

## ARTICLE

# Perceived brightness with small apertures

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**Purpose:** To quantify the relative perceived brightness when viewing through a small aperture as that used by presbyopic patients with small-aperture corneal inlays or intraocular lenses with an embedded aperture.

**Setting:** Laboratorio de Óptica, Universidad de Murcia, Murcia, Spain.

**Design:** Prospective case series.

**Methods:** The relative perceived brightness when 2 apertures (3.0 mm and 1.6 mm diameters) were presented monocularly to the participant was determined. With equal transmittances in both apertures, a flickering effect caused by the different retinal illuminance for each condition is perceived. The participant's task was to modify the transmittance of the 3.0 mm pupil until the flickering was minimized. This transmittance value indicates the relative

perceived brightness reduction. The measurements were performed under 3 average luminance levels.

**Results:** The perceived relative luminance measured ranged between 38.5% and 46.9%. This represents an increase in brightness perception with a small aperture of 1.24 and 1.51, respectively, compared with what would be expected. This trend was consistent for all the participants in the study.

**Conclusions:** The perceived brightness with a small aperture was less pronounced than what would be predicted by the reduction in retinal illuminance. Under real visual conditions, this effect could be even more significant because binocular effects and temporal adaptation might further increase the perceived brightness with the small aperture.

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The correction of presbyopia by optical means has attracted the attention of researchers and inventors since the 18th century. Today, there are an abundance of options, from spectacles to contact and intraocular lenses (IOLs) to refractive surgical procedures. Because all current approaches have associated disadvantages, alternatives have been proposed in past decades. A simple optical alternative to increase depth of focus is the use of small apertures.<sup>1</sup> This was first proposed in the form of a corneal inlay (Kamra intracorneal inlay, Acufocus, Inc.), which has been implanted in many patients.<sup>2,3</sup> This small polyvinylidene fluoride ring contains particles of carbon to make it opaque. It has a thickness of 6  $\mu\text{m}$ , a central aperture of 1.6 mm, and an outer diameter of 3.8 mm. The surface of the inlay has microperforations ranging from 6 to 12  $\mu\text{m}$  that are arranged in a random pattern to allow nutritional flow through the corneal tissue. The average light transmission is 5% with an 8400 random-hole pattern.

The small aperture also has been implemented in IOLs. The hydrophobic acrylic IC-8 IOL (Acufocus, Inc.) has a circular mask with a small 1.36 mm central aperture embedded in it.<sup>4</sup> The small aperture has been used in a modified version of the corneal inlay and the IOL.

Under clinical conditions, there is solid evidence that most patients obtain good vision at most distances when the small aperture is placed monocularly with the fellow eye set for distance vision with the natural pupil. There are several possible limitations of this technique. One is the possible decentration of the aperture during surgery, which degrades the retinal image quality, even with the small aperture. The other is reduced luminance in the eye with the small aperture compared with that in the fellow eye. It has been suggested that this could cause interocular differences in temporal responses, leading to changes in perceptions of movements.<sup>5</sup> Another, probably more severe, effect is a reduction in contrast sensitivity under low-luminance conditions.

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Although the use of small apertures reduces retinal illuminance, many patients often report less reduction in the perceived brightness in the eye with the inlay than what would be expected from a reduction in retinal illuminance. We performed a monocular study to quantify the relative perceived brightness when viewing through a small aperture in comparison with viewing through a larger pupil. The goal was to help identify the limitations of the use of a small aperture to correct presbyopia and to optimize future aperture configurations.

## PARTICIPANTS AND METHODS

This study comprised normal healthy participants with no ocular known disease. The study followed the tenets of the Declaration of Helsinki, and all participants provided informed consent.

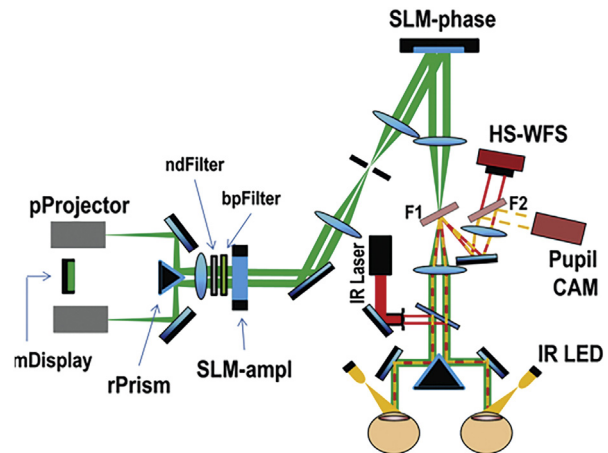
### Apparatus

The apparatus used in this experiment is a binocular adaptive optics vision simulator (Figure 1). It has been described in detail.<sup>6-9</sup> Briefly, the instrument presents visual stimuli to the participant through modified optics, including the phase of the wavefront and the light amplitude distribution over the pupil. The visual stimuli are displayed by using an organic light-emitting diode (OLED) microdisplay (Figure 1) or a couple of pico projectors. In the first case, the stimulus is the same for both eyes, whereas in the second case the retinal images on each eye might be different, as in past studies of the effect of aberrations on stereopsis.<sup>10</sup> The phase is modified by a phase-only liquid crystal spatial light modulator (Pluto-VIS, Holoeye Photonics AG), which allows manipulation of defocus, astigmatism, and higher-order aberrations in the participant's eyes. Light amplitude distribution is changed through an additional liquid crystal spatial light modulator (LC2002, Holoeye Photonics AG) sandwiched between crossed linear polarizers. This is an amplitude-only configuration that leaves the phase unaltered and permits the definition of light-intensity distribution over the modulator's active surface. This is used to limit the size and transmittance of the natural pupils of the participant, creating artificial apertures.

The driver of the spatial light modulator working in amplitude inputs an 8-bit image and converts it into the voltage distribution that modifies the alignment of the liquid crystal molecules. Hence, to determine the actual transmittance induced in the device, a previous calibration was performed to establish the relationship between the gray-level input and the corresponding transmittance. Two parameters are needed set the correct pupil size; that is, the pixel size of the spatial light modulator working in amplitude and the optical magnification between the modulator itself and the eye. This approach was validated by placing a camera in the eye's pupillary plane. The images acquired at different pupil sizes were analyzed by counting the number of pixels along any diameter. The actual pupil diameter was estimated based on the camera pixel size. In all cases, there was excellent agreement between the measured and the expected diameters. Additional elements in the apparatus are a Hartmann-Shack wavefront sensor and a pupil-monitoring system (a pupil camera plus an infrared [IR] LED).

### Testing Procedure

Although the binocular adaptive optics vision simulator has binocular capabilities, only the right eye of each participant was tested while the left was occluded. The visual stimulus consisted of a constant intensity image that was produced by displaying on the pico projector a white patch corresponding to the right eye. The image on the retina subtended 1 degree of arc. Even though the study was performed monocularly, the use of 1 of



**Figure 1.** The binocular adaptive optics vision simulator. The same visual stimuli are shown to both eyes using the OLED microdisplay or different for each one by means of a pico projector and a right-angle prism mirror. A bandpass filter and a neutral density filter can be used to select a spectral band and reduce the light intensity, respectively. Amplitude and phase are modified through a liquid crystal modulator working in amplitude and phase-only mode. A Hartmann-Shack wavefront sensor module composed of an IR laser and a short-pass filter allows measurement of ocular aberrations. A module imaging the participant's pupils consisting of 2 infrared light-emitting diodes, 2 short-pass filters, and a camera permits control over the pupil's alignment (bpFilter = bandpass filter; F1 and F2 = short-pass filters; HS-WFS = Hartmann-Shack wavefront sensor; IR = infrared; IR Laser = infrared laser; IR LED = infrared light-emitting diode; mDisplay = microdisplay; ndFilter = neutral density filter; OLED = organic light-emitting diode; pProjector = pico projector; Pupil CAM = pupil camera; rPrism = right-angle prism mirror; SLM-ampl = spatial light modulator working in amplitude; SLM-phase = phase-only spatial light modulator).

the projectors was preferred rather than the OLED microdisplay because of the higher luminance of the former.

After proper alignment of the participant's pupil with the exit pupil of the instrument, the participant's eye aberrations were measured using a Hartmann-Shack wavefront sensor module. Astigmatism was corrected through the phase-only liquid-crystal modulators in participants with values above 0.25 diopter (D). Defocus was also corrected by allowing the participant to subjectively search for his or her best focus in steps of 0.25 D. The measurement of the relative brightness perception with different pupil sizes is based on a flicker-detection procedure in which the artificial pupil produced by the spatial light modulator working in amplitude continuously alternates between 2 different sizes (3.0 mm and 1.6 mm) with an interval duration of 350 milliseconds. Each of the pupils, having equal transmittance, will produce retinal images with different illuminance and then a perception of flickering. The participant's task was to reduce the transmittance of the larger pupil to minimize and reduce flicker while the transmittance of the smaller pupil was held constant at the maximum. The participant controlled the transmittance using a keyboard connected to the computer controlling the modulator.

The transmittance ratio, or relative transmittance, of the larger to the smaller pupil is an estimation of the relative perceived brightness. Figure 2 shows a diagram of the entire procedure. A bandpass filter centered at 550 nm with a full width at half maximum was of 10 nm introduced in the optical path because it was noticed that the flicker-detection procedure produced more reliable results when using quasi-monochromatic light. For each participant, the test was performed at the following 3

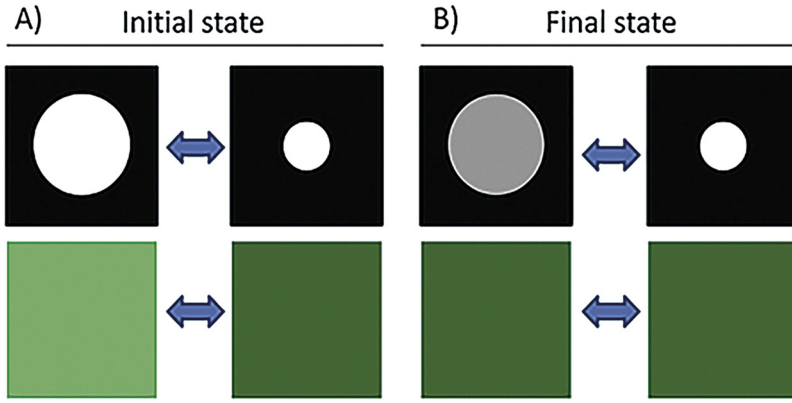


Figure 2. Procedure to estimate the relative brightness perception with different pupil sizes. Larger pupils and smaller pupils are alternatively presented to the participant. A: In the initial state, they have equal transmittance, providing different retinal illuminance and the perception of flickering. B: In the final state, the participant has reduced the transmittance of the larger pupil, minimizing the flickering, by matching the perceived brightness in the image for each pupil size.

luminance values:  $1\times$ ,  $0.1\times$ , and  $0.01\times$ , the maximum luminance provided by the pico projector ( $25 \text{ candelas/m}^2$ ). Two neutral density filters with optical densities of 1 and 2 were used to produce the  $0.1\times$  and  $0.01\times$  conditions, respectively. The final estimation of the relative transmittance that minimizes flickering was the average of 3 measurements.

### Expected Values from Theoretical Calculations

The expected relative transmittance between the larger pupil and the smaller pupil, which would produce the same brightness perception calculated based on physical and physiologic considerations. On the one hand, pupils with a different size collect different amounts of luminous power. Using only geometric calculations the relative transmittance needed to equalize the retinal illuminance can then be obtained as

$$\frac{T_L}{T_S} = \left(\frac{D_S}{D_L}\right)^2 \quad (1)$$

where  $T_L$  and  $T_S$  are the transmittances of the larger pupil and the smaller pupil, respectively, and  $D_L$  and  $D_S$  their diameters, respectively.

On the other hand, it is well known that the Stiles-Crawford effect<sup>11</sup> of the first kind limits the efficiency to produce brightness sensation of rays entering the pupil through the periphery. This is often represented as an apodization effect in the pupil, which is equivalent to variable transmission over the pupil.<sup>12,13</sup> This effect is modeled by assuming a radially decreasing transmittance distribution over the pupil area. In this case, because both pupils are constant in size, the loss of intensity produced by the transmittance distribution can be simplified to be an equivalent constant transmission producing the same net effect. Then, the relative transmittance required to equalize the retinal illuminance, including the difference in size and the Stiles-Crawford effect, can be expressed as

$$\frac{T_L}{T_S} = \frac{T_S^{(SC)}}{T_L^{(SC)}} \left(\frac{D_S}{D_L}\right)^2 \quad (2)$$

where  $T_L^{(SC)}$  and  $T_S^{(SC)}$  are the equivalent transmittances that account for the Stiles-Crawford effect for larger pupils and smaller pupils, respectively. If the Stiles-Crawford effect can be modeled as a transmittance distribution depending on the distance ( $\rho$ ) to the pupil center as<sup>14</sup>

$$t_{SC}(\rho) = 10^{-0.05 \times \rho^2} \quad (3)$$

the equivalent transmittances  $T^{(SC)}$  for the larger pupil and smaller pupil can be calculated, and equation 2, which provides the relative

transmittance needed to equalize the retinal illuminance for the 2 pupils, is transformed into

$$\frac{T_L}{T_S} = \frac{1 - 10^{-0.05 \times (D_S/2)^2}}{1 - 10^{-0.05 \times (D_L/2)^2}} \quad (4)$$

### RESULTS

Five participants with ages ranging from 26 to 55 years were tested. Two had mild myopia ( $< -3.0 \text{ D}$ ), and 3 were nearly emmetropic. Figure 3 shows the measured relative transmittance values for all participants under the 3 luminance conditions. The mean values were  $46.9\% \pm 4.9\%$  (SD),  $38.3\% \pm 2.3\%$ , and  $38.5\% \pm 2.5\%$  for the  $0.01\times$ ,  $0.1\times$ , and  $1\times$  relative luminance values, respectively. Error bars for each participant data are  $\pm 1$  SD of 3 measurements, averaging 1.5%. Error bars for the mean of all participants represent  $\pm 1$  SD of the values measured in all participants.

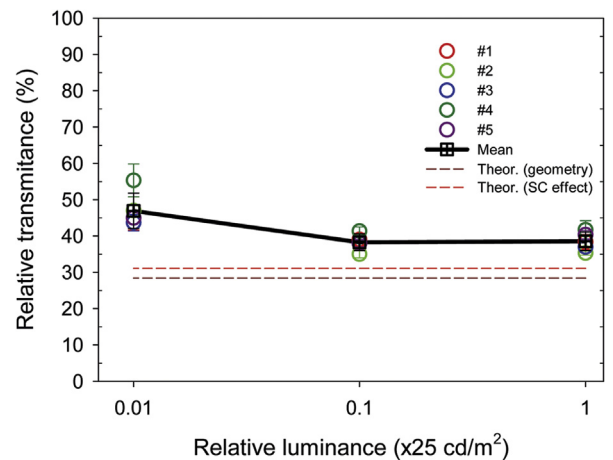


Figure 3. Relative transmittance of the larger to the smaller pupil, which matches the perceived brightness as a function of luminance for participants #1 through #5. Black symbols are the average through participants, with error bars showing intersubject variability. Constant dashed lines represent the theoretic values obtained considering only geometric calculations (28.4%) or including the Stiles-Crawford effect (#1, #2, #3, #4, and #5 = participants; cd = candelas; SC = Stiles-Crawford; Theor. = theoretic).

The mean error is  $\pm 3.2\%$ . Therefore, intrasubject variability and intersubject variability were relatively small, supporting the design of the experimental procedure and the consistency of the results.

The relevance of these results relies on a comparison with the expected values obtained from theoretic calculations. Using equation 1, the relative transmittance needed to equalize the retinal illuminance for 2 pupils with diameters  $D_S = 1.6$  mm and  $D_L = 3.0$  mm, based only on geometric considerations, is 0.284 (or 28.4%). When the Stiles-Crawford effect is included, equation 4 provides a relative transmittance of 0.311 (or 31.1%). Compared with this theoretically expected value, the measurements show a relative transmittance that is increased by factors of 1.24 and 1.51 for the 2 higher and the lowest luminance conditions, respectively. In all cases, the measured differences relative to the expected value of 0.311 were statistically significant ( $P < .01$ , Student  $t$  test). This means that the relative brightness perceived through a smaller pupil was greater than expected.

## DISCUSSION

The increase in the expected value of the relative transmittance after considering the Stiles-Crawford effect was not enough to account for the measured values. By considering this effect, the relative transmittance became 31.1% (to be compared with the 28.4% value with the simple geometrical approach). This indicates that as expected, the Stiles-Crawford effect plays a role, although the relatively small pupil considered in the study is limited. The Stiles-Crawford effect would account for around one third of the measured effect at higher luminance and less than one fifth for the lower luminance conditions. We found an even more significant effect for low luminance in the mesopic range, where it is accepted that the Stiles-Crawford effect (mediated by cones) will not operate.

We do not have a good explanation for this observation. We could speculate that some type of nonlinear retinal effect explains why with measurements of smaller pupils, the brightness responses are higher than with larger pupils. Because there are indications that this could be increased with adaptation, the effect could have a neural origin. This phenomenon would tend to equalize the brightness perception between the 2 eyes, 1 with a small pupil and the other with a natural pupil.

This relative increase in brightness perception with a small aperture could have a beneficial effect to patients in terms of overall luminance. However, the effects on contrast detection and spatial resolutions should be studied separately.

In conclusion, we found that the perceived brightness reduction with a small aperture was less pronounced than what would be predicted by the reduction in retinal illuminance. The influence of the Stiles-Crawford effect only accounted for a small fraction of this effect. Under real visual conditions, this effect might be more significant because binocular effects and temporal adaptation might further increase the perceived brightness with small apertures.

## WHAT WAS KNOWN

- Small apertures are used to extend depth of focus in presbyopic patients using either corneal inlays or IOLs with an embedded aperture. One limitation of this approach is the reduced retinal illuminance.

## WHAT THIS PAPER ADDS

- The perceived brightness reduction with a small aperture was less pronounced as what was predicted by a reduction in retinal illuminance.
- The influence of the Stiles-Crawford effect only accounted for a small fraction of this effect.

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