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PHENOMENAL REPORT

The Sunburst illusion

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Abstract

We report a new visual illusion. When a Mackay Ray figure is observed in paracentral vision or near peripheral vision, a fast but smooth pursuit eye movement produces an impression of bursting of a dazzling light in the center of the figure. We call this effect the *Sunburst illusion*. We have included movies demonstrating the effects of changing the speed and path of smooth eye movement, saccades, luminance contrast, and color combinations.

Keywords: *Mackay Ray figure*; *Flickering wheel illusion*; *smooth pursuit*; *luminance contrast*; *brightness illusion*

To access the movies for this article, please visit the article landing page or read the html version of the article where all movies are embedded.

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Radial patterns sometimes produce visual illusions. The Mackay Ray figure (Mackay, 1957) is a basic figure that induces this kind of illusion. The original Mackay Ray figure consists of radially arranged thin sectors. While the figure is being viewed, fluctuation of the sectors and pastel-colored 'mist' are perceived. The Mackay Ray figure induces motion illusions when a ring or a disk is superimposed on the figure. When a superimposed ring shares the figural center, a perception of streaming movement through the ring can be induced. This illusion was originally observed in an op art piece titled *Enigma* (Leviant, 1996). When a disk is superimposed on the central part of the MacKay Ray figure and seen in peripheral vision, the disk appears to move in the same direction as the smooth pursuit direction (*Pursuit-pursuing illusion*, Bai & Ito, 2014; Ito, 2012). Recently, the Mackay Ray figure itself has been found to induce a new illusory effect. The *Flickering wheel illusion* is a phenomenon in which the central part of the Mackay Ray figure produces a flickering impression that is related to α oscillations in electroencephalographic activity when viewed in peripheral vision, including when its afterimage is viewed (Sokoliuk & VanRullen, 2013). The Mackay Ray figure is essentially the same as the experimental stimuli used in the *Flickering wheel illusion*, except that the *Flickering wheel illusion* has been shown to produce the strongest illusory effect with stimuli containing 30–40 sectors, whereas the original Mackay Ray figure published in *Nature* contained 120 sectors. The *Sunburst illusion* reported in the current study is also produced by a MacKay Ray figure with 30 sectors (a typical case). However, the phenomenon has several unique features that distinguish it from the previously reported illusory effects described above.

Illusory effect of the Sunburst illusion

We have provided PowerPoint slideshow files demonstrating the *Sunburst illusion.* Movie 1 shows the basic version of the illusion (and the effect of eye movement noted later). As shown in Fig. 1, the figure in the movie consisted of 30 black thin sectors on a white background. The central angle of each sector is 6°. The figure can also be regarded as consisting of 60 black or white sectors alternately aligned. As a stationary figure, this stimulus is the same as the figure used in the *Flickering wheel illusion* (i.e. a 'sunburst pattern'). When the viewer tracks the moving dot with their eyes, the central area of the figure is perceived as shining, and the central dazzling area is perceived

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as exploding (if a sufficient effect is not induced, turning the head to assist the eye movements can help the illusion to occur). We call this bursting impression of the dazzling light as the *Sunburst illusion*. The perceptual dazzling light sometimes has an ivory tint. When the eye movement stops, the dazzling area shrinks and returns to the *Flickering wheel illusion* figure or a simple sunburst pattern.

Factors influencing the Sunburst illusion

Here, we demonstrate several factors that influence the illusion: the speed and path of eye movement, smooth pursuit versus saccade, and luminance contrast and color combinations of the figure.

The speed of eye movements is important for producing a strong *Sunburst illusion*. Fast pursuit eye movement induces a strong burst impression (see Fig. 1 and Movie 1). When the presented movie stimulus is viewed in full-screen mode on a 24-inch 16:9 display at a distance of 60 cm, the size of the figure subtended a visual angle of 27.9° horizontally and vertically. The traveled distance of the dot equals the horizontal size of the figure. The dot motion is fastest in the first slide. In the above viewing condition, it takes 2 sec per round trip, corresponding to a speed of 27.9°/s on average, which is well below the upper limit of smooth pursuit velocity (Meyer, Lasker, & Robinson, 1985). In the fourth slide, the dot speed was slowest (16 sec per round trip), corresponding to a speed of 3.5°/s. This very slow pursuit eye movement produces little illusory effect.

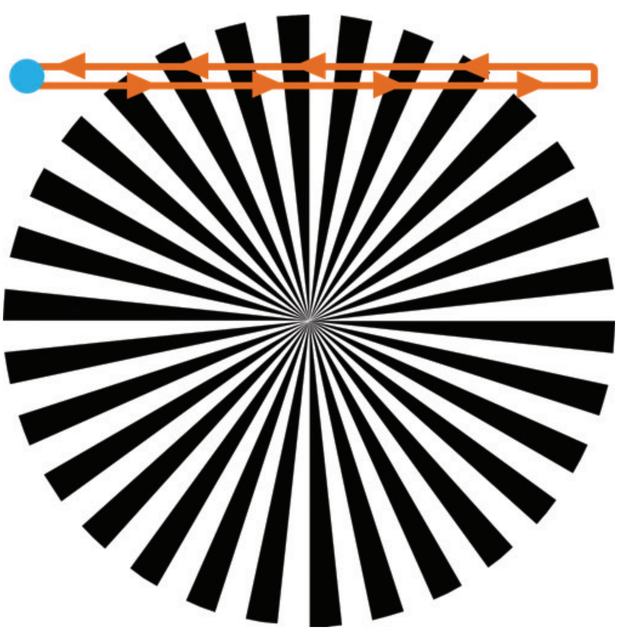

Fig. 1. The *Sunburst illusion*. Start slideshow in Movie 1. The blue dot moves horizontally on the radially arranged sectors. Smoothly track the dot with your eyes. A dazzling area appears and perceptually expands in the central part of the figure. Movie 1 consists of four slides showing four levels of dot speed. The RGB values are (R:0, G:0, and B:0) for black and (R:255, G:255, and B:255) for white. See details in the text.

When the motion path of the dot is along the sectors and running through the center (see Fig. 2 and Movie 2), the illusion still occurs, but in a less prominent manner. When the observer views the center of the figure and approaches/recedes from the figure, no illusion arises because the retinal image does not change by image expansion/contraction. When the observer approaches a peripheral point in the screen, a bursting effect arises because the image expansion on the retina produces a smooth image shift of the figure in the periphery.

Movie 3 shows a saccade version of the stimulus (see Fig. 3). The only difference between Movie 1 and Movie 3 is whether the fixation target is smoothly moving or jumping. Movie 3 does not produce the *Sunburst illusion*. Thus, the *Sunburst illusion* requires smooth image motion on the retina.

Movie 4 demonstrates the effect of luminance contrast of the figure on the *Sunburst illusion*. When the background is white, the effect becomes stronger as the sectors become darker (Fig. 4a, b and c). When the sectors and the background are dark and light grays, respectively, a higher Michelson contrast leads to a stronger illusion (Fig. 4d, e and f).

Movie 5 shows the effects of combinations of the sector and background colors. The illusion still occurs when the background color is not white. A yellow (Fig. 5a-1) or green (Fig. 5b-1) background produces a strong dazzling and expanding effect, whereas a red background (Fig. 5c-1) causes no dazzling effect, possibly because the luminance contrast between the black sectors and the red background is lower. Similarly, when the background is blue (Fig. 5d-1), neither the dazzling nor the expanding effects arise. *a-2*, *b-2*, *c-2*, and *d-2* in Fig. 5 show achromatic movie slides that are designed to roughly correspond to the colored movie slides (*a-1*, *b-1*, *c-1,* and *d-1*) in luminance. On our display (EIZO, FlexScan EV2750), each pair of the chromatic and achromatic movie slides with photometrically similar background-luminance settings (a-1 and a-2: 167 cd/m^2, b-1 and b-2: 130 cd/m^2, c-1 and c2: 38 cd/m^2, or d-1 and d2: 10 cd/m^2) induced a similar illusion impression. When the background is black, the yellow (Fig. 5e) or white (Fig. 5f) sector color is perceived as expanding. The black color does not appear to expand, regardless of whether it is used for the sectors or the background. Thus, it is possible that combinations of sector and background colors with high luminance contrast produce a strong illusory effect, in which the brighter color appears to expand. The effect may not largely depend on the hue and saturation of the sector or background color.

Movie 6 shows a striped version of the stimuli as a control (see Fig. 6). The simple vertical stripes do not produce the *Sunburst illusion* or a brightness illusion,

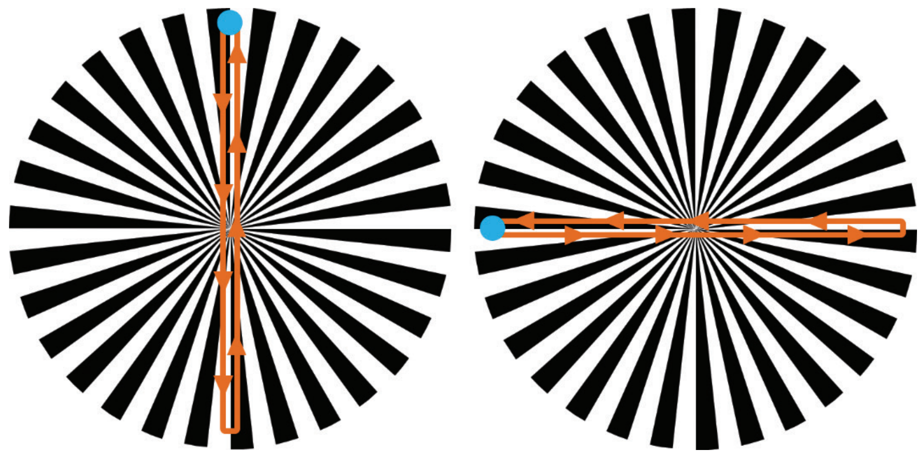

Fig. 2. The *Sunburst illusion* with a moving dot crossing the center. This condition still produces the illusion, but more weakly (start slideshow in Movie 2). The dot speed and the size of the figure are the same as those of the fastest stimulus in Movie 1.

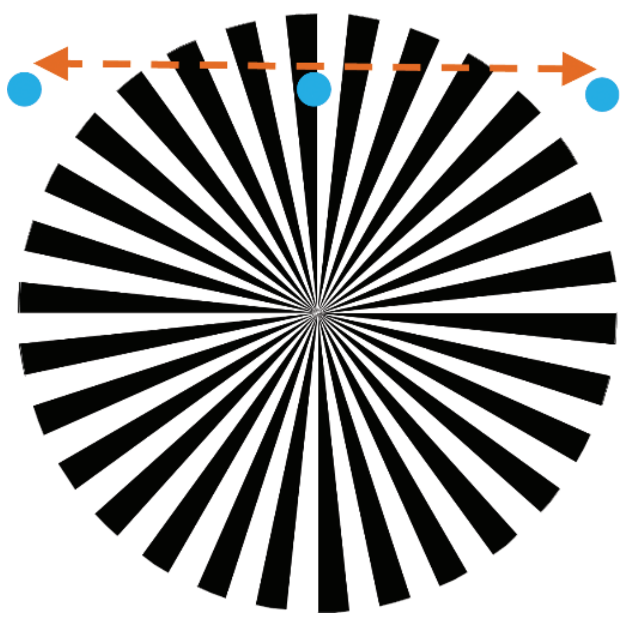

Fig. 3. Loss of the *Sunburst illusion* with saccades. Start slideshow in Movie 3. After each 0.5-s stay, the fixation dot jumps 13.9° horizontally (under the viewing condition described earlier). Saccades do not induce the *Sunburst illusion*.

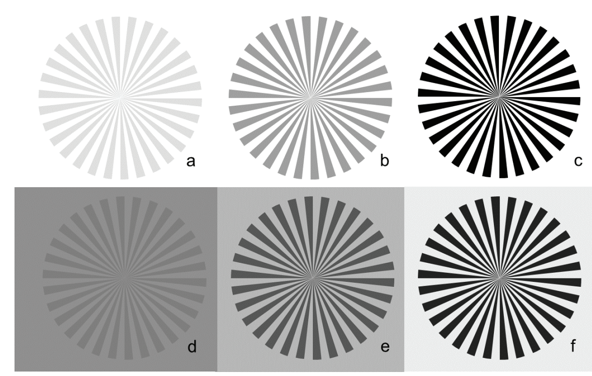

Fig. 4. Contrast effect in the *Sunburst illusion* (start slideshow in Movie 4). RGB values of sectors are (R:224, G:224, and B:224) in *a*, (R:160, G:160, and B:160) in *b*, and (R:0, G:0, and B:0) in *c,* whereas RGB values of the white background in *a*, *b*, and *c* are the same (R:255, G:255, and B:255). RGB values of the sectors and the background in *d* are (R:128, G:128, and B:128) and (R:144, G:144, and B:144). Those in *e* are (R:88, G:88, and B:88) and (R:184, G:184, and B:184). Those in *f* are (R:36, G:36, and B:36) and (R:236, G:236, and B:236). The motion of the dot and the size of the figure are the same as those of the fastest stimulus in Movie 1. The illusion strength is $a < b < c$ and $d < e < f$.

indicating the importance of the radial configuration of the components.

Discussion

At first glance, the present figure and illusory effects appear to be similar to those of the *Dynamic Luminance-Gradient Illusion* shown in Fig. 2 in Gori and Stubbs (2006). However, in their figure, the central area is brighter than the peripheral area on average, because of the luminance gradient in the sectors. In contrast, the *Sunburst illusion* is produced with a MacKay Ray figure, in which the averaged luminance is constant over the figure. The dynamic effect reported by Gori and Stubbs (2006) (i.e. when approaching the figure, the central bright area becomes brighter or expands the bright area) is produced by head movement along the line of sight, as reported in some previous studies of motion illusions (e.g. the *Rotating-Tilted-Lines illusion*, Gori & Hamburger, 2006; *Pinna & Brelstaff illusion*,

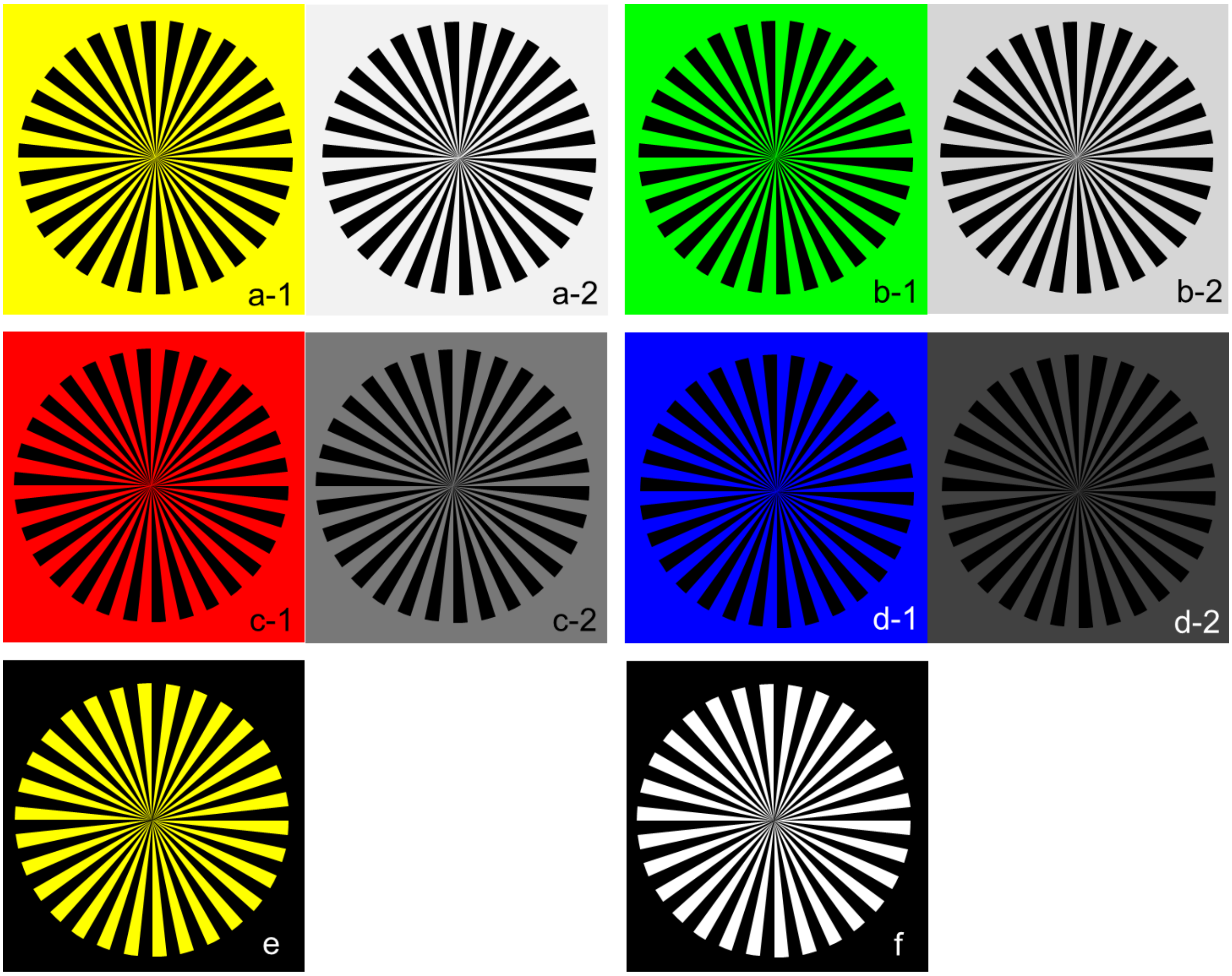

Fig. 5. Color variations. Sector colors and background colors are varied (start slideshow in Movie 5). The sector color is black (R:0, G:0, and B:0) for *a-1, a-2*, *b-1, b-2*, *c-1, c-2*, *d-1,* and *d-2*. The background color is yellow (R:255, G:255, and B:0), green (R:0, G:255, and B:0), red (R:255, G:0, and B0), or blue (R:0, G:0, and B:255) for *a-1*, *b-1*, *c-1,* or *d-1*, respectively. Regarding luminance, the gray background in *a-2* (R:242, G:242, and B:242), *b-2* (R:214, G:214, and B:214), *c-2* (R:120, G:120, and B:120), or *d-2* (R:65, G:65, and B:65) is designed to roughly correspond to the colored background in *a-1*, *b-1*, *c-1,* or *d-1*, respectively. The background is black (R:0, G:0, and B:0) for *e* and *f*, while the sectors are yellow (R:255, G:255, and B:0) or white (R:255, G:255, and B:255) for *e* and *f*, respectively. The motion of the dot and the size of the figure are the same as those of the fastest stimulus in Movie 1.

Pinna & Brelstaff, 2000). The *Sunburst illusion* does not arise when the viewer approaches the center of the figure, as noted above. The present dynamic illusion is produced by lateral image motion on the retina caused by smooth pursuit eye movements, despite the illusory figure consisting of a radial configuration of sectors. The present illusion and the *Pursuit-pursuing illusion* (Ito, 2012) share this feature.

The *Scintillating-luster illusion* (Pinna, Spillmann & Ehrenstein, 2002) is also similar to the *Sunburst illusion* in its effect and the spatial configuration. When a central circular area of a black radial line pattern is empty, the area forms a subjective disk and is perceived as brighter than the white background (Ehrenstein, 1941). When a gray disk is superimposed on the center of a radial line pattern, the *Scintillating-luster illusion* is induced when viewed in peripheral vision. The *Scintillating-luster illusion* has been shown to be enhanced by using fins or sectors instead of lines (Takahashi, Fukuda, Watanabe, & Ueda, 2012). This suggests that the *Scintillating-luster illusion* could be related to the illusions that appear on the Mackay Ray figure. The *Scintillating-luster illusion* is an automatically arising illusion often triggered by eye or visual pattern movements (regarding this characteristic, the

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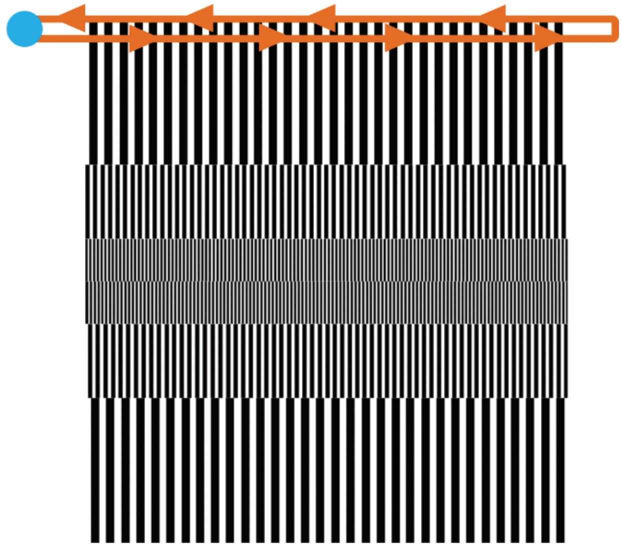

Fig. 6. A striped pattern as a control. The stripes do not induce a brightness illusion or an impression of expansion (start slideshow in Movie 6).

Scintillating-luster illusion and *the Flickering-wheel illusion* are similar). The *Sunburst illusion* is seen only during smooth eye movement (or possibly during smooth object motion), and the strength or area of illusory brightness depends on the speed. That is, the occurrence of the *Sunburst illusion* can be fully controlled by an observer.

The stimulus figure that causes the *Flickering-wheel illusion* is the same as that for the *Sunburst illusion*. Both illusions arise at the center of the sunburst pattern. In the *Flickering-wheel illusion*, the flicker effect is an automatic change in perceived brightness with an average frequency of 9 Hz (Sokoliuk & VanRullen, 2013). The flicker frequency is thought to reflect brain activity and is not determined by a visual stimulus or observational condition. Sokoliuk and VanRullen (2013) reported that small eye movements enhanced the *Flickering-wheel illusion,* although the illusion arises even in the afterimage of the test stimulus. In contrast, the *Sunburst illusion* induces a continuously dazzling impression (not flickering) during smooth eye movement. When the smooth eye movement stops or slows down, the illusory dazzling area shrinks to the center and the *Flickering-wheel illusion* arises. Thus, the two illusions alternatively arise depending on the eye (or the object) movement condition.

The following mechanisms have been proposed in previous studies of the phenomena on the Mackay Ray figure: fluctuation of accommodation for the shimmer effect of the Mackay Ray figure (Gregory, 1993), microsaccades for the illusory stream in *Enigma* (Troncoso, Macknik, Otero-Millan, & Martinez-Conde, 2008), relative motion detection for the *Pursuit-pursuing illusion* (Bai & Ito, 2014; Ito, 2012), rivalry between relative motion detectors for the illusory stream and the flicker impression in *Enigma* (Tomimatsu & Ito, 2016), rivalry between brightness and darkness subsystems for the *Scintillating-luster effect* (Pinna et al., 2002), and the occipital α rhythm on electroencephalography for the *Flickering-wheel illusion* (Sokoliuk & VanRullen, 2013). Because the present illusion was observed during smooth pursuit eye movements, saccades or microsaccades may not be necessary. Furthermore, the *Sunburst illusion* is sensitive to the retinal speed and luminance contrast between the sectors and the background, possibly suggesting that flickering on the retina is related to the illusion. Clarifying the details of the mechanism may require quantification of the present illusion. This issue should be examined in future studies.

We speculate that this illusion requires smooth retinal motion rather than pursuit eye movement. However, the radial pattern used here has very fine lines in the central region. Fast, smooth, and precise retinal motion of this pattern is difficult to produce using apparent motion on the computer screen. The best method for demonstrating this illusion is to display the figure on a liquid crystal display monitor without flicker and to move the eyes smoothly.

In summary, the *Sunburst illusion* consists of a figural component (i.e. the MacKay Ray figure) and a motion component (i.e. lateral image motion produced by smooth pursuit). The strength of the illusion may change depending on parameters of both components. A higher luminance contrast in the figure may result in a more dazzling impression. Faster (but smooth) pursuit eye movements may result in a stronger and larger burst impression.

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