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## CLASSICAL ARTICLES IN COLOR

### The Stiles-Crawford-Effect

H. Goldmann

"Stiles-Crawford-Effekt", *Ophthalmologica*, Vol. 103, pp. 225-229, (1942).

Translation by Sophie Wuerger

Commentary by Sophie Wuerger

Center For Neural Science, New York University

New York, NY 10003

*Stiles and Crawford (1933)<sup>1</sup> reported that a narrow beam of light appears brighter when it enters through the pupil center, than when it enters the pupil peripherally. The magnitude of the Stiles-Crawford-Effect (SCE) is shown in Goldmann's reproduction of the Stiles & Crawford data (Figure 1; Goldmann, 1942<sup>2</sup>): for foveal vision, the luminous efficiency of a light beam entering the pupil centrally is five times higher than for an otherwise identical beam entering the pupil 4mm away from the center.*

*Stiles and Crawford suggested that this change in sensitivity as a function of the pupil entrance position is due to the directional sensitivity of the receptors (retinal effect) and does not originate in the ocular media (media effect). A retinal interpretation is supported by the fact that the SCE (i) is larger at photopic than scotopic light levels in the parafovea (Crawford, 1937<sup>3</sup>), (ii) is independent of the light level for foveal vision (Crawford, 1937), (iii) disappears for short-wavelength light below 600nm in the parafovea at scotopic brightness levels (Flamant and Stiles,*

1948<sup>4</sup>), and (iv) differs for observers with retinal pathology from that for normal observers. More specifically, these findings suggest, that primarily the cones and not the rods are responsible for the SCE. Prior to Goldmann's elegant experiment, however, no direct proof had been given that the SCE is caused by the properties of the receptors in the retina<sup>5</sup>.

Goldmann proved that the SCE originates in the retina by inspecting with an ophthalmoscope the stimulus after it passed through the optical media. Figure 2 demonstrates the rationale of Goldmann's experiment: the upper part shows two beams of light (A and B) both entering through the center of the pupil; in the lower part a prism is inserted into the field stop forcing one of two beams (B) to enter the pupil in the periphery. Now the operator of the ophthalmoscope adjusted the intensities of the two beams of light with different angles of incidence, A and B, such that they looked equally bright when he viewed them at the back of the subject's eye. If the SCE is caused by the optics of the eye, then these two beams of light are perceived as equally bright by the subject as well. On the other hand, if the effect has its origin in the receptors, then the subject perceives them as unequally bright. Goldman reports the latter outcome, hence providing decisive evidence for the retinal hypothesis.

As early as 1844 Brücke<sup>6</sup> had noted that the refractive index of the cylindrical retinal elements (i.e. rods) was higher than that of the surrounding tissue. He proposed that multiple internal reflection within the cylindrical retinal elements could increase the efficiency of light absorption. About a hundred years later, in 1936, Wright and Nelson<sup>7</sup> put forward this principle of 'total internal reflection' to explain the SCE. O'Brien<sup>9</sup> refined this concept stressing the importance of the ellipsoid and its taper angle (fig. 3). He suggested the possibility that receptors might concentrate light from the large cone inner segments into the narrow cone outer segments. This geometrical optics model is demonstrated in figure 3. The geometrical shape of the cone acts like a 'light funnel' concentrating the light incident on the cone inner segment into the cone outer segment which has a smaller diameter. This funneling is possible only if the refractive

index is high enough such that the light does not escape before the outer cone segment is reached. Since the outer cone segment contains the photosensitive pigment, this funneling increases the efficiency of light absorption for rays entering the inner segment of the cone along its axis (thin dotted line in lower part of fig. 3). Rays of oblique incidence (solid line in lower part of fig. 3) will escape through the inner segment before they reach the outer segment and hence will not be absorbed. The 'critical angle for internal reflection' is indicated by the thick dashed line (lower part of fig. 3), that is, all rays incident at an angle larger than  $\Theta$  will suffer total internal reflection.

Toraldo di Francia<sup>10</sup> pointed out that a model based solely on the geometrical optical characteristics cannot provide a quantitative description of SCE since the retinal receptors have diameters (as small as  $1 \mu\text{m}$ ) of the order of the wavelengths of visible light. He suggested viewing the photoreceptors as dielectric antennas, so that diffraction effects might be taken into account. The waveguide explanation of the SCE assumes that the amount of light absorption depends on the receptor dimensions and the refractive index relative to its surround (fig. 3) as well as upon the wavelength and angle of incidence of the light.

What is the functional importance of directional sensitivity? The insensitivity of the cones to rays of oblique incidence has the advantage that straylight, for example coming from the fundus of the eye, is suppressed. Overall, however, the insensitivity of the cones to light coming from the outer part of the pupil is probably of no great consequence for vision since under normal viewing conditions the cones do not receive light from the peripheral part of the pupil. When the pupil is dilated, that is, under scotopic viewing conditions, rods are more sensitive than cones. The significance of directional sensitivity lies presumably less in the suppression of stray light but more in the enhanced sensitivity to direct light through the funneling mechanism.

### References

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### Figure Legends

Figure 2. The upper part shows two beams of light (A and B) entering the pupil both at the center. The lower part depicts a situation where a prism is inserted into the field stop causing one of the light beams (B) to enter the pupil in the periphery.

*Figure 3. Geometrical optics description of the SCE. The figure shows a schematic drawing of the cone inner segment (ellipsoid and myoid) and the cone outer segment. The light is entering from the left. The parameters of the cone inner segment and cone outer segment are based on data provided by Enoch and Tobey (1981; tables 2.1, 2.4, 6.1; figures 6.4, 6.5). The relative size of the cone inner segment to the cone outer segment is 4.5; the relative diameter is 2; the refractive index is assumed to be 1.39 for the cone inner segment and 1.33 for the extracellular medium. For this relative refractive index of 1.045 (cone inner segment to extracellular medium), the 'critical angle of total reflection'  $\Theta$  (to the interface normal), for which the refracted ray travels along the interface, is 73 degree (upper part of figure 3). This critical angle of total reflection is indicated by the thick, dashed line in lower part of figure 3 and can be derived from the ratio between the outer and the inner refractive index via Snell's law:  $\Theta = \arcsin(\frac{n_o}{n_i})$ . Light incident at angles larger than this critical angle undergoes total internal reflection (dotted line in lower part); light incident at angles smaller than this critical angle undergoes refraction and reflection (solid line in lower part). The angle of refraction is given by Snell's law; the angle of reflection ( $\Theta'$ ) equals the angle of incidence.*

*Acknowledgements-I would like to thank John Krauskopf and Vivianne Smith for sharing with me their expertise in optics and for improving the English translation.*

In 1933, Stiles and Crawford (1) discovered that the perceived brightness of an object depends on the point at which the light ray travelling from the object to the retina enters the pupil of the observer. An object is perceived as brightest if its emitted light rays enter approximately through the middle of the pupil; the perceived brightness decreases the more peripheral the point on the pupil is even though the patch of retina is the same (4) (Fig. 1).

Two possibilities are available to explain this curious effect: 1. The light rays that enter peripherally through the media undergo, for some reason, a reduction in intensity (media effect).

2. The receptors in the retina are most sensitive to light rays that enter them longitudinally; oblique incident rays excite the retinal elements less than axial ones (retinal effect) (Wright and Nelson, 2).

Until now only two indirect pieces of evidence have been presented that the second explanation is more plausible than the first one. Crawford (3) showed that for threshold stimuli this effect may only be elicited in the fovea, and almost never outside of the fovea in the dark-adapted eye. Stiles (4) was able to confirm this finding and demonstrated that the effect does not occur in the dark-adapted eye for monochromatic extra-foveal threshold stimuli if light below 580 nm is used. Whereas Stiles and Crawford interpret this difference between light- and dark-adapted eye as proof for the effect originating in the retina, Best (5) explains this difference in behavior by claiming, "that more dispersed light is lost on the retina through the blurred image when light is incident through the peripheral points on the pupil, whereas under dark adaptation the rods make up for this brightness error by summation in the synapses."

In addition, hue differences occur, when identical monochromatic light is sent through the pupil axially and eccentrically (Stiles, 6).

Craik (7) cut out a piece of the back of a cat's eye and replaced it by a photocell. A diaphragm was moved back and forth in front of the cornea; the photocell did not indicate any intensity change, that is, no Stiles-Crawford-Effect. Craik believed one could conclude that the SCE is not a media effect but a retinal phenomenon; however he tacitly assumed that the cat *has* a SCE, which cannot be proven, and, quite the contrary, if it were a matter of a media effect, differences between species would be quite plausible.

Considering the cited evidence, the investigations by Stiles and Crawford made it very likely that the described effect constitutes a retinal phenomenon. On the other hand, the arguments by Best, which are not entirely clear to me, show that the question of the locus of the SCE

would be clearly decided only if it were investigated *directly* in humans, whether the *same retinal illumination yields different brightness sensations depending on the incidence of rays through the pupil*. Based on these considerations, in the following an experiment will be described, whose result will decide whether the SCE is indeed a retinal phenomenon or not.

The rationale of the experiment is that the observer (from now on called the 'subject') is presented with two adjacent half-fields. Both pencils of light rays pass through the pupil plane at widely separated locations, one of them central, the other one peripheral. At the same time the experimenter (the 'investigator' or the 'operator of the ophthalmoscope') inspects the back of the subject's eye at which the two half fields are imaged. This experimental design allows the investigator to detect, whether the half fields, that appear equally bright to the subject, hence eliciting the same sensation, correspond to images of identical luminance when imaged on the back of the eye. If the subject perceives two half fields as equally bright whenever the experimenter does, then the SCE is a media effect. If the observer perceives retinal half fields of unequal brightness as equally bright, or equally bright ones as unequally bright, then the SCE is a retinal effect.

The experiment was carried out as follows: As is known, the illumination device of the large Gullstrand ophthalmoscope creates a sharp illuminating bipartite image in the pupil of the subject. The subject himself perceives a circular field of luminance, which is created by imaging a field stop on his retina. In our experiments, fields of approximately 15 and 8 degrees of visual angle (hence half fields of 7.5 and 4 degrees, respectively) were used. In this stop one inserts a prism of 4 degrees of angle such that the prism edge exactly bisects the field stop, and the subject perceives the circular patch as vertically bisected by the edge of the prism (otherwise one would have a double image of the edge due to the reflecting glass surface of the ophthalmoscope [sic]). Covering the half field stop with the prism has the effect, that the subject only sees the field stop divided in the middle by a line, those rays however that pass through the prism take a different course than the ones that do not go through the prism; in the pupil of the subject two images

instead of one image are created, which are in our case separated by 3.5 mm. One is able to put one of the images in the center, the other one in the periphery of the dilated pupil, that is, one can create the conditions for the occurrence of the Stiles-Crawford-Effect. Between the two images in the pupil one puts the (small) exit pupil of the monocular Gullstrand ophthalmoscope, such that the back of the subject's eye can be viewed without reflection. For technical reasons (avoidance of effects of vignetting, usage of non-blinding light, facilitation of the absence of reflection) the illumination slit of the ophthalmoscope was shortened to approximately 1 mm, such that only two illuminated points lay in the pupil of the subject.

When the subject fixates the middle of the edge of the prism, the experimenter sees on the back of the subject's eye two half fields with a sharp border, which appear equally bright, whether the two split fields in the pupil are symmetric to each other, or if one of them is in the center of the pupil, the other one in its periphery. *The subject, however, perceives something very different:* for approximately symmetric passage of the pencils of rays through the pupil he perceives the two split fields as equally bright; if one of the pencils of rays enters peripherally, the other one centrally, then the subject perceives the field corresponding to the peripheral incidence, much darker than the other one; meanwhile, as pointed out before, the investigator observing the back of the eye perceives both fields always as equally bright.

If a neutral density filter of approximately 40 percent absorption is placed in front of one of the half fields and the beam of light is made to pass through the pupil such that the attenuated light enters at the center of the pupil, the unattenuated one at the periphery, then it is still the case that the subject perceives the half field corresponding to the peripheral beam of light as darker than the other one, whereas conversely the experimenter perceives that half field on the back of the eye as brighter that corresponds to the peripheral beam of light. If one shifts the two half fields conjointly over the pupil then the sensation changes constantly for the subject; the originally darker field becomes brighter, equals the second one in brightness at some stage, and finally

surpasses it by far. The experimenter, however, perceives on the back of the subject's eye *no unchanging fields of unequal brightness*. (The entrance pupil of the observers binocular did not change its position during these experiments).

I have conducted this experiment with several people whose pupils have been dilated with Glaukosan, always with the same outcome. *From this it follows uniquely, that the Stiles-Crawford-Effect is a retinal phenomenon, that is, the perceived brightness depends upon the angle of light incidence on the retinal elements*. We cannot yet determine what causes this phenomenon. A migration of the pigment in the light-adapted eye, which would account for the effect most readily, has never been proven in humans. For the eyes of planaria it is known, that their neurons are insensitive to light of oblique incidence though they have no pigment sheath (Tagliaferro, 8); hence the SCE seems to be phylogenetically very old. The phenomenon certainly is of great practical significance for vision, since it eliminates disturbing stray light. For large pupils though, the high luminance of images would not be fully utilized; but we have and need large pupils only in the dark, and precisely in the dark-adapted eye the Stiles-Crawford-Effect largely disappears.

#### *Summary.*

Description of an experiment arrangement with the help of which proof is obtained that the *Stiles-Crawford-Effect* is produced in the retina.

#### *References.*

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*Figure Legend.*

Figure 1. Abscissa: Distance of point of entry of beam from the middle of the pupil in mm.  
Ordinate: Percentage of intensity reduction of the beam of central pupil incidence required to be perceived as equally bright to the peripheral beam (adapted from *Stiles and Crawford*).

Abszisse: Abstand des Strahlendurchstoßpunktes von der Pupillenmitte in mm.

Ordinate: Betrag in %, auf den die Intensität des zentral die Pupille durchstoßenden Bündels herabgesetzt werden muß, um dem peripheren Bündel gleich hell zu erscheinen.

(Nach *Stiles und Crawford.*)





