inward 'bending' effect by the background circular configuration, as seen in *Movie 3*, canceled each other out. However, as we will mention later, we tested the hypothetical outward 'bending' effect with a random texture background rotating in the opposite direction to the dot's revolution and found that the effect was not large.

The illusory inward or outward 'bending' may also depend on the stimulus configuration. For example, in *Movie 7*, when the dot moves, the sides of the dot's trajectory are perceived to be outwardly curved.

Rotating radial lines

We have produced movies using radial lines. Radial lines are orthogonal to concentric circles, eliminating a possible factor causing the illusion due to circular contours. If the radial lines rotate at a speed equal to the average speed of dot revolution, does the illusion occur without relative motion in radial directions? The amounts of illusion were measured. The radial pattern consisted of 16 lines.

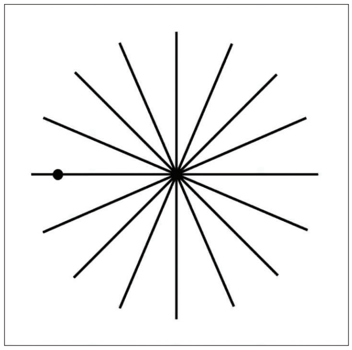
Demonstration movies (Movies 8 – 12, shown in Fig.5)

Movie 8 (Radial lines)

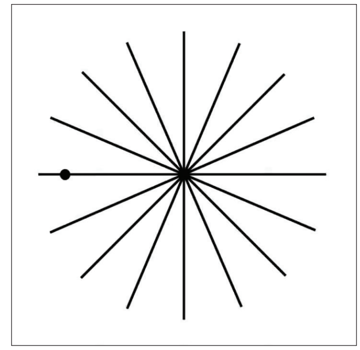
The background consists of static radial lines. The motion trajectory and the radial lines could produce the Hering illusion or its motion version (Hering, 1861; Swanston, 1984), which could perceptually bend the sides outward. In *Movie 8*, however, the possible effect seems to be small.

Movie 9 (Rotating radial lines [same direction])

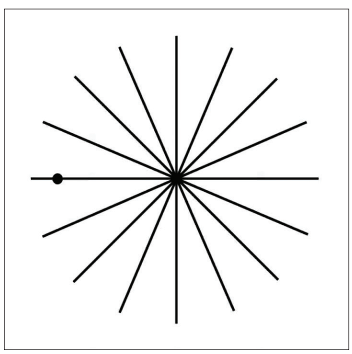
The radial lines rotated in the same direction as the dot's revolution. The angular velocity of the rotating radial



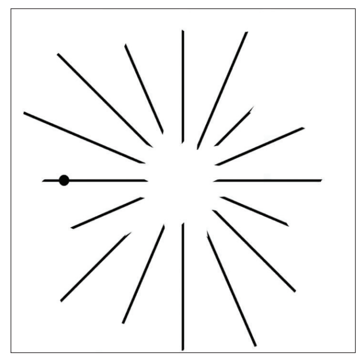
Movie 9



Movie 11



Movie 10



Movie 12

lines was constant and equal to the average angular velocity of the dot's revolution (45°/s). The amount of illusion was large (23.6%), but slightly smaller than that in *Movie 4* (*Rotating Dashed Circles*, 30.0%). This decrease in effect could be due to the loss of the circular contours that could create the Orbison illusion and indicate the radial position of the dot, and to the lack of relative motion of the dot in a radial direction.

Movie 10 (Rotating radial lines [opposite direction])

The radial lines rotated in the opposite direction to the dot's revolution at the same angular velocity as in *Movie 9*. A slightly bulging trajectory was recorded for some observers. However, the averaged amount of the illusion was only 1.1% outward.

Movie 11 (Rotating radial lines [double speed])

The radial lines rotated in the same direction as the dot's revolution at twice the average angular velocity. The amount of illusion here (22.1%) was almost the same as in *Movie 9* (23.6%). The effect seems to be saturated as observed in *Movie 6*.

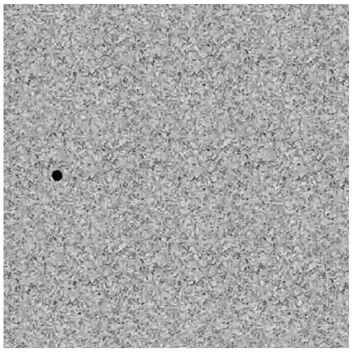
Statistical analysis

In the measurement, *Movie 1* was also included as a control. A one-way repeated measures ANOVA was performed. As the Mauchly's test indicated a violation of sphericity, a Greenhouse-Geisser epsilon was used to adjust the degrees of freedom. The main effect was significant (F (2.02, 18.15) = 38.6423, $p < 0.0001$, $\eta_p^2 = 0.8111$). The results of multiple comparisons ($p < 0.05$) showed that the amount of illusion was significantly greater in *Movie 9* and *Movie 11* than in the others. No significant difference was found between *Movie 10* and *Movie 1* and between Movies 9 and 11.

Discussion

In *Movie 9*, while the circular motion component is common to the dot's revolution and the radial line rotation, the radial motion component of the dot may be perceived as motion along the radial lines, which could distort the perceived trajectory of the dot.

The rotating background of radial lines seems to act as a frame of reference for the dot's motion as in that of dashed circles. Both frames or backgrounds play a role to perceptually decompose the dot's revolution into circular (rotational) and radial motions. However, the role of the rotating radial lines to indicate the radial motion component seems to be different from that of the rotating dashed circles. In the rotating dashed circles movies (i.e. *Movie 4*), the dashed circles appear to indicate the relative position in the circles with various diameters. In the rotating radial lines movies, the radial lines appear to provide an axis along which the dot moves.



Movie 13

It is interesting to compare the present illusion with 'Tusi' motion (Shapiro & Rose-Henig, 2013). In the present radial line movie (*Movie 9*), the revolutionary motion of the dot was decomposed into the motion shared with the lines (the rotational component) and the motion along the line (the radial component). In 'Tusi' motion, although the radial lines are stationary and the discs physically move along the lines, the observer perceives a circular figure made up of discs rolling inside the outer circle. This suggests that the straight motion of the discs is decomposed into the rotational component of the circular figure and the motion component along the outer circle. In the present illusion, the perceived motion along the line is a result of motion decomposition, whereas in the 'Tusi' motion, the physical motion along the line perceptually disappears due to motion decomposition.

The rotating radial lines could create a subjective circular contour at the outer edges of the lines. We tried to eliminate this effect by dynamically changing the length of each line in *Movie 12 (Changing Line Length)*. Although the inner and outer edges do not produce subjective circles, the curvature of the dot's trajectory is clearly visible. The illusory effect does not entirely depend on the subjective circular shape or the circular motion of the line edges.

Rotating random-texture background

As shown in Fig. 6, *Movie 13 (Rotating Random Texture)* does not use a geometric contour. However, the background is filled with a random texture in rotational motion. *Movie 13* contains a large amount of rotational motion signals of the background without ambiguity. When the random texture was rotated in the same direction as the dot's revolution, the amount of illusion was 22.2%, close to *Movie 9*. When the texture was stationary or rotated in the opposite direction, the illusion was almost non-existent (0.36 or 2.2% in convexity).

Rotating two-dot frame

The minimal condition that preserves the circular motion component of the background would be something like *Movie 14 (Rotating Two-Dot Frame)* (see Fig. 6). There are two dots moving on circular trajectories inside and outside of the moving dot. There is relative motion in a radial direction, while the circular motion component is shared by the three dots. The amount of illusion was 19.5%. This movie could be considered as a circular transformation of Johansson's (1975) classic demonstration of a moving frame of reference.

The rotating two-dot frame could show the changes in relative position of the dot between the inner and outer elements, resulting in the illusion. Thus, the relative position of the dot could be a component of the illusion. However, in the rotating radial line (*Movie 9*) and rotating random texture (*Movie 13*) movies, there was no inner or outer circle to define the relative position of the dot. We hypothesize that relative position could be one of the main factors influencing the magnitude of the illusion, but not a necessary factor.

Triangular trajectory

We also produced movies with a dot moving on a triangular trajectory as shown in Fig. 6. The illusion inducing mechanism for the triangular trajectory movies may be the same as for those with the square trajectory movies. However, we feel that the impression of the illusion (i.e. how surprising it is) seems to be stronger for the triangular trajectory movies than for the square trajectory movies. Eight new observers and two authors participated in the measurements.

Demonstration movies

We produced seven movies with triangular trajectories and measured the amounts of illusion using the same method described in the measurement section for square trajectories, but with a triangular scale. The tested conditions are listed as follows.

Movie 15 (Control)

A dot moving on a triangular trajectory was presented without a background.

Movie 16 (Kinetic Orbison illusion with solid circles [triangle])

This movie shows a triangular version of the kinetic Orbison illusion. The amount of illusion was 23.6%. This is 1.4 times as large as that with the square trajectory.

Movie 17 (Dashed circles [triangle])

This movie shows the triangular kinetic Orbison illusion with dashed circles, avoiding the aperture problem for motion as shown in Fig. 2a. The amount of illusion measured was 12.3%. This is 1.8 times as large as that with the square trajectory. The reduction in the effect when compared with *Movie 16* may be due to the loss of the aperture problem as in the corresponding square trajectory movie (*Movie 3*).

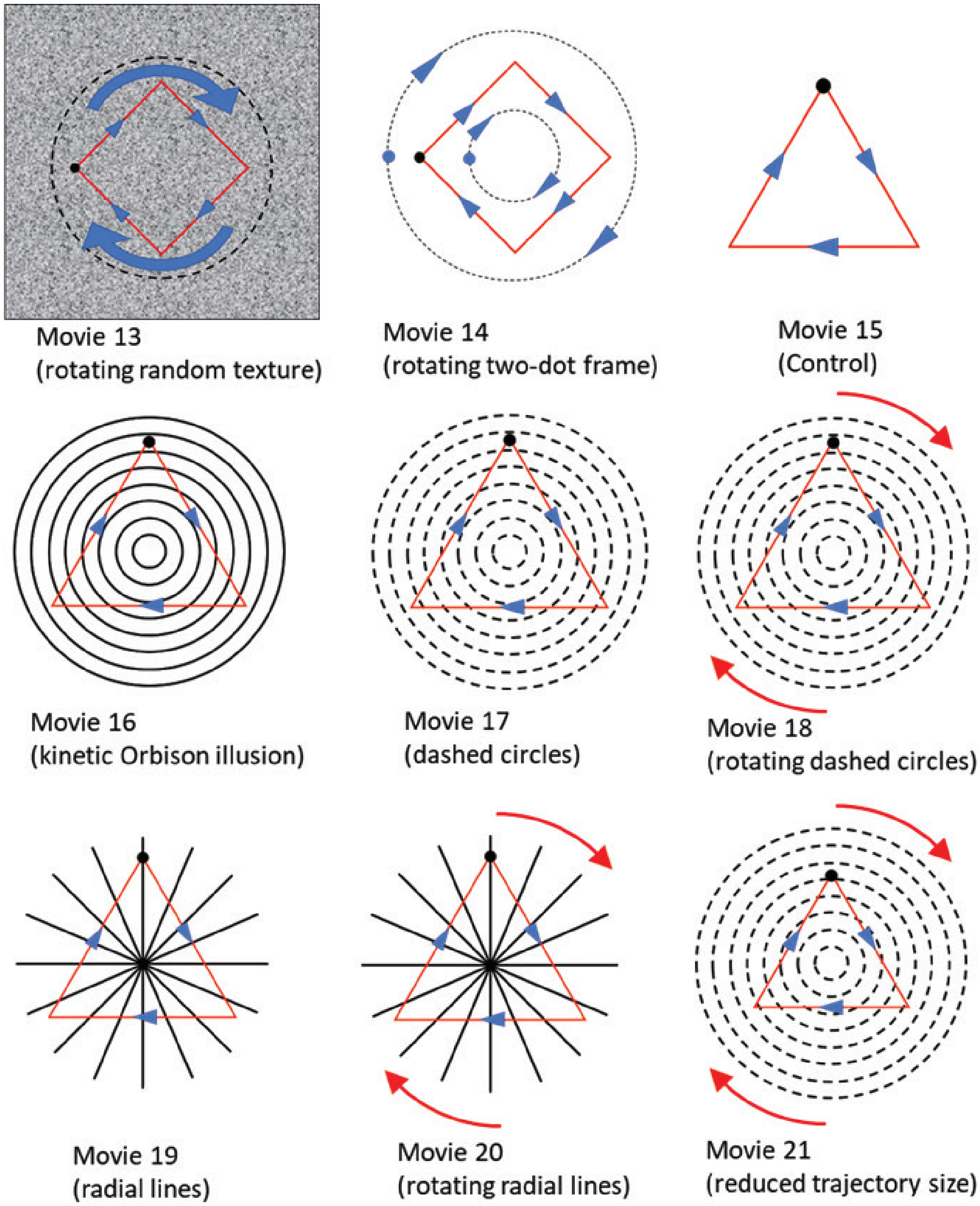


Fig. 6. Schematic illustration of Movies 13–21.

Movie 18 (Rotating dashed circles [same direction, triangle])

The rotation speed was 45 deg/s, the same as the average angular velocity of the dot's revolution. This speed was also the same as the square trajectory movies. *Movie 18* produced a surprisingly large effect of perceptual 'bending' of the dot's trajectory. The amount of illusion reached 41.3% in average, that is, 1.4 times as large as the *Rotating Dashed Circles (same direction)* with the square trajectory condition (*Movie 4*).

Movie 19 (Radial lines)

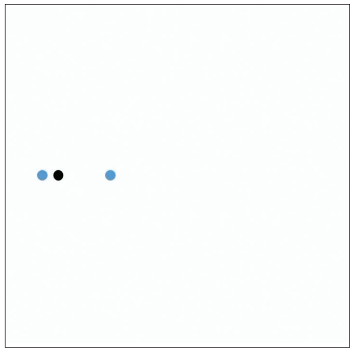
The radial line background was the same as in *Movie 8*. Little illusion was observed.

Movie 20 (Rotating radial lines [same direction, triangle])

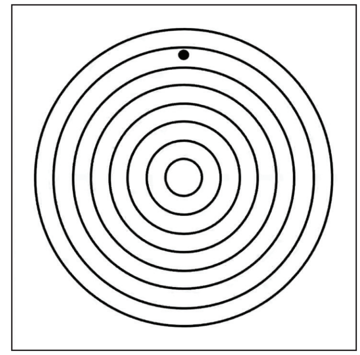
The amount of illusion with a background of rotating radial lines in the same direction as the dot's revolution was 35.6% for the triangular trajectory movie. This is 1.5 times as large as the corresponding square trajectory movie (*Movie 9*).

Movie 21 (Reduced trajectory size)

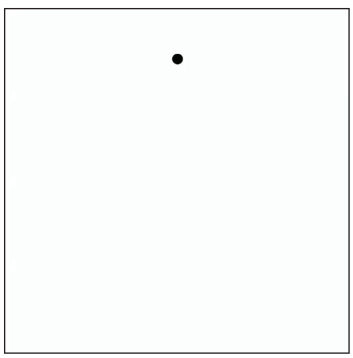
One may consider that the triangular trajectory enhances the illusion because the sides of the triangular trajectory here were longer than those of the square trajectory. To test this, we reduced the trajectory size to match the length of the sides of the square trajectory and measured the illusion. The background was dashed circles rotating in the same direction



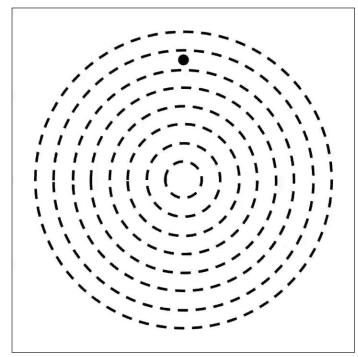
Movie 14



Movie 16



Movie 15



Movie 17

as the dot's revolution. The speeds of the background rotation and dot revolution were kept at 8 s/rev (the same as that in the square and the other triangular trajectory movies).

The result showed that the amount of illusion was 45.4% in average, which was the largest out of the all conditions tested in this paper. Therefore, longer sides are not a decisive factor in enhancing the illusion with a triangular trajectory.

Statistical analysis

A one-way repeated measures ANOVA was performed on the seven movies. As the Mauchly's test indicated a violation of sphericity, a Greenhouse-Geisser epsilon was used to adjust the degrees of freedom. The main effect was significant (F(2.13, 19.18) = 52.0755, $p < 0.0001$, $\eta_p^2 = 0.8526$). Shaffer's modified sequential rejective Bonferroni procedure was used for multiple comparisons. Significant differences ($p < 0.05$) were found between all pairs of movies except the following three: *Control* (*Movie 15*) and *Radial Lines* (*Movie 19*) conditions, *Rotating Dashed Circles (same direction, triangle)* (*Movie 18*) and *Rotating Radial Lines (same direction, triangle)* (*Movie 20*) conditions, and *Rotating Dashed Circles (same direction, triangle)* (*Movie 18*) and *Reduced Trajectory Size (triangle)* (*Movie 21*) conditions.

To compare the amount of illusion under the triangular trajectory with that under the square trajectory, we conducted an ad hoc two-way ANOVA with data from eight observers for each trajectory-type movie (between-subject factor). The two factors were the trajectory type (square and triangle) and the background type (solid and rotating dashed circles [same direction]). The differences between the trajectory types (F (1, 14) = 7.0133, $p = 0.0191$, $\eta_p^2 = 0.3338$) and between background types (F(1, 14) = 38.6737, $p < 0.0001$, $\eta_p^2 = 0.7342$) were significant. The interaction between them was not significant (F (1, 14) = 0.8342, $p = 0.3765$, $\eta_p^2 = 0.0562$). Therefore, we confirmed that the triangular trajectory induced a larger amount of illusion in the *kinetic Orbison illusion* movies and the *rotational dashed circles* movies than the square trajectory.

Discussion

The results show that the effect of the varied background was similar between the two trajectory types (square and triangle). That is, the amounts of illusion of the *Dashed Circles* movies (*Movies 3* and *17*) were smaller than those of the *Solid Circles* movies (*Movies 2* and *16*). Those from the *Rotating Dashed Circles (same direction)* movies (*Movies 4* and *18*) were larger than those from the *Solid Circles* movies. The *Rotating Radial Lines (same direction)* movies (*Movies 9* and *20*) produced a great effect, while stationary *Radial Lines* movies (*Movies 8* and *19*) did not. This similarity may suggest the common cause of the illusion between the movies in the two trajectory types.

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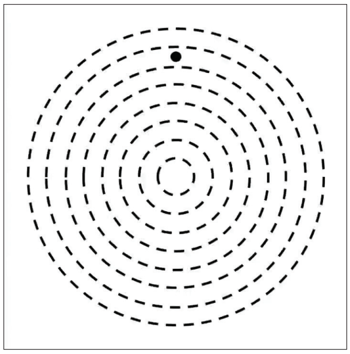
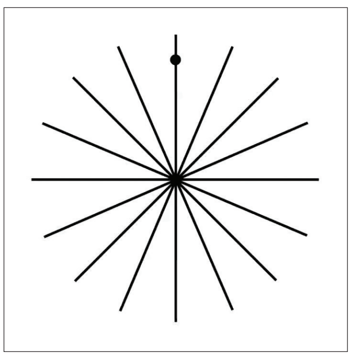
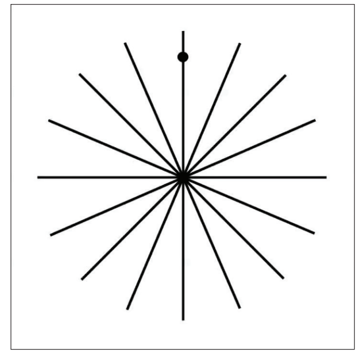


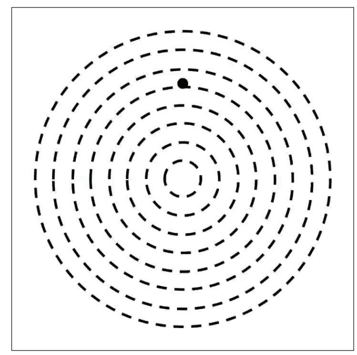
Movie 18



Movie 19



Movie 20



Movie 21

However, the amount of illusion was much greater for triangular trajectory movies than for square trajectory movies when compared with the corresponding background movies. In these movies, the four outermost points (vertices) of the square trajectory and the three outermost points of the triangular trajectory were the same in distance from the central point of the background. So, the sides of the triangular trajectory are longer than that of the square trajectory. Our results from the *Reduced Trajectory Size* movie (*Movie 21*) showed that the illusion did not diminish even when the sides were shortened. We conclude that it is not the longer side length that enhanced the illusion with a triangular trajectory. At the same time, there are two factors to be investigated for the triangular trajectory movies. First, in the *Reduced Trajectory Size* movie (*Movie 21*), the innermost position through which the dot passes through was closer to the center of the circles than in the *Rotating Dashed Circles (triangle)* movie (*Movie 18*), which could enhance the illusion and cancel out the effect of the shortened sides. Second, the linear speed of the dot was slower in the *Reduced Trajectory Size* movie. The slower speed of the dot could enhance the illusion (Matsunaga et al. 2023). What enhances the illusion of the triangular trajectory movies is not clear at present.

General discussion

Table 1 summarizes the effect measured across all conditions. We found the following points:

1. The kinetic Orbison illusion was attenuated with static dashed circles but greatly enhanced when dashed circles were rotated in the same direction as the revolution of the dot.
2. The illusion also occurred with a background of radial lines or random texture, but only when these rotated in the same direction as the revolution of the dot.
3. Even when the speed of rotation of the background doubled, the illusion did not increase.
4. The amount of illusion was close to zero when the background rotated in the direction opposite to the dot's revolution.
5. The illusion was much stronger when the dot followed a triangular trajectory compared to a square trajectory.
6. The illusory effect of the triangular trajectory did not change when the size of the triangular trajectory was reduced to shorten the sides.

From the results, we conclude that several factors affect the magnitude of the present illusion: the shape of a dot's trajectory (square or triangle), line type (solid or dashed circle), background type (circles, radial lines, random texture, or two elements), and background motion (stationary, moving in the same or opposite direction). These are in addition to the factors found in Matsunaga et al. (2023), that is, trajectory orientation, number of circles, dot speed, and fixation or tracking eye movement. These are directly indicated in the demonstration movies or experiments.

There are other possible factors that could be investigated, such as the innermost position that the dot passes, or the difference between the innermost and outermost positions on a radial axis. It is true that the physically innermost position of the triangular trajectory is closer to the innermost circle than that of the square trajectory in *Movies 16* and *18*. However, as noted before, the *Rotating Radial Lines* movies (*Movies 9* and *20*) and the *Rotating Random Texture* movie (*Movie 13*), which produce a large illusion, do not contain a circle inside the trajectories. Meaning, the position closest to the innermost circle did not seem to determine the illusion. Also, the position closest to an assumed center of the trajectory cannot explain the variation in the amount of illusion measured here. This is because the assumed distance was the same in all movies with a square trajectory of the dot, and in those with a triangular trajectory respectfully. Thus, the closest position to the innermost circle or the assumed center could affect the illusion, but they alone cannot predict the amount of illusion.

However, it is possible to assume that the physical position of the moving dot when it is closest to the center will determine the greatest amount of illusion when all conditions for the illusion are optimal. When the dot moves along a square trajectory, the innermost dot position (the midpoint of the sides) is 70.7% of the outermost dot position (at the vertices) along a radial axis. Thus, the radial position of the dot changes between 100 and 70.7% according to the revolution of the dot. Similarly, for a triangular trajectory, the innermost dot position is 50% of the outermost dot position. The greatest amount of illusion measured here was 30.01% for square trajectory movies and 45.35% for triangular trajectory movies. These values seem to correspond to the amount of physical change in the proportion of the dot positions along a radial axis. However, the amount of illusion here was not defined as the proportion between the outermost and innermost dot positions along a radial axis on the drawn trajectory, subtracted from 100%, but as the proportion between the position on a physical square and the innermost position on the drawn trajectory (see Fig. 3), subtracted from 100%. This means that in a typical case, if the amount of illusion for a square trajectory is 30%, the innermost position on the drawn trajectory could be 70% of the mid-position of the sides of the square trajectory along a radial axis, that is, 49.5% of the outermost position at the four vertices. If changes in radial position are perceived directly, the amount of illusion will be zero with the present method of measurement, and the perceived trajectory of the dot will be as it is without a bending impression.

The concentric circles and the radial lines represent the two axes of polar coordinates. In addition to the effect of the traditional Orbison illusion, the concentric circles

Table 1. Averaged amount of illusion under various types of background conditions (%)

Trajectory of dot motion	Background	Control		Stationary background	Rotating background			
		Dot only	Concentric solid circles		Same direction	Opposite direction	Double speed	Reduced trajectory size
Square (n = 10, η_p^2 = 0.71)	Dashed circles	0.21 (*SD* = 4.77) Movie 1	16.64 (*SD* =9.43) Movie 2	6.83 (*SD* = 7.64) Movie 3	30.01 (*SD* = 7.19) Movie 4	4.88 (*SD* = 8.40) Movie 5	27.28 (*SD* = 9.57) Movie 6	
Square (n = 10, η_p^2 = 0.81)	Radial lines	0.86 (*SD* = 4.40) Movie 1		-2.70 (*SD* = 6.02) Movie 8	23.56 (*SD* =8.11) Movie 9	-1.10 (*SD* =9.89) Movie 10	21.11 (*SD* = 7.73) Movie 11	
Square (n = 10, η_p^2 = 0.90)	Random texture			-0.36 (*SD* = 1.70)	22.23 (*SD* = 3.96) Movie 13	-2.19 (*SD* =6.25)		
Triangle (n = 10, η_p^2 = 0.85)	Dashed circles	2.50 (*SD* = 1.91) Movie 15	23.58 (*SD* = 7.26) Movie 16	12.32 (*SD* = 7.49) Movie 17	41.33 (*SD* = 9.84) Movie 18			45.35 (*SD* = 8.83) Movie 21
	Radial lines			3.17 (*SD* = 7.57) Movie 19	35.55 (*SD* = 8.96) Movie 20			

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act as a scale to indicate the radial position of the dot from all orientations, which could enhance the perception of the dot changing its radial position. For the rotating dashed circles, the relative motion between the contours and the dot directly indicates the radial motion component of the dot. For the radial lines, they act as an axis indicating the radial direction. The radial component of the dot's motion is easily visible although there is no relative motion component in the radial direction. The rotational lines seem to act as radial axes that rotate with the dot's revolution, reducing the effect of the circular motion component. In both rotating backgrounds, the radial motion component is strong around the corners of the square or triangular trajectory, while the radial motion component is absent at the midpoints of the sides. The corners of the trajectory are perceptually sharpened due to the misperceived radially outward or inward direction of the dot's motion, giving the opposite impression of an inward 'bending' of the sides.

The illusion of relative motion has been reported. Duncker (1929) reported induced motion of a stationary light spot on a horizontally moving background. Wallach et al. (1978) moved a spot vertically and its background horizontally. Their manipulation showed that the induced motion component due to relative motion could be additional to the actual object motion. Johansson (1973) proposed the visual vector analysis to extract an event from relative motion components. The flying bluebottle illusion (Anstis, 2006) also showed that a circular path of a moving object is perceived to be distorted by induced motion caused by background motion. These phenomena may be related to our rotating dashed circle movies from an induced motion point of view. However, in movies with rotating radial lines, there is no relative motion in a radial direction between the dot and the lines as mentioned earlier. The contribution of induced motion in rotating radial line movies should be small. The rotating radial lines may be useful in separating the radial motion component from the circular motion component in the revolution of the dot by reducing the perception of circular motion of the dot.

Matsunaga et al. (2023) showed that the kinetic Orbison illusion was attenuated by fixating the center of the stimulus, compared to the pursuit eye movement condition. One possible difference between the two conditions is the presence or absence of retinal motion of the circles. For example, in *Movies 4, 9, 13, 14, 18*, and *20*, the background necessarily produces the retinal motion. Therefore, the relative motion between the dot and the background is visible even without the eyes tracking the dot. In fact, these movies do not require the dot to be tracked in order to perceive a strong illusion. However, whether observing the dot in central vision enhances the illusion is not yet clear.

In this report, we have presented new types of movies that produce a strong illusory effect of dot motion. Although a dot moves on a square (or triangular) trajectory, the sides of the trajectory were perceived to 'bend' inward. To create a strong illusion, a clearly visible rotation of the background in the same direction as the dot's revolution is important. We believe that the rotating background acts as a frame of reference for the dot's motion. However, the role of the rotating radial lines seems to be different from that of the rotating dashed circles. The difference is in how the radial component of the dot's revolution is clarified.

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