Night myopia is reduced in binocular vision

Emmanuel Chirre
Laboratorio de Óptica, Universidad de Murcia, Instituto Universitario de Investigación en Óptica y Nanofísica, Murcia, Spain

Pedro M. Prieto
Laboratorio de Óptica, Universidad de Murcia, Instituto Universitario de Investigación en Óptica y Nanofísica, Murcia, Spain

Christina Schwarz
Center for Visual Science, University of Rochester, Rochester, NY, USA

Pablo Artal
Laboratorio de Óptica, Universidad de Murcia, Instituto Universitario de Investigación en Óptica y Nanofísica, Murcia, Spain

Night myopia, which is a shift in refraction with light level, has been widely studied but still lacks a complete understanding. We used a new infrared open-view binocular Hartmann-Shack wave front sensor to quantify night myopia under monocular and natural binocular viewing conditions. Both eyes' accommodative response, aberrations, pupil diameter, and convergence were simultaneously measured at light levels ranging from photopic to scotopic conditions to total darkness. For monocular vision, reducing the stimulus luminance resulted in a progression of the accommodative state that tends toward the subject's dark focus or tonic accommodation and a change in convergence following the induced accommodative error. Most subjects presented a myopic shift of accommodation that was mitigated in binocular vision. The impact of spherical aberration on the focus shift was relatively small. Our results in monocular conditions support the hypothesis that night myopia has an accommodative origin as the eye progressively changes its accommodation state with decreasing luminance toward its resting state in total darkness. On the other hand, binocularity restrains night myopia, possibly by using fusional convergence as an additional accommodative cue, thus reducing the potential impact of night myopia on vision at low light levels.

Introduction

Since the first mention of the phenomenon of night myopia by Maskelyne in 1798 (Levene, 1965; Rayleigh, 1883), many studies on the myopic shift under low light levels have been conducted. Over the years, a large range of values between −4 and +1.5 D has been reported for night myopia under monocular conditions (Arumi, Chauhan, & Charman, 1997; Epstein, Ingelstam, Jansson, & Tengroth, 1981; Johnson, 1976; Leibowitz & Owens, 1975b; Otero & Durán, 1941; Wald & Griffin, 1947). Under binocular viewing conditions, night myopia is less severe but still relevant (Ivanoff, 1955). The variability across subjects probably comes from the number of contributing or even interfering factors and, to date, has prevented a complete explanation of the phenomenon.

Historically, a number of potential sources of night myopia have been proposed and studied. Chromatic aberration (Bedford & Wyszecki, 1947; Levene, 1965; Otero, Plaza, & Salaverri, 1949; Wald & Griffin, 1947) in combination with the Purkinje effect plays a moderate role in night myopia. Depending on the light source used for visual testing, it can provoke a refractive change of no more than 0.4 D (Wald & Griffin, 1947). The increase in spherical aberration as the pupil dilates at low luminance levels can also cause a myopic shift (Arnulf, Flamant, & Françon, 1948; Ivanoff, 1955; Koomen, Scolmik, & Tousey,

Citation: Chirre, E., Prieto, P., Schwarz, C., & Artal, P. (2016). Night myopia is reduced in binocular vision. *Journal of Vision*, *16*(8):16, 1–10, doi:10.1167/16.8.16.

doi: 10.1167/16.8.16 Received January 7, 2016; published June 22, 2016 ISSN 1534-7362

1951; Koomen, Tousey, & Scolnik, 1949; Otero & Durán, 1941; Rayleigh, 1883). Finally, the resting state of accommodation of the eyes could play a role in the onset of night myopia in the absence of visual stimuli (Owens & Leibowitz, 1980). Although dark vergence and dark accommodation seem to be independent from each other (Kotulak & Schor, 1986), vergence and accommodation are cross-coupled (Fincham, 1962; Jiang, Gish, & Leibowitz, 1991; Wolf, Bedell, & Pedersen, 1990). Accommodative-induced vergence and vergence-induced accommodation are only weakly correlated but differ widely across subjects. Additionally, spherical aberration becomes relatively more negative as the eye accommodates. Recently, Artal, Schwarz, Cánovas, and Mira-Agudelo (2012) demonstrated, by using an adaptive optics-based instrument, that monocular night myopia is mainly caused by an accommodative error, and spherical aberration and chromatic aberration only play minor roles.

The purpose of this work was to investigate the interaction of binocular vision, including vergence and accommodation, on night myopia using an infrared binocular Hartmann-Shack (H-S) wave front sensor in open view and to reevaluate the importance of the contributing factors. To this end, convergence, aberrations, and natural pupil size were measured under low light levels and in absolute darkness.

Methods

Experimental system

A binocular infrared open-view H-S wave front sensor combined with an infrared pupil tracker has been used (Chirre, Prieto, & Artal, 2014). The instrument enables long sequences of unobtrusive measurement of accommodation, vergence, pupillary dynamics, and ocular aberrations using an invisible 1050-nm light source (Fernández & Artal, 2008) while subjects perform the visual task of choice under realistic viewing conditions. The instrument has proved to be a versatile tool for the study of the dynamics of accommodative and convergence responses (Chirre, Prieto, & Artal, 2015).

During the measurements, the subject has an unobstructed view straight ahead, where different stimuli or tests can be placed. As described elsewhere (Chirre et al., 2014), the H-S sensor is located below the line of sight of the subject by means of a large long-pass dichroic mirror (see Figure 1). This dichroic mirror is used both for illuminating the eyes with two IR beams and to collect the retinal reflection from both eyes for wave front sensing. A twin periscope reduces the spacing between the outgoing beams in order to fit both pupils onto a single H-S sensor. A custom-made binocular pupil-tracker algorithm is used to determine the pupil centers for correct wave front sensing and, furthermore, to detect changes in convergence and pupil size. A separate pupil-monitoring system using a CCD camera (Hamamatsu, Japan) and an array of IR LEDs (900 nm) is inserted by means of a flip mirror at the beginning of the experiment.

The visual target consisted of a high-contrast letter on a white circular background, displayed on a flat LCD monitor located 2.75 m in front of the subject. A linear polarizer sheet was used to increase the contrast of the monitor. The letter subtended 1.3°, and the white circular background was 2.5° in diameter. The use of a large letter allowed subjects to see the target even at very low light levels.

To decrease the target luminance, absorptive neutral density filters (NDF) with flat transmittance across the visible spectrum from 400 to 700 nm were placed in the lines of sight covering a large field of view (See Figure 1). For monocular conditions, the nondominant eye's (NDE) view of the stimulus was blocked between the dichroic mirror and the visual stimulus, thus permitting binocular wave front and convergence measurements. Luminance was measured with a luminance meter (LC-100, Konica Minolta, Japan) when a white background was displayed on the monitor. The luminance levels used in our measurements ranged from 183 cd/m^2 (photopic) to 0.0032 cd/m^2 (scotopic). In order to avoid residual stray light at low-luminance conditions, the system was encased in a box with a rectangular aperture smaller in size than the NDFs.

Combining the LCD monitor spectrum, which consists of three narrow peaks, with the eye's luminous efficiency functions for photopic and scotopic conditions resulted in a negligible 0.2-nm shift in the peak luminance wavelength. Therefore, chromatic aberration was ruled out as a possible source of night myopia in our experiment.

Subjects

We measured 10 normal young nearly emmetropic subjects. All subjects were able to clearly see the visual stimulus under photopic light levels and binocular vision. The mean age was 28.4 ± 5.5 years. Mean spherical equivalent was –0.43 ± 0.27 D and ranged from –0.14 to –0.82 D. Mean cylinder was –0.37 ± 0.2 D and ranged from –0.17 to –0.77 D. All subjects presented natural pupil radii larger than 2.5 mm for all light levels except for the brightest one. The study adhered to the tenets of the Declaration of Helsinki.

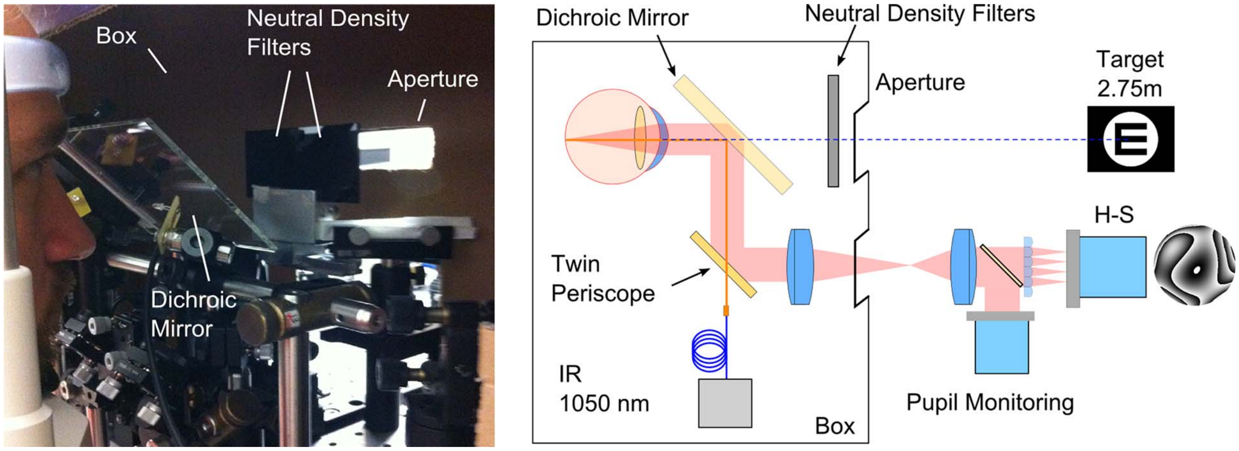

Figure 1. Apparatus. Left panel: The elements inside the box, including the chin rest for the subject, the dichroic hot mirror to direct the IR measurement light toward the H-S sensor while allowing direct view of the stimulus, and the neutral density filter holder for calibrated stimulus dimming to scotopic levels. Right panel: Schematic side view of the experimental setup. The H-S sensor is located in a lower level and does not interfere in the subject's line of sight.

Procedure

Spherical equivalent, pupil diameter, and apparent interpupillary distance (IPD) were measured simultaneously under binocular and monocular (dominant eye [DE]) vision. Measurements were performed for seven light levels in decreasing order: 183, 100, 10, 1, 0.1, 0.01, and 0.0032 cd/m^2. The first three light levels (photopic) were achieved by adjusting the monitor brightness. The lower light levels were achieved by using NDFs with optical densities 1, 2, 3, and 3.5 (NE205/10/20/30B, Thorlabs GmbH, Germany) when the monitor brightness was set to 10 cd/m^2. In photopic conditions, room light was adjusted with a dimmer to be concordant with the target luminance. In mesopic and scotopic conditions, room light was turned off. When changing between luminance levels, subjects were given at least 5 min to adapt. A longer adaptation period of 30 min was provided for the dimmest condition. Three 5-s videos of binocular H-S images were recorded and averaged for each luminance condition. The whole experiment took around 60 to 90 min to complete.

In a separate experiment, the accommodative state in total darkness was measured in seven of the subjects. To compare results to those of the main experiment, a reduced number of luminance levels (183, 1, and 0.0032 cd/m^2) was repeated.

Data processing

The accommodation response was quantified by means of the spherical equivalent (SE) in both eyes, calculated first by means of Equation 1, which only considers the defocus Zernike coefficient, C_2^0, and then by using Equation 2, which includes the contribution of spherical aberration, C_4^0 (Thibos, Bradley, & Applegate, 2004):

$$SE_2\,[\mathrm{D}] = \frac{-4\sqrt{3} \times C_2^0\,[\mu\mathrm{m}]}{r^2\,[\mathrm{mm}]} \tag{1}$$

$$SE_4\,[\mathrm{D}] = \frac{-4\sqrt{3} \times C_2^0\,[\mu\mathrm{m}] + 12\sqrt{5} \times C_4^0\,[\mu\mathrm{m}]}{r^2\,[\mathrm{mm}]} \tag{2}$$

where r is the radius of the measurement pupil. In this work, a standard value of 2.5 mm was selected. However, two subjects had natural pupils at the highest luminance level that were smaller than this value, and we were forced to use a radius of 2 mm for that luminance only. This reduction should not affect the trend found.

The pupil-tracking algorithm processed each frame of the measurement sequence in order to determine the size of both pupils and also their position on the H-S plane. Due to the twin periscope used to fit both pupils onto a single detector, the distance between eyes provided by the algorithm is an offset version of the actual IPD that we will denote oIPD. However, because the twin periscope is adjusted only at the beginning of the experiment for each subject, the change in oIPD exactly mirrors the change in IPD and can be used to estimate the shift of the binocular fixation point along the axis, whose inverse we take as the relative convergence in diopters, ΔV (Chirre et al., 2015):

$$\Delta V\,[\mathrm{D}] = \frac{\Delta \mathrm{oIPD}}{R \times \mathrm{IPD}} \tag{3}$$

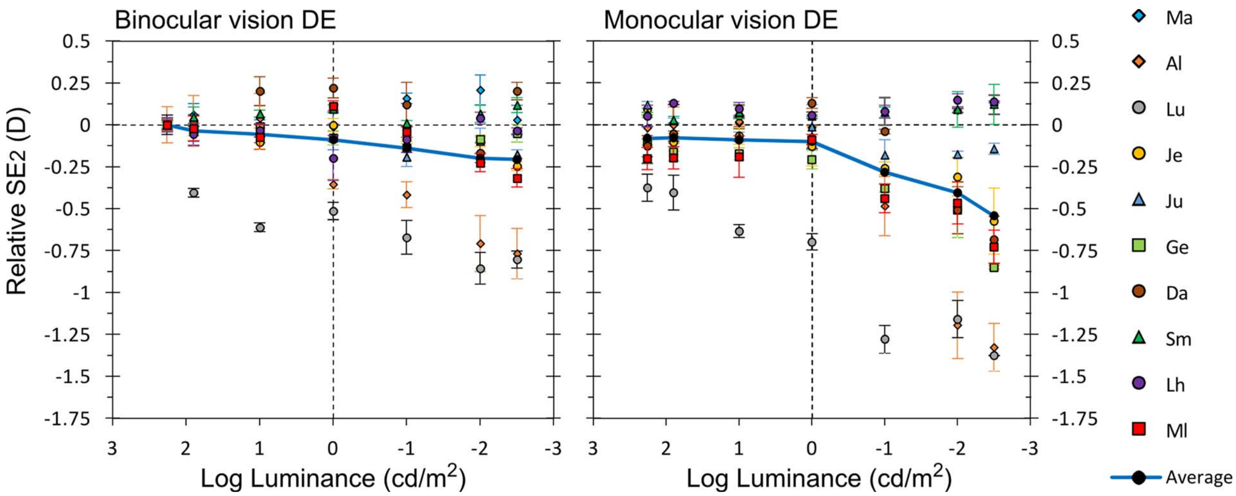

Figure 2. Relative second-order spherical equivalent, SE_2, in diopters as a function of log luminance under binocular (left) and monocular DE vision (right). Blue lines represent average values, and symbols correspond to individual subjects. The error bars represent the standard deviation across three measurements for each subject at each luminance.

where R is the distance between the center of rotation of the eye and the pupil plane, and IPD is the real IPD measured with an ophthalmic ruler. R was estimated to be 11.5 mm, assuming a distance of 15 mm from the center of rotation of the eye to the cornea (Fry & Hill, 1962) and 3.5 mm from the cornea to the anterior surface of the lens (Atchison & Smith, 2000). IPD was 63 ± 2.2 mm for our group of subjects.

Results and discussion

Accommodative responses

The SE_2 decreased with decreasing luminance as shown in Figure 2. The average myopic shift under monocular vision was –0.54 ± 0.57 D from the highest to the lowest luminance considered (Figure 2, right). A large variability in behavior was observed with some subjects showing a progressive increase in accommodation resulting in night myopia, and the refraction of others remained stable or even showed a slight increase. Individual changes in SE ranged from +0.16 D to –1.37 D. This variability is found in previous studies (Artal et al., 2012; Epstein, 1983; Fejer & Girgis, 1992; Leibowitz & Owens, 1975b; Owens & Leibowitz, 1976a).

Binocularity reduced the magnitude of the phenomenon (Figure 2, left) to –0.21 ± 0.34 D on average and for every subject individually. Individual changes in SE ranged between +0.20 D and –0.85 D. Comparing symbols between left and right panels in Figure 2, it can be seen that the behavior of binocular and monocular night myopia was always individually consistent—that is, the subjects with large monocular myopic shifts also had the largest values of binocular night myopia, and the subjects showing night hyperopia, although slight, did so for both monocular and binocular conditions.

As can be seen from the error bars is Figure 2, variability across repetitions for each subject and luminance condition was relatively low, in both monocular and binocular conditions. There was a tendency toward increased variability in dim light levels, but the intrasubject standard deviation was always below 0.2 D. These results indicate that monocular night myopia is fairly repetitive for different luminance levels as previously reported (Mershon & Amerson, 1980; Miller, 1978), and the phenomenon is also stable in binocular conditions.

Figure 3 plots the relative fourth-order spherical equivalent, SE_4 (Equation 2), in order to illustrate the impact of spherical aberration on monocular and binocular night myopia. We found a similar behavior of SE compared to Figure 2 in both viewing conditions. The decrease of the SE from the brightest to the dimmest case was –0.23 ± 0.44 D and –0.60 ± 0.65 D on average under binocular and monocular DE vision, respectively, with values ranging between +0.35 D and –1.08 D binocularly and between +0.37 D and –1.50 D under monocular viewing. Comparing these values with those obtained by using the second-order formula in Equation 1, it can be seen that including spherical aberration in the calculation of SE produces virtually the same mean values but slightly increases the standard deviation as a result of the increased spread of values across subjects. The contribution of spherical aberration was small in all cases and, furthermore, always consistent with that of the defocus term: myopic for subjects with night

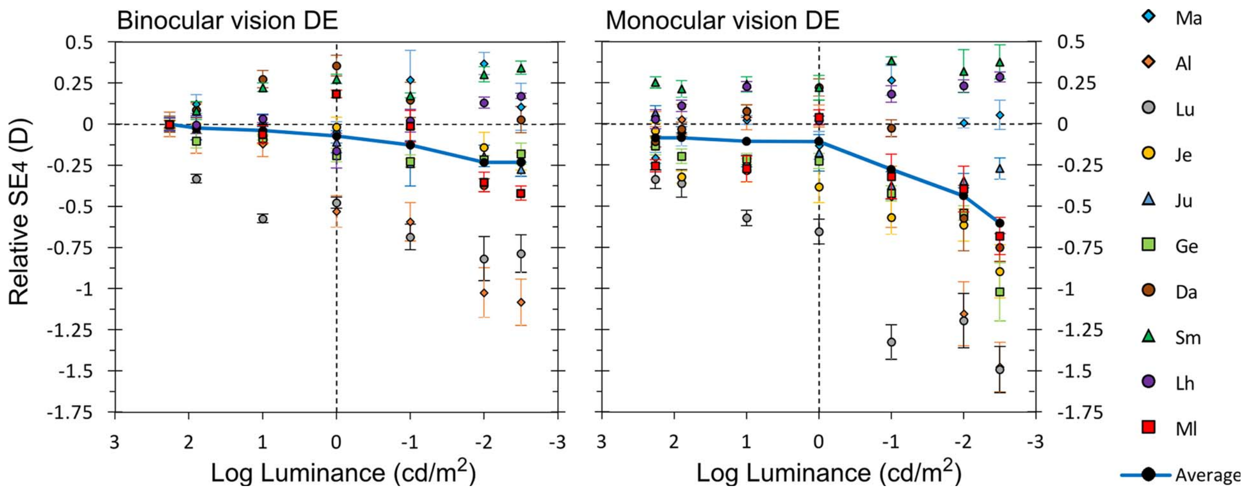

Figure 3. Relative fourth-order spherical equivalent including spherical aberration, SE_4, in diopters as a function of log luminance under binocular (left) and monocular DE vision (right). Blue lines represent average values, and symbols correspond to individual subjects. The error bars represent the standard deviation across three measurements for each subject at each luminance.

myopia, hyperopic for subjects with night hyperopia, and very small for subjects without either. Due to the small size of the CCD and the fact that we are fitting both eyes in a single sensor, we were unable to reliably measure spherical aberration in the large natural pupils occurring for dim light conditions. However, considering an r^4 behavior for C_4^0, extrapolation from 5 mm to the natural pupil size would result in a factor between two and three for the contribution of spherical aberration to the SE, still smaller than SE_2. These results suggest that spherical aberration does not play a major role in night myopia on average in agreement with previous studies (Artal et al., 2012).

The difference between monocular and binocular conditions can be more easily observed in Figure 4, left, in which the average changes in SE_2 are presented for both monocular (red line) and binocular (blue line) conditions together.

Our results show that binocularity reduces night myopia on average and for each individual subject. A possible cause of this reduction would be the convergence cue produced by fusional vergence. Then, vergence accommodation drives accommodation and reduces the mismatch between the accommodative state of the eye and the stimulus distance (Leibowitz, Gish, & Sheehy, 1988). Because most studies in the literature were performed under monocular conditions, there probably is a tendency to overestimate night myopia when compared to natural viewing conditions.

Pupil diameter and convergence response

The central panel in Figure 4 shows the behavior of pupil size with luminance. As expected, natural pupil size increased with decreasing light level up to the point at which the subjects reached their natural fully dilated state, around 0.1 cd/m^2. Also to be expected, the pupil

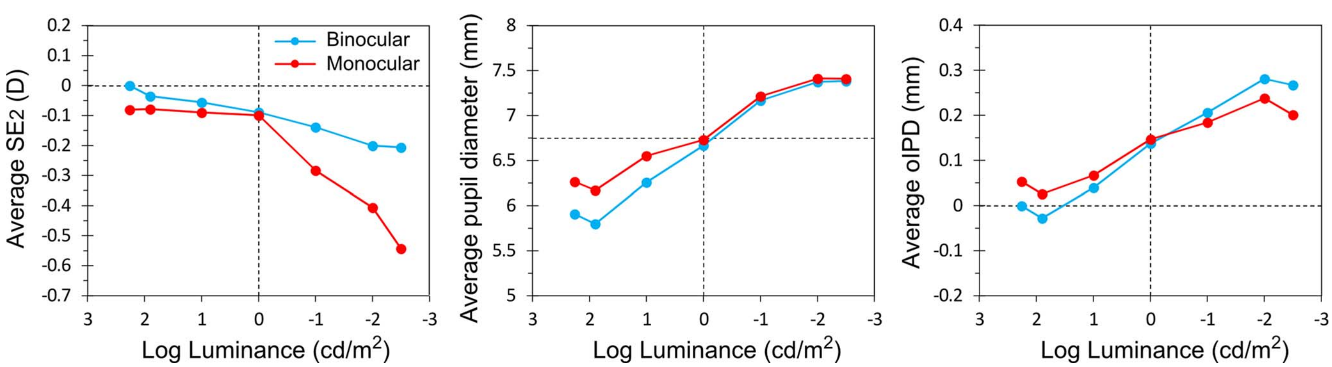

Figure 4. Average values across subjects of SE_2 (left), pupil diameter (center), and offset IPD (right) as a function of log luminance (cd/m^2). Blue and red lines correspond to binocular and monocular conditions, respectively.

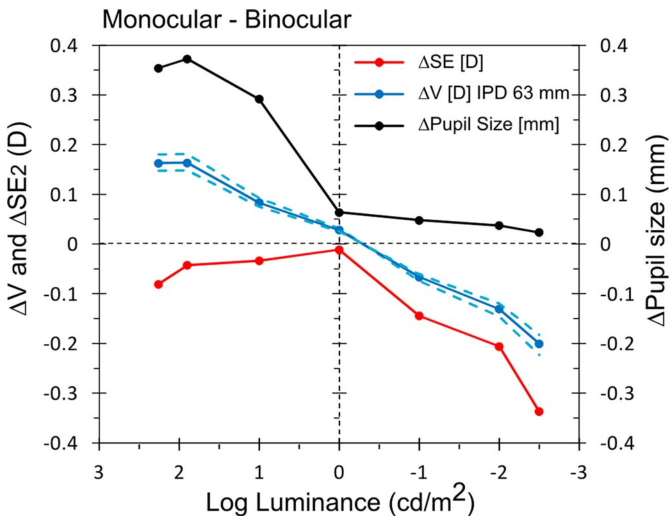

Figure 5. Changes in SE_2 (red) and convergence (blue), both of them in diopters (left-hand side axis), and pupil size (black) in mm (right-hand side axis) from binocular to monocular conditions as a function of log luminance of the stimulus. Convergence was calculated by means of Equation 3. Dashed lines represent the confidence interval for the estimate of convergence corresponding to a ±5 mm tolerance for the value of IPD.

for luminance values in the upper part of the range was slightly larger in monocular conditions than binocularly, but the difference tended to disappear as the pupil approached its maximum size.

Figure 4, right, shows the behavior of the oIPD on average with decreasing luminance. For photopic to midmesopic levels, oIPD gradually increases as the luminance decreases. This behavior should not be due to an induced divergence, which is not to be expected, but to shifts in temporal direction of both pupil centers with pupil dilation. Yang, Thompson, and Burns (2002) found shifts of the pupil center typically smaller than 0.3 mm with a mean value of 0.133 mm temporal from mesopic to scotopic conditions. However, important variations have been observed among studies, and values up to 0.6 mm temporal have been reported (Walsh, 1988; Wilson, Campbell, & Simonet, 1992; Wyatt, 1995). On the contrary, for luminance levels lower than 0.1 cd/m^2, the pupils are almost fully dilated for most subjects, and consequently, the pupil centers should remain stable. Therefore, changes in oIPD in this range can be attributed to changes in convergence.

Figure 5 shows the differences in convergence, accommodation, and pupil size between binocular and monocular conditions. For photopic conditions (down to 1 cd/m^2), accommodation and convergence apparently have different behaviors: Although there was virtually no difference between monocular and binocular SE, there were changes in oIPD that suggested an unexpected apparent divergence. However, for these luminance values, pupil size was larger, as expected, under monocular vision (positive difference), and the change in IPD can probably be attributed to a shift in the pupil center. In fact, the larger the pupil size difference, the larger the observed change in oIPD, and therefore, the apparent divergence somehow mimics the change in pupil size in this luminance range. Below 1 cd/m^2, there was little difference between monocular and binocular pupil size (black line). As a consequence, the change in oIPD from binocular to monocular vision observed in mesopic and scotopic conditions should be mostly due to a change in convergence. In this range, estimated convergence and accommodation follow a similar tendency toward the subject when one eye is blocked. In other words, the eye monocularly presented with a stimulus in low light levels tends to over-accommodate and to overconverge accordingly. As a final comment on Figure 5, we would like to point out that, although the differences in this luminance range are very small, monocular pupils are still larger than their binocular counterparts, and therefore, the change in convergence may be slightly overestimated, accounting for part of the gap between the red and blue lines.

Dark focus and dark vergence

Figure 6 compares binocular and monocular night myopia (log luminance = –2.5) and dark focus in the DE (left panel) and NDE (right panel). On average (bars), dark focus was myopic with mean values –0.64 ± 0.59 D in the DE and –0.61 ± 0.66 D in the NDE. Monocular night myopia was on average –0.36 ± 0.43 D for DE and –0.42 ± 0.41 D for NDE—closer in both cases to dark focus than binocular night myopia (Mean values –0.15 ± 0.17 D for DE and –0.16 ± 0.21 D for NDE). Individually (symbols and colors), there was a large variability in focus shift across subjects but a good agreement between eyes for all the subjects. Five subjects showed myopic dark focus shifts and monocular and binocular night myopia in descending order of magnitude in all cases; one subject exhibited a hyperopic dark focus shift and smaller amounts of monocular and binocular night hyperopia; and one last subject had virtually no dark focus shift and neither night myopia nor hyperopia, both monocularly and binocularly. In all subjects, the results for these selected levels were in good agreement with earlier measurements.

These results suggest that night myopia may be induced by dark focus, i.e., by the progressive shift of the accommodative state of the subject toward its default state in total darkness. As the luminance decreases, eyes presented with a stimulus in monocular conditions tend to accommodate or disaccommodate

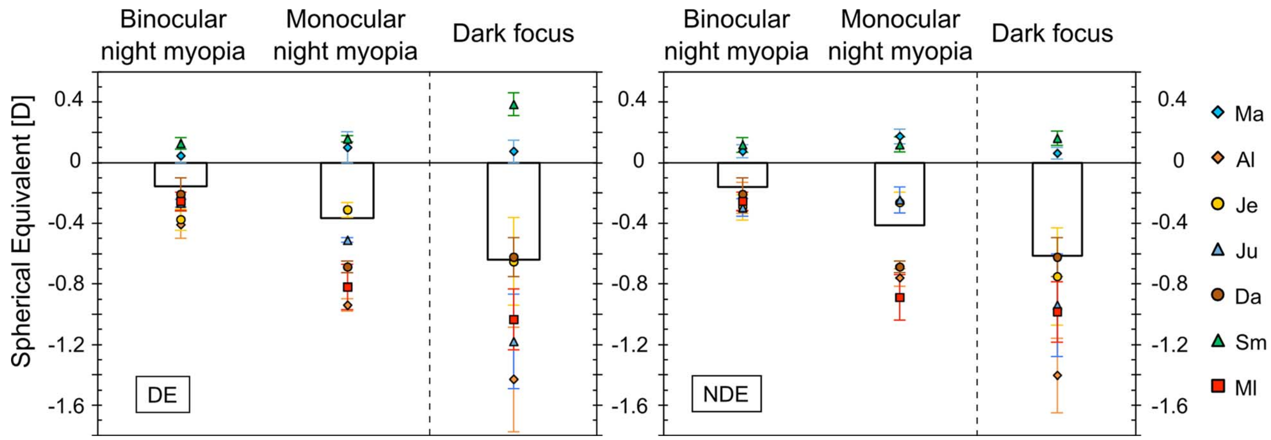

Figure 6. SE shift when viewing the stimulus in binocular and monocular vision for a −2.5 log luminance stimulus and in total darkness in the DE (left panel) and NDE (right panel). All values are referred to the corresponding highest luminance binocular case. Symbols and colors correspond to individual subjects, and bars represent average values. The error bars represent the standard deviation across three measurements for each subject.

toward their dark focus. For subjects with myopic dark focus, which in our study was the typical case, this tendency generates night myopia. On the contrary, subjects with hyperopic dark focus showed a small amount of night hyperopia. These results are in agreement with previous works (Leibowitz & Owens, 1975a, 1975b, 1978).

The relative dark vergence and dark focus are represented in Figure 7, left. Because of the shift of the pupil center with dilatation at low luminance, the increase of oIPD in most cases biased the vergence estimates. To circumvent this problem and for this figure alone, the reference was taken at 1 cd/m^2 when pupils are close to their dilated state and when the shift of convergence toward the resting state can be expected to be small. Comparing dark vergence and dark focus, we observed that subjects Ma, Sm, and Da have a relatively similar resting state of accommodation and vergence. In the case of subjects Ma and Sm, the hyperopic dark focus seems to be in concordance with the position of the eyes. Subjects Ml, Je, Ju, and Al have different values of dark focus and dark vergence. Subject Ju seems to overconverge compared to the dark focus, and subjects Je, Ml, and Ju underconverge. We found a moderate correlation of $R^2 = 0.43$ between dark vergence and dark accommodation with high intersubject variability in agreement with previous studies (Fincham, 1962; Jiang et al., 1991; Kotulak & Schor, 1986; Owens & Leibowitz, 1976b; Wolf et al., 1990). The right panel in Figure 7 shows a high correlation ($R^2 = 0.90$) between dark focus of DE and NDE.

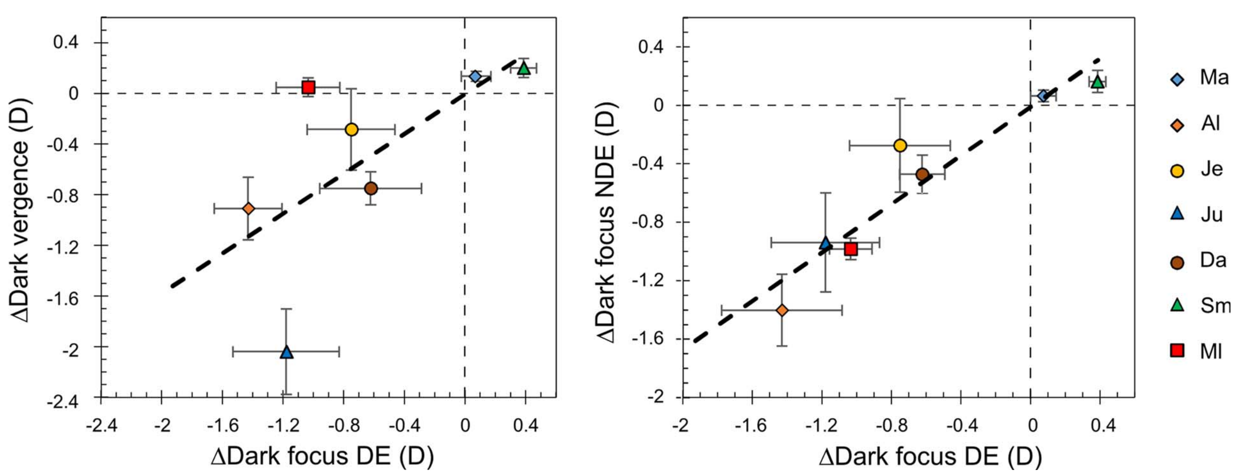

Figure 7. At left: Dark vergence (*y*-axis) as a function of dark focus of the DE (*x*-axis). At right: Dark focus of the NDE (*y*-axis) as a function of dark focus of the DE (*x*-axis). Each symbol corresponds to an individual subject. The error bars are the standard deviation among three measurements. The dashed black line is the linear fit (R^2).

Conclusions

In order to investigate the possible sources of night myopia, we measured the changes in spherical equivalent and convergence as a function of stimulus luminance under natural binocular viewing conditions in a group of normal subjects, using an infrared open-view binocular wave front sensor. Additionally, we performed measurements when the stimulus was viewed monocularly.

On average, the monocular accommodative error for decreasing luminance tends toward the average dark focus, producing night myopia. Under binocular vision, the average accommodative error is smaller than its monocular counterpart for each luminance level, meaning that binocularity mitigates night myopia when vergence accommodation is available.

Individually, the same trend can be observed although there is a wide range of behaviors with some subjects showing large myopic changes in the accommodative state for low light levels and others remaining stable or even having a slight hyperopic shift. In each case, the subject's dark focus seems to be an indicator of the evolution of night myopia in both monocular and binocular conditions, and binocularity has a weakening effect. Possible causes for the binocular reduction would be the convergence cue produced by retinal disparity and the binocular summation, which improves the detection threshold. Despite the large intersubject variability in the behavior of night myopia and dark focus, we have found that the defocus shift with decreasing luminance follows a very similar trend in both eyes of the same subject, both for monocular and binocular stimulation, and this is consistent with the strong correlation found in dark focus between eyes.

Spherical aberration apparently does not play a major role in night myopia. Although including the spherical aberration in the calculation of SE slightly increases the spread of the results across subjects, the contribution was always in the same direction as the defocus shift and small compared to the total amount of night myopia in all subjects.

Convergence values obtained individually were biased by pupil size changes, which may be one reason for the moderate correlation, in agreement with the literature, between dark converge and dark focus. However, comparing the difference between monocular and binocular values, an induced monocular convergence was observed at low luminance—similar on average to the difference between binocular and monocular night myopia. This result is in agreement with the idea that binocular mitigation of night myopia was due to a convergence cue improving the precision of the accommodative state although the interaction between night myopia and night convergence could be more complex.

Keywords: night myopia, dark focus, binocular vision, dark vergence, H-S wave front sensor

Acknowledgments

This research has been supported by the European Research Council Advanced Grant ERC-2013-AdG-339228 (SEECAT) and the Spanish SEIDI, grant FIS2013-41237-R. E. Chirre acknowledges a FPI predoctoral fellowship by the Ministerio de Ciencia e Innovacion (Spain) (Grant n° FIS-2010-14926).

Commercial relationships: none.
Corresponding author: Emmanuel Chirre.
Email: emmanuel.chirre@um.es.
Address: Laboratorio de Óptica, Universidad de Murcia, Instituto Universitario de Investigación en Óptica y Nanofísica, Murcia, Spain.

References

Arnulf, A., Flamant, F., & Françon, M. (1948). Etude expérimentale de la myopie acquise par l'oeil en vision de nuit. [Experimental study of myopia acquired by the eye in night vision.]. *Revue d'Optique Théorique et Instrumentale, 27*, 741–745.

Artal, P., Schwarz, C., Cánovas, C., & Mira-Agudelo, A. (2012). Night myopia studied with an adaptive optics visual analyzer. *PLoS One, 7*(7), 1–6.

Arumi, P., Chauhan, K., & Charman, W. N. (1997). Accommodation and acuity under night-driving illumination levels. *Ophthalmic and Physiological Optics, 17*(4), 291–299.

Atchison, D. A., & Smith, G. (2000). *Optics of the human eye*. Oxford: Butterworth-Heinemann.

Bedford, R. E., & Wyszecki, G. (1947). Axial chromatic aberration of the human eye. *Journal of the Optical Society of America, 47*(6), 564–565.

Chirre, E., Prieto, P. M., & Artal, P. (2014). Binocular open-view instrument to measure aberrations and pupillary dynamics. *Optics Letters, 39*(16), 4773–4775.

Chirre, E., Prieto, P. M., & Artal, P. (2015). Dynamics of the near response under natural viewing conditions with an open-view sensor. *Biomedical Optics Express, 6*(10), 4200–4211.

Epstein, D. (1983). Accommodation as the primary cause of low-luminance myopia. Experimental evidence. *Acta Ophthalmologica, 61*(3), 424–430.

Epstein, D., Ingelstam, E., Jansson, K., & Tengroth, B. (1981). Low-luminance myopia as measured with a laser optometer. *Acta Ophthalmologica, 59*(6), 928–943.

Fejer, T. P., & Girgis, R. (1992). Night myopia: Implications for the young driver. *Canadian Journal of Ophthalmology, 27*(4), 172–176.

Fernández, E. J., & Artal, P. (2008). Ocular aberrations up to the infrared range: From 632.8 to 1070 nm. *Optics Express, 16*(26), 21199–21208.

Fincham, E. F. (1962). Accommodation and convergence in the absence of retinal images. *Vision Research, 1*, 425–440.

Fry, G. A., & Hill, W. W. (1962). The center of rotation of the eye. *American Journal of Optometry and Archives of American Academy of Optometry, 39*, 581–595.

Ivanoff, A. (1955). Night binocular convergence and night myopia. *Journal of the Optical Society of America, 45*(9), 769–770.

Jiang, B.-C., Gish, K. W., & Leibowitz, H. W. (1991). Effect of luminance on the relation between accommodation and convergence. *American Academy of Optometry, 68*(3), 200–225.

Johnson, C. A. (1976). Effects of luminance and stimulus distance on accommodation and visual resolution. *Journal of the Optical Society of America, 66*(2), 138–142.

Koomen, M., Scolmik, R., & Tousey, R. (1951). A study of night myopia. *Journal of the Optical Society of America, 41*(2), 80–90.

Koomen, M., Tousey, R., & Scolnik, R. (1949). The spherical aberration of the eye. *Journal of the Optical Society of America, 39*(5), 370–376.

Kotulak, J. C., & Schor, C. M. (1986). The dissociability of accommodation from vergence in the dark. *Investigative Ophthalmology and Visual Science, 27*(4), 544–551.

Leibowitz, H. W., Gish, K. W., & Sheehy, J. B. (1988). Role of vergence accommodation in correcting for night myopia. *American Journal of Optometry and Physiological Optics, 65*(5), 383–386.

Leibowitz, H. W., & Owens, D. A. (1975a, August 22). Anomalous myopias and the intermediate dark focus of accommodation. *Science (New York, N.Y.), 189*(4203), 646–648.

Leibowitz, H. W., & Owens, D. A. (1975b). Night myopia and the intermediate dark focus of accommodation. *Journal of the Optical Society of America, 65*(10), 1121–1128.

Leibowitz, H. W., & Owens, D. A. (1978). New evidence for the intermediate position of relaxed accommodation. *Documenta Ophthalmologica, 46*(1), 133–147.

Levene, J. R. (1965). Nevil Maskelyne, F.R.S., and the discovery of night myopia. *Notes and Records of the Royal Society of London, 20*(1), 100–108.

Mershon, D. H., & Amerson, T. L. (1980). Stability of measures of the dark focus of accommodation. *Investigative Ophthalmology & Visual Science, 19*(2), 217–221.

Miller, R. J. (1978). Temporal stability of the dark focus of accommodation. *American Journal of Optometry and Physiological Optics, 55*(7), 447–450.

Otero, J. M., & Durán, A. (1941). Rendimiento fotométrico de sistemas ópticos a bajas luminosidades. [Photometric performance of optical systems at low luminosities.]. *Anales de Física y Química, 37,* 337–349.

Otero, J. M., Plaza, L., & Salaverri, F. (1949). Absolute thresholds and night myopia. *Journal of the Optical Society of America, 39*(2), 167.

Owens, D. A., & Leibowitz, H. W. (1976a). Night myopia: Cause and a possible basis for amelioration. *American Journal of Optometry and Physiological Optics, 53*(11), 709–717.

Owens, D. A., & Leibowitz, H. W. (1976b). Oculomotor adjustments in darkness and the specific distance tendency. *Perception & Psychophysics, 20*(1), 2–9.

Owens, D. A., & Leibowitz, H. W. (1980). Accommodation, convergence, and distance perception in low illumination. *American Journal of Optometry and Physiological Optics, 57*(9), 540–550.

Rayleigh, J. W. S. (1883). On the invisibility of small objects in a bad light. *Proceedings of the Cambridge Philosophical Society, Vol. 4* (p. 324). Cambridge: University Press.

Thibos, L. N., Bradley, A., & Applegate, R. A. (2004). Accuracy and precision of objective refraction from wavefront aberrations. *Journal of Vision, 4*(4):9, 329–351, doi:10.1167/4.4.9. [PubMed] [Article]

Wald, G., & Griffin, D. R. (1947). The change in refractive power of the human eye in dim and bright light. *Journal of the Optical Society of America, 37*(5), 321.

Walsh, G. (1988). The effect of mydriasis on the pupillary centration of the human eye. *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists), 8*(2), 178–182.

Wilson, M. A., Campbell, M. C., & Simonet, P. (1992). Change of pupil centration with change of illumination and pupil size. *Optometry and Vision Science: Official Publication of the American Academy of Optometry, 69*(2), 129–136.

Wolf, K. S., Bedell, H. E., & Pedersen, S. B. (1990). Relations between accommodation and vergence in darkness. *American Academy of Optometry, 67*(2), 89–93.

Wyatt, H. J. (1995). The form of the human pupil. *Vision Research, 35*(14), 2021–2036.

Yang, Y., Thompson, K., & Burns, S. A. (2002). Pupil location under mesopic, photopic, and pharmacologically dilated conditions. *Investigative Ophthalmology & Visual Science, 43*(7), 2508–2512.