Spatial summation is one of the basic features of the early visual processes. It is commonly encapsulated by Ricco's law: this law states that up to a certain area, defined as Ricco's area, the light energy increment needed to detect a stimulus is constant regardless of the area of the stimulus [1]. Correspondingly, the irradiance threshold is inversely proportional to the area of the stimulus. The area of complete summation has been shown to vary with light level [2], eccentricity [3,4], and age [5]. Neuronal receptive fields are often regarded as the physiological entities determining Ricco’s area [6]. However, Davila and Geisler [7] have proposed that what they refer to pre-neural mechanisms, the optical impulse response of the eye and the summation over photoreceptors, may in fact be the main contributors to the foveal spatial summation in the photopic light regime. They obtained a good fit between human performance and the performance predicted with an ideal observer that takes into account quantum fluctuations, the optics of the eye, the receptor aperture, and the receptor lattice.

The energy light distribution on the photoreceptor mosaic is dictated by diffraction, scatter, and ocular aberrations. Measurements of spatial summation curves (energy or intensity threshold versus stimulus area) are typically performed after a refractive correction of the subjects. Different optical configurations have been used, with the light passing through various pupil sizes from one system to the other. When a Maxwellian-view optical system is used, the image size in the pupil plane is typically 1.5 mm in diameter [4] yielding a minimum diffraction spot of 2.5 arc min diameter on the retina for a short-wavelength stimulus (λ = 440 nm). For larger defined pupils, the residual second order and the higher-order monochromatic aberrations affect the image spread [8]. Adaptive optics (AO) has recently emerged as an efficient tool to manipulate these ocular aberrations [9] and investigate the limits of vision (see a review in [10]). The purpose of this work was to use AO to correct ocular aberrations and retrieve the role of natural ocular aberrations in the spatial summation from measurements of Ricco’s area with and without correction of ocular aberrations. Furthermore, it was to measure the spatial summation with a minimized point spread function.

The apparatus, an AO vision simulator, has been described elsewhere [11]. It consists of a near-IR laser diode beacon to focus a spot on the retina, a Shack–Hartmann wavefront sensor to measure the ocular aberrations, a Badal optometer and cylindrical lenses to correct defocus and astigmatism, and a biprism deformable mirror (AOptix, Inc.) to correct the residual aberrations of the eye. Additionally, the laser beacon is scanned on the retina to average speckle, being descanned before arriving at the Shack–Hartmann sensor. Various displays have been implemented in the system to perform visual tests. For the purpose of this experiment, a color digital light-processing projector was modified to provide a 766 gray-level stimulus. The micromirror chip was reimaged through the system such that a pixel corresponded to 0.11 arc min on the retina. A green filter (550 nm; bandwidth 10 nm) was placed in front of the projector. The chromatic difference of focus between the wavefront sensing laser beacon and the projector light was corrected subjectively by an experienced observer [11]. An artificial pupil was set in the system such that the green light entered the eye through a diameter of 6 mm in the pupil plane.

The visual test consisted in measuring the intensity increment threshold to detect a square stimulus superimposed on a 1° field circular background of luminance 20 cd/m² in a two alternative forced-choice task. The stimulus was presented in a Gaussian temporal envelope of standard deviation 133 ms at 10 arc min vertical eccentricity from the horizontal line formed by the wavefront sensing beacon. For each presentation, it appeared randomly below or above the laser line and the subject's task was to discriminate its location. A schematic of the visual task is given in Fig. 1. A two-down, one-up staircase procedure was used and the test was terminated after seven reversals. The threshold was estimated as the mean of the last four reversals.

Three subjects, all emmetropes and aged from 24 to 38 years old, were tested in this study. The tested
eye was dilated with Tropicamide 1%, and the subject was aligned in front of the system with a bite bar. The subject initially adjusted the best focus for a fixation cross by moving the Badal optometer in a step of 0.1 D. The relative intensity increment threshold ($\Delta I/I$) was then measured for a set of stimulus sizes ranging from $-1.3$ to $2.3$ log arc min$^2$. The measurements were repeated alternatively with and without the AO correction of ocular aberrations. In condition "no AO" the deformable mirror was kept static with the commands applied to correct only the optical aberrations of the system; in condition “AO” the mirror was continuously updated to correct the measured aberrations of the subject. In both conditions, the laser line was continuously visible. For stimulus sizes up to 0.24 log arc min$^2$, three measurements in each condition were obtained and averaged; for larger sizes, the stimulus was presented further away from the laser line (15 arc min instead of 10 arc min) and only two measurements were obtained. The measurements were spread over several sessions lasting 1 h each.

The set of data points obtained over the range of stimulus area was fitted with a bilinear curve with a variable breakpoint. The slope of the first segment was fixed to 1 to reflect complete summation and the slope of the second segment was left variable. The least-squares fit was performed with STEPIT [12].

The average amount of ocular aberrations measured over a 6 mm pupil without and with the AO correction is shown in Table 1 in terms of wavefront error rms. The values were calculated from five measurements of a few seconds repeated at different points during the measurement sessions. The initial ocular aberrations of the three subjects are consistent with the statistics of typical ocular aberrations [13].

Figure 2 shows the spatial summation curves for the three subjects. The relative intensity increment threshold after the AO correction of ocular aberrations is lower than that without correction. The difference between the two, averaged over the range from $-1.3$ to $0.5$ log arc min$^2$ and among the three subjects, is 0.26 log units, which corresponds to a factor of 1.83. The estimations of Ricco’s area from the least-squares bilinear fit are presented in Table 2. On average, the area was reduced after the AO correction by $0.42\pm0.14$ (mean±standard error of the mean) log unit, which corresponds to a factor of 2.6. The log difference was found statistically significantly greater than 0 ($p<0.01$ in a paired t test).

We demonstrated a difference in the intensity increment threshold and in the estimated Ricco’s area with and without the AO correction of ocular aberrations.

### Table 1. Average and Standard Deviation rms Wavefront Error of the Three Eyes Measured without and with AO Correction and Given in Micrometers

<table>
<thead>
<tr>
<th>Subject</th>
<th>rms without AO</th>
<th>rms with AO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.38±0.08</td>
<td>0.07±0.01</td>
</tr>
<tr>
<td>2</td>
<td>0.4±0.1</td>
<td>0.10±0.02</td>
</tr>
<tr>
<td>3</td>
<td>0.27±0.07</td>
<td>0.08±0.01</td>
</tr>
</tbody>
</table>
In conclusion, the ocular optics affects the confinement of the light energy on the retina mainly through aberrations for large pupils and through diffraction for small pupils. In all cases, this influences the measurement of the intensity or energy increment thresholds for small stimuli, and hence, the estimate of Ricco's area. The present data are in agreement with the statement by Davila and Geisler that preneural factors (including ocular optics and photoreceptor sampling) mainly account for Ricco's area in the fovea, in photopic light conditions [7]. However, when the background light level is decreased or the eccentricity is increased, some evidence indicate that the area of complete summation is related to neuronal receptive fields [4,7].

We thank Roger Anderson for his suggestion on the line of inquiry of this project and Tony Redmond for his help with the bilinear fit. This research was funded by Science Foundation Ireland under grant SFI/07/IN.1/1906.

**References**


**Table 2. Estimated Ricco’s Area**

<table>
<thead>
<tr>
<th>Subject</th>
<th>AO Condition</th>
<th>Ricco’s Area (min²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No AO</td>
<td>8.73</td>
</tr>
<tr>
<td></td>
<td>AO</td>
<td>2.02</td>
</tr>
<tr>
<td>2</td>
<td>No AO</td>
<td>17.77</td>
</tr>
<tr>
<td></td>
<td>AO</td>
<td>7.49</td>
</tr>
<tr>
<td>3</td>
<td>No AO</td>
<td>9.98</td>
</tr>
<tr>
<td></td>
<td>AO</td>
<td>5.57</td>
</tr>
</tbody>
</table>

In conclusion, the ocular optics affects the confinement of the light energy on the retina mainly through aberrations for large pupils and through diffraction for small pupils. In all cases, this influences the measurement of the intensity or energy increment thresholds for small stimuli, and hence, the estimate of Ricco’s area. The present data are in agreement with the statement by Davila and Geisler that preneural factors (including ocular optics and photoreceptor sampling) mainly account for Ricco’s area in the fovea, in photopic light conditions [7]. However, when the background light level is decreased or the eccentricity is increased, some evidence indicate that the area of complete summation is related to neuronal receptive fields [4,7].

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