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Size of the foveal blue scotoma related to the shape of the foveal pit but not to macular pigment

Yun Chen [a], Weizhong Lan [a,b], Frank Schaeffel [a,*]

[a] Section of Neurobiology of the Eye, Ophthalmic Research Institute, 72076 Tuebingen, Germany
[b] State Key Laboratory of Ophthalmology, Zhongshan Ophthalmic Center, 510060 Guangzhou, China

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ABSTRACT

When the eye is covered with a filter that transmits light below 480 nm and a blue field is observed on a computer screen that is modulated in brightness at about 1 Hz, the fovea is perceived as small irregular dark spot. It was proposed that the "foveal blue scotoma" results from the lack of S-cones in the foveal center. The foveal blue scotoma is highly variable among subjects. Possible factors responsible for the variability include differences in S-cone distribution, in foveal shape, and in macular pigment distribution. Nine young adult subjects were instructed to draw their foveal blue scotomas on a clear foil that was attached in front of the computer screen. The geometry of their foveal pit was measured in OCT images in two dimensions. Macular pigment distribution was measured in fundus camera images. Finally, blue scotomas were compared with Maxwell's spot which was visualized with a dichroic filter and is commonly assumed to reflect the macular pigment distribution. The diameters of the foveal blue scotomas varied from 15.8 to 76.4 arcmin in the right eyes and 15.5 to 84.7 arcmin in the left and were highly correlated in both eyes. It was found that the steeper the foveal slopes and the narrower the foveal pit, the larger the foveal blue scotoma. There was no correlation between foveal blue scotoma and macular pigment distribution or Maxwell's spot. The results are therefore in line with the assumption that the foveal blue scotoma is a consequence of the lack of S-cones in the foveal center. Unlike the foveal blue scotoma, Maxwell's spot is based on macular pigment as previously proposed.

1. Introduction

In 1894, Arthur König presented a lecture to the "Preussische Akademie der Wissenschaften" at Berlin, in which he claimed that the human fovea is "blue blind" and that subjects are "dichromatic" in the fovea (p. 591). His conclusion was based on psychophysical studies in which subjects had to fixate small monochromatic light spots presented at different wavelengths. He found that subjects had difficulties to distinguish between "blue" and "green" (König, 1894). Later, histological (Willmer & Wright, 1945) and psychophysical studies (Wald, 1967) confirmed that there is a tritanopic zone of about 20 arcmin in diameter in the center of the fovea (Williams, MacLeod, & Hayhoe, 1981). More recently, Curcio et al. (1991) mapped the foveal photoreceptors and found that a 20–25 arcmin S-cone free zone exists in the human foveola with sparsely and irregularly distributed S-cones in the adjacent foveal slopes. Under normal viewing conditions, the foveal blue scotoma is not visible because of the neural process of filling-in (Gerrits & Vendrik, 1970; Magnussen et al., 2001, 2004; Spillmann & Werner, 1996; Williams, MacLeod, & Hayhoe, 1981). However, Magnussen et al. (2001, 2004) described two procedures to make the blue scotoma visible. In the first study (Magnussen et al., 2001), subjects were presented with a blue field in Maxwellian view with a peak wavelength around 450 nm that was sinusoidally modulated in luminance at a frequency of 1–2 Hz. In this case, subjects could see their blue scotomas as a small dark spot that moved with their point of fixation. Apparently, the process of filling-in was compromised by the brightness modulation of the blue field. When subjects were asked to rate the visibility of the blue scotoma at different wavelengths, their ratings matched about the spectral sensitivity of the S-cones. In their second approach, Magnussen et al. (2004) showed that the foveal blue scotoma becomes visible as a bright spot in a negative afterimage when subjects were adapted to a bright blue field. Again, the subjects' rating as to how clearly they could see the blue scotomas varied with the peak wavelength of the adapting field and followed the spectral sensitivity function of the S-cones. The diameters of the perceived blue scotomas ranged from 24.8 to 44.3 arcmin, similar to the diameter of the S-cone free zone that was histologically identified in the foveal center by (Curcio et al., 1991).

* Corresponding author. Fax: +49 7071 295196.
E-mail address: frank.schaeffel@uni-tuebingen.de (F. Schaeffel).

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The primate fovea is histologically recognized as a pit with tightly packed M- and L-cones, providing maximal visual acuity. In this area, one single cone (M- or L-) is connected to 3–4 bipolar cells and 3 ganglion cells. This ratio decreases to one ganglion cell per cone at an eccentricity of 15–20 deg (3–4 mm). In peripheral retina there are more cones than ganglion cells. The ganglion cell density changes by a factor of 1000–4000 between peripheral and central retina (Wässle & Boycott, 1991; Wässle et al., 1990). Excluding S-cones from the foveal center appears to be an elegant trick to cope with chromatic defocus that results from longitudinal chromatic aberration of the optics of the eye (Rodieck, 1973). Shapes of foveas can be divided into two extremes: 'convexiclivate' and 'concaviclivate' (Polyak, 1951). Since the retinal tissue has a substantially higher refractive index than the vitreous (1.38 vs 1.335), the vitreo-retinal interface acts as a refracting surface. In a convexiclivate fovea, the interface acts as a magnifying glass to the image projected on the photoreceptors on the back of the retina. This design is found in reptiles, birds and some fishes. Harkness and Bennet-Clark (1978) have simulated the optical effects of the deep convexiclivate fovea and found that the perceived image distortions vary with the focus of the eye and could therefore be used as "focus indicator". On the other hand, in a concaviclivate fovea the image is minified because a flatter fovea is combined with a photoreceptor layer that is bulged out towards the center of the fovea pit, generating the effects of a concave lens. This case is mostly found in primates (Harkness & Bennet-Clark, 1978) but it is not clear what the advantage might be of minifying the projected image. The minification effect appears very small (<1%, see Section 4).

Interestingly, the shape of the foveal pit in human subjects is highly variable (see, for instance, OCT data in the current study) but probably not random since a negative correlation was found between the steepness of the foveal slopes and foveal diameter (Knighton & Gregori, 2012).

In the central region of the human retina, a yellowish macular pigment, consisting of lutein and zeaxanthin, is embedded in the cone axons and in the inner-plexiform layer. It acts as a screening pigment for the underlying photoreceptors (Hammond, Wooten, & Snodderly, 1997; Werner, Bieber, & Schefrin, 2000; Werner, Donnelly, & Kliegl, 1987) and is assumed to protect photoreceptors from photo-oxidative damage by short wavelength light (Kirschfeld, 1982; Nussbaum, Pruett, & Delori, 1981; Werner, Bieber, & Schefrin, 2000). The peak absorption of the macular pigment is around 460 nm (Bone, Landrum, & Cains, 1992), close to the spectral sensitivity peak of the S-cones (Stockman & Sharpe, 2000). The distribution of macular pigment varies considerably among subjects (Wooten & Hammond, 2002; Wooten et al., 1999). It is assumed that the percept of Maxwell's spot is related to the macular pigment distribution.

Since foveal shape, foveal blue scotomas, and macular pigment distribution are all highly variable among subjects, it is interesting to study how they are related. Furthermore, there is recently increasing interest in this question (i.e. the ongoing MacTel project https://web.emmes.com/study/mactel/). To further elucidate the relationship between macular pigment distribution and foveal blue scotoma, we also explored how they are related to the appearance of Maxwell's spot.

2. Methods

2.1. Subjects

Nine subjects (5 female and 4 male) with an average age of 29.6 ± 7.7 years (ranging from 22 to 49 years) and normal color vision were recruited for the experiments. The Chinese subjects (1, 3, 5, 8) had undergone color vision testing with the Ishihara pseudo-isochromatic color plates prior to their enrollment at their home universities. The remaining German subjects were tested at school and had no known color vision deficiencies. The study adhered to Code of Ethics of the World Medical Association (Declaration of Helsinki) and was approved by the local University Ethics Commission.

2.2. Psychophysical experiments

2.2.1. Measurement of the foveal blue scotomas

A blue field (size 900 × 900 pixel), sinusoidally modulated in luminance at a frequency of 1 Hz between RGB (0, 0, 255) and RGB (0, 0, 0), was presented on a thin film transistor (TFT) display (screen refresh rate 60 Hz, EIZO FlexScan S1921, 19 in.). Maximal pixel radiance of the "B" channel (RGB (0, 0, 255)), as measured by a photometer (Minolta LS100), was 10.70 cd/m^2. Since the "blue" gun of computer screen contains energy also in the middle wavelength range, M- and L-cones were also stimulated by the B gun. To preferentially stimulate the S-cones, a filter excluding light above 500 nm was needed. We used the bandpass glass filter BG25 (Schott, Germany) with a peak transmission at about 400 nm and a FWHM of about 50 nm. Subjects viewed the modulated "blue" field on the screen in a dark room from a distance of 74 cm. The blue field had a diameter of 26.4 × 26.4 cm on the screen which converts into a visual angle of 20.2 deg. Assuming a retinal image magnification for the human eye of 290 μm/deg (Gullstrand, 1909), the linear size of the retinal image was about 5850 μm.

Subjects were instructed to draw their foveal blue scotomas, one eye after the other, with a marker pen on a transparent plastic sheet that was attached in front of the screen. The procedure was repeated four times. The four drawings were averaged pixel by pixel using "ImageJ" (http://rsb.info.nih.gov/ij/). Image J offers an "image calculator" function which calculates the arithmetic mean of each pixel gray value from two or more images. The resulting "average" of several drawings made it more easy to measure the diameters of the foveal blue scotomas, or of Maxwell's spots, and also increased the confidence in the measurements.

2.2.2. Visualization and measurement of Maxwell's spot

Maxwell's spot was visualized as described by Isobe and Motokawa (1955). A bright white field was generated by aiming a video projector (Sharpe XG-NV21SE) at a white paper that was attached to the wall. Subjects were instructed to look into the bright white field through a dichroic filter in front of one eye, the other eye was covered (KIF 483, Schott, Germany; light transmission below 480 nm and above 610 nm, with prominent attenuation between 500 and 600 nm). Typically, Maxwell's spot becomes visible as a brownish or reddish spot on bright white background with variable shapes and diameters among different subjects, as shown in Fig. 6. Transmission of the dichroic filter also at longer wavelengths is necessary and was already recommended by Maxwell himself to counteract retinal adaptation. When subjects look into white light without a filter, Maxwell's spot disappears almost immediately due to rapid adaptation of macular photoreceptors (Miles, 1954). In order to maintain visibility of Maxwell's spot, a dichromatic filter was also used by Holm (1922), Walls and Mathews (1952), and Isobe and Motokawa (1955). As in the previous experiments where the blue scotoma was measured, the distance between the subject and the wall was 74 cm. The instructions to the subjects were to draw the pattern that they saw directly on the paper. It was mentioned to them that, while the blue scotoma appears as a dark gray or black spot, Maxwell's spot looks reddish or brownish.