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LAST BUT NOT LEAST

## Scotopic foveal afterimages

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Received 9 June 2008, in revised form 23 October 2008

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**Abstract.** If, after being in the dark for many minutes, one views an extended surface under dim (scotopic) illumination, one fails to see any hint of the dark spot at the center of gaze that might be expected from the absence of rods in the fovea. Here we report that, if the surface is suddenly completely darkened, one sees for a few seconds a relatively bright spot, about 2 deg in size, at the point of fixation. If the surface is now restored to its original brightness, a dark spot of similar size appears where one fixates, that again lasts for several seconds. All this can be observed with no elaborate apparatus.

### 1 Introduction

When humans view a scene, an image of the point on which they fixate is projected onto the region of the retina known as the foveal pit. This area is about 200  $\mu\text{m}$  in diameter and receives input from about  $\frac{1}{2}$  deg of the visual field. Because the foveal pit contains only cones, and no rod photoreceptors (Polyak 1941), it is blind to light at intensities below cone threshold, ie scotopic intensities. The rest of the retina, containing rods, can respond to such low light intensities, as can be easily demonstrated by dark-adapting and fixing one's gaze on a spot whose luminance is below cone threshold and whose diameter is  $\frac{1}{2}$  deg or less. The spot vanishes, but reappears when gaze is diverted.

Strangely, when one views an extended diffusely lit surface of the same low scotopic luminance, one does not observe any discontinuity or dark region at or around the point of fixation. The blind region is said to have been 'filled in' by a mechanism that is debated, and not fully understood (Pessoa et al 1998). We wondered what we would see if such a dimly lit surface were suddenly made completely dark. Would the filled in region maintain its relative brightness for a time, or immediately become dark along with its surround? And, if the surface were re-illuminated at scotopic levels, would filling-in occur immediately or only after a delay, with a transient dark spot appearing at the region of fixation?

We began by testing this without any elaborate apparatus. On a clear night, a full moon shining through a window lit a patch of floor a few feet square. Small spots of that same luminance vanished when fixated, indicating that the illumination was below cone threshold, ie was scotopic. On gazing at the large moonlit patch for a few tens of seconds and then looking away at an adjacent unlit region of floor we saw, within a second or so, a clear white spot at the point of fixation, about 2 deg in diameter. The spot, whose borders were fuzzy, persisted for several seconds before gradually fading. When we looked back at the original patch of light, a dark spot of similar size appeared at the fixation point and then gradually disappeared. We observed these bright and dark spots only when the extended patch of light was scotopic.

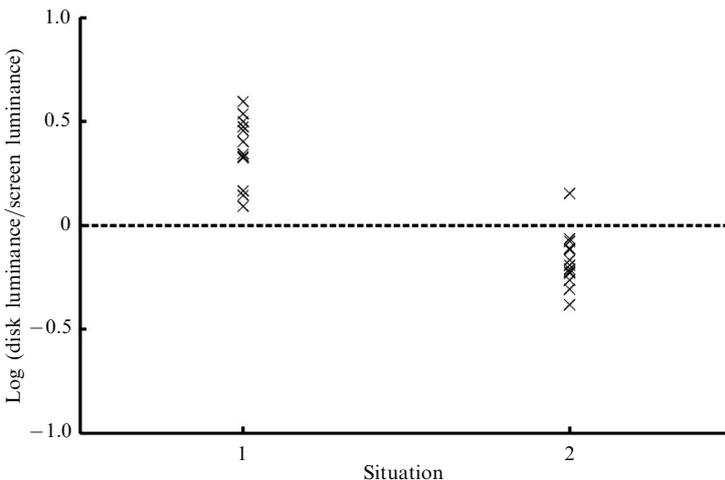
The purpose of this project was to study the transient bright and dark spots under more controlled conditions. We will refer to the bright and dark spots as 'afterimages', without wishing to imply any particular mechanisms or any relationship to the various afterimages seen under photopic conditions.

## 2 Methods

Thirteen subjects viewed, from a distance of 75 cm, a CRT monitor (Barco Display Systems, Krotijk Belgium), which had been calibrated with a Prichard Photometer (Photo Research PR-1980A). Subjects dark-adapted for at least 20 min. Then they varied the intensity of an achromatic spot  $\frac{1}{2}$  deg in diameter to find the maximum level at which it vanished when fixated. This procedure was repeated at the end of the experiment and for no subject was this level ever less than  $2.3 \times 10^{-2}$  cd m $^{-2}$ . Consequently, we took this value to be the cone threshold and the screen luminance was always kept well below this level to ensure scotopic conditions. During the course of the experiment the screen would switch from a value of  $7.8 \times 10^{-3}$  cd m $^{-2}$  to  $3.5 \times 10^{-4}$  cd m $^{-2}$  and back again. (At the lower level the borders of the monitor screen could only barely be made out.) Subjects always adapted to the screen for at least 60 s before it switched luminance. For each subject and for each situation the brightness of the afterimage was measured four times and the results averaged. We estimated the afterimage brightness by positioning a 3-deg achromatic circle 8 deg to the left of a dim fixation point. The subjects varied the luminance of this circle until it had the same brightness as the afterimage. This luminance was divided by the screen luminance and then the logarithm was taken to obtain the brightness of the afterimage. This last step was performed so that equal steps on the brightness scale would correspond to approximately equal perceptual changes. Values above zero represent bright afterimages; those below zero represent dark afterimages.

## 3 Results

The results are shown in the accompanying figure. All experiments were performed at scotopic luminance levels. In the *first* situation subjects viewed a dimly lit screen, adapted to it, and then the screen was made completely dark. After about a second, all subjects saw a white afterimage, centered on the point of fixation, whose brightness faded over some tens of seconds. Brightness was assessed by varying the intensity of a nearby matching spot (see section 2). The time variation of the afterimage made its brightness hard to assess, but its brightness never exceeded that of the original screen.



**Figure 1.** The brightness of the afterimage generated in each of the two situations. Subjects varied the luminance of a disk, 3 deg in diameter, positioned 8 deg to the left of the fixation point, until it appeared to have the same brightness as the afterimage. The afterimage brightness was then estimated by taking the logarithm of the ratio of the disk luminance to the screen luminance. Values above zero represent bright afterimages, those below zero represent dark afterimages. Because some crosses overlap, each cross may represent data from more than one subject.

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The afterimage had indistinct outer borders that subtended roughly 2 deg, with an inner 1 deg of relatively uniform brightness.

The size of the afterimage, which greatly exceeded that of the foveal pit, is what one would expect given the scarcity of rods just outside this region. Progressing from the foveal pit, the rod density increases, at first gradually (Osterberg 1935), and is maximal at about 10 deg.

In the *second* situation, subjects viewed the dark screen and adapted to it before the screen returned to its previous brighter, but still scotopic, level. All but one subject saw a dark 2 deg spot whose brightness was less than that of the final screen but greater than that of the initial screen. Unlike the bright afterimage, this afterimage was most striking immediately after the screen changed its luminance. The afterimage gradually disappeared over several tens of seconds.

#### 4 Discussion

Given the ease with which these effects can be observed, even with no special equipment, it would be surprising indeed if they had not previously been described. The dark afterimage described here may be related to the spot described by Maxwell (1856) and subsequently by Exner (1868) who observed it on a surface illuminated “by ordinary daylight”—whereas our dark spot was seen only at scotopic final levels of illumination. The bright afterimage may have been seen by Helmholtz (1897/1962), who briefly mentions having “on getting up in the morning accidentally seen the Maxwell spot, bright on a dark ground, in case the eye was first directed to a bright window with a broad luminous surface”. He goes on to say that he has “so far not succeeded in eliciting the phenomenon deliberately”.

We do not know whether these afterimages are to be attributed solely to the absence of rods in the fovea and their relative scarcity close to it, or in part to the macular pigment that forms the yellow spot, which would reduce the light arriving at the rods that are present. One might hope to distinguish these possibilities by varying the spectral content of the diffuse light, but we suspect that our present methods of assessing the brightness of the afterimages are too crude for this.

We have two further interpretations of our observations. In an ‘afterimage’ interpretation, we note that, when a spot of light on a black background is extinguished, it is replaced with a spot that appears darker than the black background, presumably because of the bleaching of visual pigment. Of course, under scotopic conditions no bleaching of visual pigment occurs in the foveal pit. Thus, when the screen luminance is suddenly reduced, the region near the point of fixation appears brighter than its surround. In this interpretation there is no reason to expect the foveal afterimage to be *brighter* than the original screen, and indeed our crudely measured brightnesses never exceeded that level.

A second possible interpretation involves the ‘filling-in’ already referred to. When we view a diffusely and dimly lit surface, we are aware of no black or blank region in our center of gaze. We say that the scotoma is ‘filled in’, with no very clear idea of how the filling-in occurs (Pessoa et al 1998). In the present context, it is possible that, when the surface is suddenly darkened, the foveal filling-in persists for some seconds, causing a bright spot. And, similarly, when the screen is brightened, the filling-in takes a few seconds to assert itself and so we see a dark area near the center of gaze.

A common example of filling-in is encountered with the fading of images that are stabilized on the retina in order to overcome involuntary microsaccadic eye movements (Ditchburn and Ginsborg 1952; Riggs et al 1953). Like our bright afterimage, the fading of stabilized images takes several seconds to occur. Obviously the foveal scotopic blind spot is stabilized.

A problem with any interpretation is that we do not know why filling-in sometimes does not occur. For example, if, under scotopic conditions, one fixates on the center of a line, the portion of the line that projects to the foveal pit is not seen and the line appears to contain a gap (Hubel 1997). We have no explanation why surfaces and lines are treated differently by the filling-in mechanism.

**Acknowledgments.** The research was supported by NIH grant EY00605 to DHH, a postdoctoral fellowship from the Helen Hay Whitney foundation to PDLH, and by ARO grant 46961 to Margaret Livingstone. We are indebted to Imme S Kaschner for help in translation of Exner's article, and to John Mollon and Nicholas Wade for useful comments in reviewing the paper.

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ISSN 0301-0066 (print)

ISSN 1468-4233 (electronic)

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VOLUME 38 2009

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