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PHENOMENAL REPORT

Fast positive motion aftereffect arising in the afterimage of rotating 'Enigma'

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Abstract

Enigma is an Op art piece that induces an illusory flow in rings on a radial sunburst pattern. We report that, after an Enigma pattern was slowly rotated and then removed, a fast rotation of the rings' afterimage in the same direction as the previous rotation was perceived. The phenomenon is demonstrated with movies and experimental results.

Keywords: *Enigma*; *motion aftereffect*; *afterimage*; *illusion*; *relative motion*

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Introduction

Radial sunburst patterns often create visual illusions (Ito, 2012b; Ito & Ding, 2022; Mackay, 1957a, 1957b; Sokoliuk & VanRullen, 2013). 'Enigma' (Leviant, 1996) is an Op art painting that causes illusory flow in the rings on a sunburst pattern (Enigma flow). In this report, we use the term 'Enigma pattern' to refer to a figure consisting of a sunburst pattern with rings on it. We report here a new motion aftereffect (MAE) phenomenon produced by adaptation to a rotating Enigma pattern (see Fig. 1). That is, even when the Enigma pattern is removed during the test period, the afterimages of the rings alone are perceived as rotating in the same direction as the previous rotation, and at a faster angular velocity than the previous rotation. We demonstrate and discuss this phenomenon with movies and experimental results supporting our findings.

It has been shown that the illusory flow within the rings appears to either cease or rotate in the opposite direction while the Enigma pattern rotates (Tomimatsu & Ito, 2016; Tyler, 2022). Tomimatsu and Ito (2016) showed that after viewing a rotating Enigma pattern, an illusory flow in the stationary Enigma pattern was initially perceived in the same direction as the previous rotation, followed by an unstable flow perception. They proposed that adaptation to relative motion (Anstis & Reinhardt-Rutland, 1976) and its aftereffect were the cause of the MAE. As their test stimulus was a static Enigma pattern, the test figure alone could produce an illusory flow. The positive MAE observed by Tomimatsu and Ito (2016) was measured as a directional bias of illusory flows. *Movie 1* demonstrates this effect (see Fig. 1).

In this report, we removed the test stimulus as shown in Fig. 1 (*Movie 2*). While the sunburst pattern did not leave an afterimage after rotation, the purple-magenta rings produced a yellow-green afterimage as it had been stationary on the retina. Here, we demonstrate that (1) the ring afterimages alone seem to rotate despite the ring areas not being exposed to any movement, (2) the MAE arises in the same direction as the rotation of the adaptation stimulus, and (3) the MAE rotation is perceived as faster than the rotation of the adaptation stimulus.

Experiment

An experiment was conducted to quantitatively demonstrate the effect. We reproduced 'Enigma' as an adaptation stimulus and presented it on an LCD monitor with

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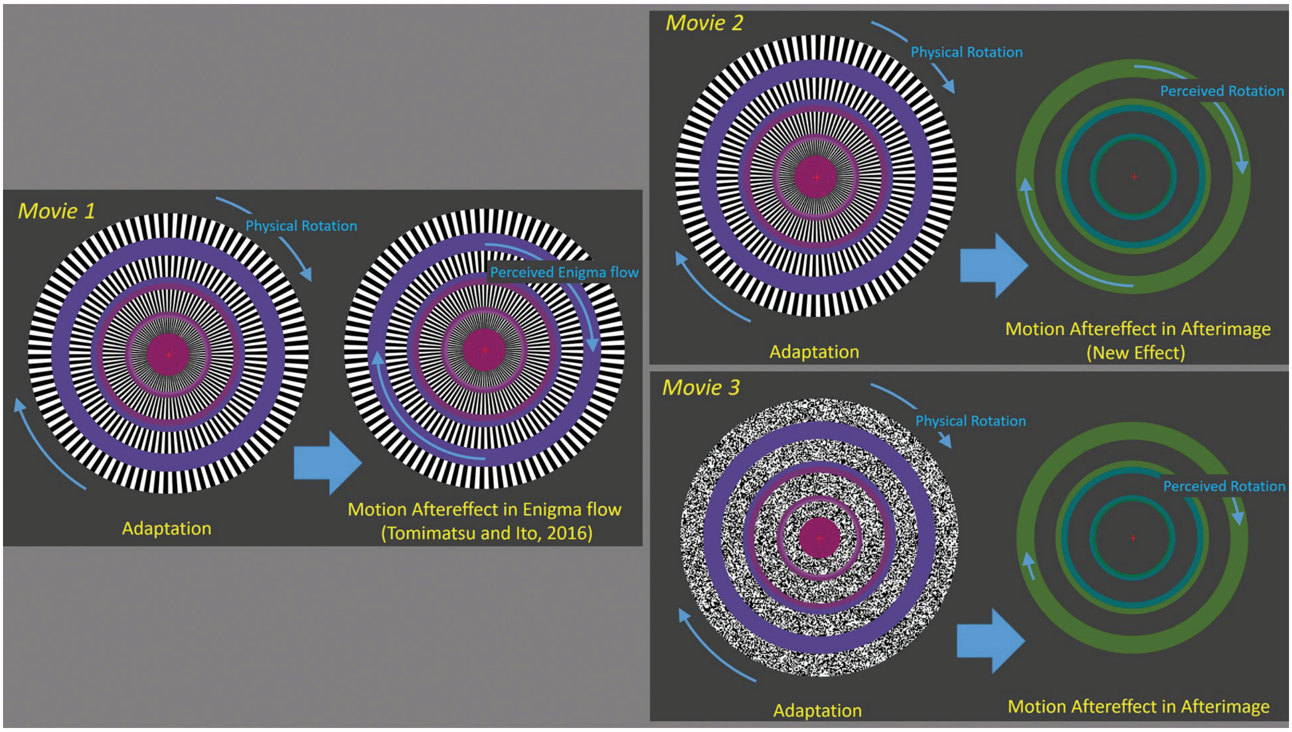

Fig. 1. Demonstration movies of positive MAEs (MP4, FHD, 60 fps). *Movie 1* demonstrates that after viewing a rotating Enigma pattern, a directionally-biased illusory flow emerges within the static Enigma pattern (reproduced from Tomimatsu and Ito [2016]). *Movie 2* demonstrates the present effect where the MAE of the yellow-green afterimages of the rings appears in the same direction as the previous rotation at a speed that is faster than the adaptation stimulus. *Movie 3* demonstrates a control condition using rotating random dots as an adaptation stimulus. See details in the text. MAE: motion aftereffect.

a resolution of 1920 × 1080 pixels (Eizo, FG2421). We also used a control stimulus in which the sunburst pattern was replaced with random dots, while the rings remained unchanged (Fig. 2b). A random-dot stimulus could precisely display the stimulus rotation, include a wide range of spatial frequency components in all orientations, and produce, to a small degree, an Enigma flow within the ring areas. The adaptation stimulus rotated in a clockwise or counter-clockwise direction. The viewing distance was 57 cm. The experiment was conducted in a darkened room. Eleven observers (aged 22–26), including the second and third authors, participated in the button-press and speed-estimation sessions. In the former session, data from one observer were not processed due to an error in obtaining data.

A fixation cross was displayed at the center of the screen. An adaptation stimulus rotated for 6 seconds (the adaptation period) and then disappeared (see Fig. 2c). The observers then pressed one of two buttons to indicate the perceived MAE direction of the ring afterimage (clockwise or counter-clockwise). When the afterimage perceptually disappeared or when they could not judge the direction, they released the button. The button status was sampled at 0.1-second intervals for 8 seconds (the test period). Twenty trials (10 repetitions for the Enigma or the random-dot condition) were conducted in a random order. The clockwise and counter-clockwise conditions were assigned equally.

As shown in Fig. 3a, for the Enigma condition, positive MAEs were dominant 1–4 seconds after the stimulus disappeared. For most observers, positive MAEs arose instantly after the disappearance of the adaptation stimulus. Some observers exhibited a clear shift in MAE direction (see Fig. 3b). One possible reason of the direction change is that because the positive MAE in the ring areas instantly arises and disappear earlier than the negative MAE of the sunburst rotation, the negative MAE of the sunburst rotation gradually fills in the ring areas.

Judging from Fig. 3a, the positive MAE seems to have arisen also under the random-dot condition to some degree. However, when the results of perceived speed (Fig. 3c, described below) are taken into consideration, it is clear that the impression of a positive MAE under the random-dot condition was much less prominent than under the Enigma condition (in fact, the first author did not observe a positive MAE with the random-dot stimulus). The reason of the weak effect in the random-dot condition will be discussed later. There was a significant difference in the duration of positive MAEs between the stimulus conditions ($t(9) = 2.9037$, $p = 0.0087$).

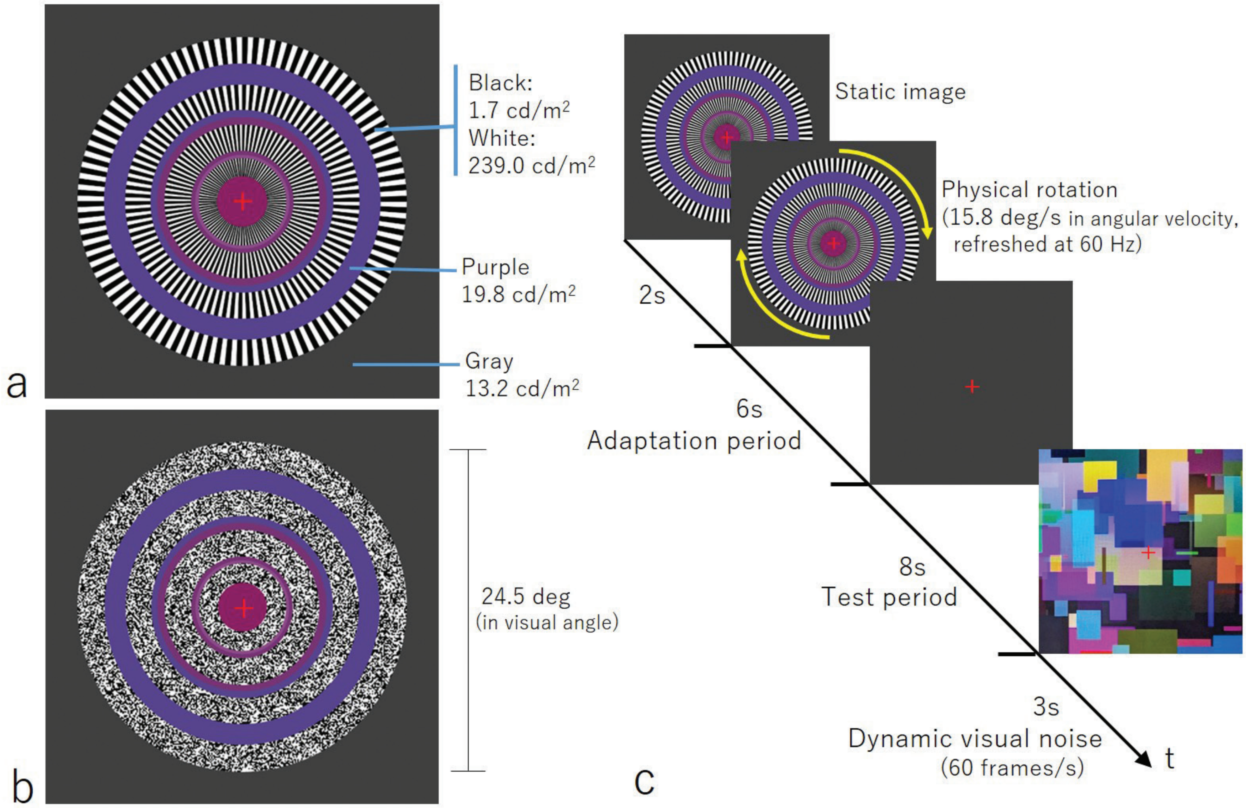

Fig. 2. Experimental conditions. *a* and *b* indicate the Enigma and the random-dot stimulus for adaptation (*Movie 2* and *Movie 3*, respectively). *c* shows a trial sequence.

We measured the subjective angular velocity of MAEs using magnitude estimation. Observers judged this for both directions (same or opposite to adaptation stimulus) for each of the 20 trials. The physical angular velocity of the adaptation stimulus was defined as 10. When the MAE was not perceived, the estimated speed was treated as zero. As shown in Fig. 3c, the average value for positive MAEs of the Enigma stimulus (13.1) was significantly higher than 10 ($t(10) = 6.8181$, $p < 0.0001$), i.e. the positive MAEs were perceived as faster than the rotation of the adaptation stimulus, whereas for the random-dot stimulus, it was only 2.9. The values for negative MAEs were substantially lower. These results demonstrate that positive MAEs for the Enigma pattern are unique in terms of speed. Although the sunburst pattern and the afterimage of the rings differ in terms of object type, the difference in phenomenal speed is clearly demonstrated.

Observation

As shown in *Movies 4–10* (see Fig. 4), some factors may (or may not) affect the present phenomenon. The first one is spatial frequency of the sunburst pattern. In *Movies 4* and *5*, the numbers of rays are halved (45 rays) or doubled (180 rays), respectively, contrary to *Movie 2* (90 rays). The Enigma flow is perceived only from the doubled frequency pattern when the pattern is stationary. After viewing the pattern's rotation, one may observe a negative MAE in *Movie 4* or no MAE in *Movie 5*, i.e. the present effect may not be observed in these stimuli. The present effect seems to arise within a specific range of spatial frequency conditions. The random-dot stimulus included a wide range of spatial frequency components in all orientations. Some components may produce the present effect, but others do not or even cancel the effect. This may be a reason for the weak effect in the random-dot condition.

The second factor is luminance contrast of the sunburst pattern. *Movie 6* is a low contrast version. The present effect may be observed but weakened. *Movie 7* is a red-green version. Although the precise equiluminance setting depends on the reader's display and eyes, little Enigma flow may be seen when the pattern is stationary and little MAE may be perceived in this movie. Strength of the present effect may depend on luminance contrast of the sunburst pattern.

The third factor is an adaptation duration. *Movies 8* and *9* are produced with short (2.0 seconds) and long

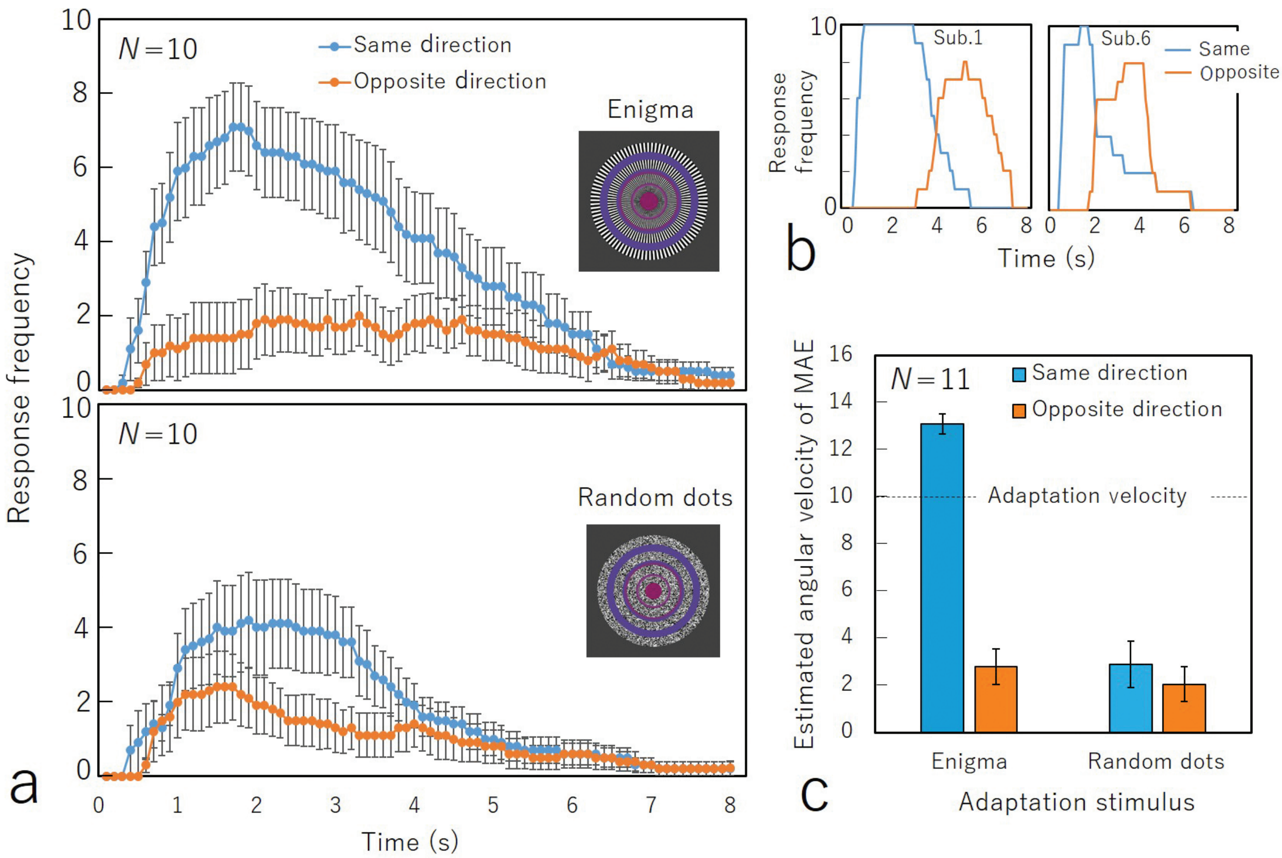

Fig. 3. Results. *a*. Time course of the average response of button-press frequency across 10 trials for each observer. Each symbol reflects button-press data from 100 trials. *b*. Typical responses in which two perceived directions switched during the test period. *c*. Estimated angular velocity of MAEs. Error bars indicate standard errors (SEs). MAE: motion aftereffect.

(12.0 seconds) adaptation durations, respectively. *Movie 8* may exhibit the present MAE effect. Some may perceive the present effect clearer in *Movie 8* than in *Movie 2*. Although the present effect can be observed even with 1-second adaptation, the afterimage itself vanishes quickly. The long-term adaptation may not necessarily produce a long-lasting positive MAE as expected. The long-term adaptation also strengthens the negative MAE of the sunburst pattern and may overwhelm the present effect soon as noted above.

Finally, *Movie 10* employs a lower speed for the adaptation stimulus (6.0 deg/s in angular velocity). Even with this movie, a positive MAE that is much faster than the previous rotation may be observed. The speed of the positive MAE does not directly reflect the adaptation speed.

These descriptions noted above are based on our observations and not officially tested. However, our observations could help to design a detailed quantitative study in future.

Discussion

There are phenomena in which an MAE arises in retinal areas that were not exposed to motion (e.g. Snowden & Milne, 1997; Wade et al., 1996). Snowden and Milne (1997) reported the 'phantom MAE' and assumed that a cell with a large receptive field covering the non-stimulated retinal areas adapted to rotational optic flow. The MAE in the present report differs from the phantom MAE in that its direction is the same as that of the previous rotation. If a cell with a large receptive field covering the ring areas adapted to rotational motion, the MAE of the rings would mainly arise in the opposite direction to the previous rotation as a whole (this type of MAE was sometimes observed after the positive MAE vanished).

Positive MAEs are sometimes observed in the aftereffects of relative motion, or as induced motion of surrounding MAEs (Anstis & Reinhardt-Rutland, 1976; Wade et al., 1996). Wade et al. (1996) presented vertical gratings in three positions (top, center and bottom). After viewing the leftward motion of the top and bottom gratings during the adaptation period, the central grating exhibited a leftward MAE during the test period. The MAE in the central grating was only observed when the stationary top and bottom gratings were also presented in the test period. However, presenting the central grating during the adaptation period was not necessary to produce the MAE of the central grating. Our phenomenon accords with

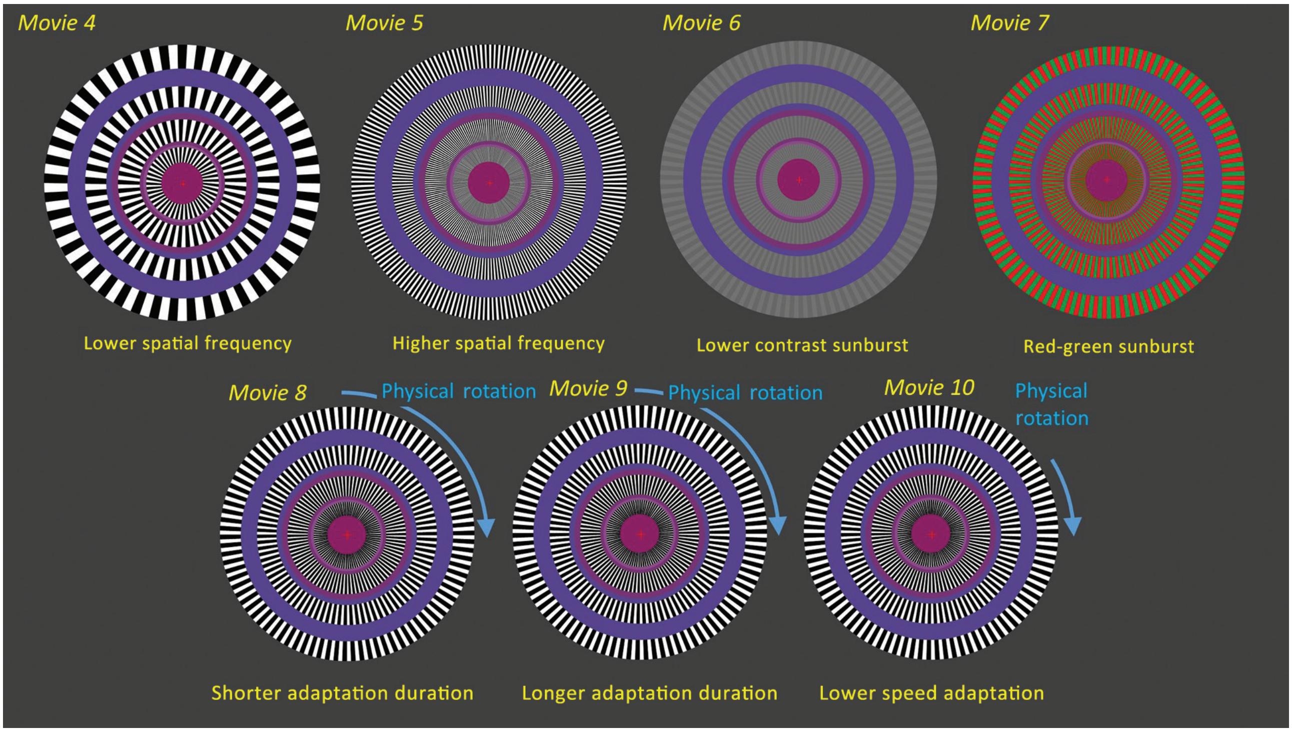

Fig. 4. Varied adaptation stimuli. Numbers of the rays in *Movie 4* and *Movie 5* are halved and doubled, respectively, compared to *Movie 2*. Luminance contrast of the sunburst in *Movie 6* is lower than *Movie 2*. *Movie 7* uses a red-green version of the sunburst pattern. *Movie 8* and *Movie 9* employ shorter (2.0 seconds) and longer (12.0 seconds) adaptation periods, respectively. *Movie 10* uses a lower angular velocity of rotation. Except for *Movie 8* and *Movie 9*, the adaptation period is 6 seconds. The angular velocity of rotation is 15.8 deg/s, except for *Movie 10* (6.0 deg/s).

Wade et al. (1996): non-exposure to motion in the ring area during the adaptation period does not eliminate the occurrence of the positive MAE. However, there are no stationary surroundings during the test period in our demonstration even if the afterimage of the rings functions as a test stimulus. According to Wade et al. (1996), little MAE should be expected under the present test-period setting, i.e. no surroundings. As suggested in Anstis and Reinhardt-Rutland (1976), induced motion by the MAEs that occurred in the surrounding areas also could cause a positive MAE in the ring area. However, no surroundings were presented during the test period in our demonstration.

Nevertheless, at present, we have to state that relative motion adaptation is an important (but not complete) hypothesis because the conditions where the effect arises are partly common with Anstis and Reinhardt-Rutland (1976) and Wade et al. (1996). If the present effect is a result of relative motion adaptation, the MAE direction of the afterimage could be 'negative' in terms of the *mechanism*. However, as a *phenomenon*, we only observe that the MAE direction is in the same rotation direction as the physical rotation of the stimulus. Therefore, we refer to this effect here as a positive MAE. Band-pass filtered stimuli could also cause positive MAEs (Nishida & Sato, 1992). In this case, the perceived and energy-based motion directions were set in opposite directions during the adaptation period, resulting in a positive MAE as a phenomenon arising from a negative MAE of the underlying mechanism.

Grindley and Wilkinson (1953) reported an MAE in a plain field in the absence of a test stimulus. As they described in their report, viewing a rotating sunburst pattern during an adaptation period and then removing it during the test period result in an MAE perceived as the motion of countless fine particles moving along with the flow of a viscous liquid. However, in the present demonstration, the ring area was not exposed to motion. Furthermore, it was the afterimage of the ring itself that was seen to rotate, rather than particles within the ring areas. Moreover, the afterimage is not perceived as a plain field. The afterimage of the rings appears to exhibit uneven perceived brightness and does not appear perfectly circular, but somewhat angular (Ito, 2012a). We show *Movie 11* (see Fig. 5) to demonstrate that a ring afterimage can be seen to rotate as an illusory polygonal shape (typically hexagon).

We produced another demonstration (*Movie 12*), in which the rings remain visible throughout the test period, in order to ensure that the ring areas are physically plain. In *Movie 12*, an illusory flow in the ring areas is perceived

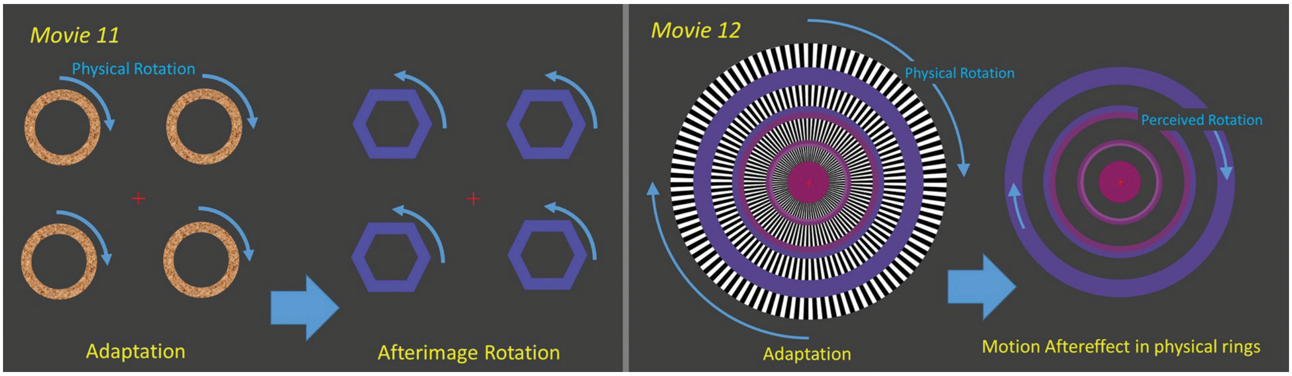

Fig. 5. Additional movies. *Movie 11* demonstrates afterimage rotation of rings as negative MAE. After viewing rings with sand-like texture in rotation, afterimages in an illusory hexagonal shape appear to rotate in the opposite direction to previous rotation. *Movie 12* uses the physical rings as it is as a test stimulus.

for a short period as a positive MAE, which is perceived as faster than the subsequent negative MAE of the rings. This is an intermediate phenomenon between Tomimatsu and Ito (2016) and the present illusion (*Movie 2*). Tomimatsu and Ito (2016) presented both the sunburst pattern and rings during the test period, but in *Movie 12*, only rings were presented, and in *Movie 2*, neither was presented. On one hand, it is possible that the latent illusory flow in *Movie 1* captures the afterimage of the rings in *Movie 2* and that the illusory flow seen as a positive MAE in *Movie 12* originates in an MAE of the Enigma flow seen in *Movie 1*. On the other hand, it is also possible that the Enigma flow seen in the stationary Enigma pattern and an illusory flow seen as an MAE in *Movie 2* and *Movie 12* are not the same illusion because the Enigma flow continues to appear as flickering, whereas *Movie 2* and *Movie 12* produce a non-flickering flow in MAE. Furthermore, as shown in *Movie 5* (see Fig. 4), although a higher spatial frequency version produces the Enigma flow when stationary, the present effect is not produced after its rotation. A future study should investigate the relationship between the Enigma flow in a stationary pattern and the illusory flow appearing in MAE.

In this study, we demonstrate that even when the rotating Enigma pattern disappears, the afterimages of the rings continue to be perceived as rotating in the same direction, and at a faster angular velocity than the previous rotation. The fast, positive MAEs reported here may be a rare occurrence, except the 'high phi' phenomenon reported by Wexler et al. (2013) where visual transients produce illusory jumps of a rotating stimulus in a direction that is the same as (or opposite to) the previous rotation. However, what makes the present effect even more special is that the effect arises in afterimages and is perceived as continuous motion. We believe that the present effect not only exhibits a new motion illusion but also suggests the possibility of the existence of an unstudied motion processing mechanism.

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