Shedding light on night myopia

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First described during the 18th century, the cause of night myopia remains a controversial topic. Whereas several explanations have been suggested in the literature, particularly related with accommodation or chromatic shift in scotopic light conditions, no definitive explanation for its aetiology has been provided. We describe an experiment in which ocular refractive state was objectively and subjectively measured while viewing two kind of stimulus: letters on a bright background and a punctual source of light in a dark background. We found that under photopic conditions the optimum refractive state of the accommodating eye is significantly more myopic when maximizing perceived quality of a point source on a dark background compared to a conventional letter chart with black letters on a white background. Optical modeling suggested this difference in refractive state is due to spherical aberration. Since isolated point sources are more likely encountered at night, whereas extended objects are more likely encountered in the daytime, our results suggest that a significant part of the night myopia phenomenon is determined by the nature of the visual stimulus and the visual task used to assess ocular refractive state.

Keywords: night myopia, spherical aberration, accommodation

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Introduction

Night myopia is a tendency for eyes to become nearsighted in dim illumination. Astronomers were the first to describe this phenomenon (Levene, 1965) as a need for correcting lenses of negative power to improve viewing of the stars. The phenomenon gained considerable importance during the Second World War because of the crucial need to visually detect points of light at sea or in the night sky (Otero, Plaza, & Salaverri, 1949; Otero & Duran, 1943). More recently it has been suggested that night myopia is a potential hindrance to safe driving at night (Charman, 1996; Cohen et al., 2007; Fejer, 1995).

The simplest explanation of night myopia is that uncorrected myopia (or deliberate under-correction of myopia produced by maximum-plus refractions (Borish, 1970) is less noticeable during the day when high levels of ambient luminance reduce the size of the eye's pupil, thereby reducing the amount of blur on the retina (Charman, 1996). When ambient luminance declines, the pupil dilates, and retinal blur becomes noticeable subjectively; thus, the eye appears to have become nearsighted when, in fact, it was always nearsighted, but the manifestations of myopia had not been noticed. Although this explanation may account for Rayleigh's original description of night myopia (Rayleigh, 1883), and for much of the clinical incidence of night myopia in the general public (Charman, 1996), more sophisticated optical explanations are required to account for evidence obtained in carefully controlled laboratory experiments. One such explanation is based on the fact that most eyes have positive spherical aberration (SA) when accommodation is relaxed (Salmon & van de Pol, 2006). Like defocus, the blurring effect of SA is greatest when the pupil is large, a condition which implies the visual effects of SA will be most noticeable under dim illumination conditions.

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Night myopia might also be an artifact of increased accommodation to compensate for the increased blurring effects of SA when the pupil dilates. Positive ocular SA declines during accommodation (Young, 1801; Ivanoff, 1947; Lopez-Gil, Fernandez-Sanchez, Legras, Montes-Mico, Lara, & Nguyen-Khoa, 2008; Lopez-Gil & Fernández-Sánchez, 2010) and therefore vision for distant objects benefits by viewing through a negative lens (or misfocusing a telescope) to stimulate accommodation (Ivanoff, 1947; Otero, & Duran, 1943). In this case preference for a negative viewing lens is misinterpreted as a sign of myopia. A similar misinterpretation might occur for presbyopic eyes with significant amounts of positive spherical aberration since retinal image quality for point sources will improve when viewing through a weak negative lens. (Mahajan, 1991).

All of the aforementioned explanations for night myopia refer to foveal vision under photopic conditions. When ambient illumination is reduced to mesopic levels, accommodation becomes less accurate and eventually vanishes in the scotopic domain where cones are no longer active (Campbell, 1953; Johnson, 1976). Moreover, as ambient light levels decline, the eye assumes a resting state (dark focus) for which its focusing power is somewhat greater than when viewing distant objects at higher luminances (Johnson, 1976) and thus the eye appears to have become relatively more myopic (Owens & Leibowitz, 1976; Simonelli & Roscoe, 1979; Braddick, Ayling, Sawyer, & Atkinson, 1981; Epstein, 1983; Kotulak, Morse, & Rabin, 1995). The Purkinje shift may also contribute to the night myopia phenomenon under scotopic illumination. If the scotopic refractive state is measured at the wavelength of peak sensitivity of rod photoreceptors (504 nm), then ocular chromatic aberration will make the scotopic eye appear relatively myopic compared to a photopic measurement at the peak of photopic sensitivity (555 nm).

Although optical instruments may be used to measure objectively the refractive state of the eye, most of the published evidence for night myopia was obtained by subjective procedures of the kind used routinely by clinical optometrists (Bohman & Saladin, 1980; Cohen et al., 2007; Fejer, 1995; Leibowitz, Gish, & Sheehy, 1988). Yet none of the mechanistic explanations for night myopia reviewed above makes particular reference to the visual stimulus or the visual task used to assess subjectively the focus state of the eye. This omission is surprising, given that optimum focus depends on spatial frequency in normally aberrated eyes (Koomen, Scolnik, & Tousey, 1951; Green & Campbell, 1965; Charman, Jennings, & Whitefoot, 1978). If different visual targets are used for subjective determination of refractive error during daytime and nighttime viewing, then differences in spatial frequency content of those targets might account, at least partially, for night myopia. Choice of visual target might also explain the failure of some experiments to elicit the phenomenon (Arumi, Chauhan, & Charman, 1997) which has given night myopia a reputation for being an enigmatic topic resting on a controversial foundation.

In an attempt to resolve some of the controversy surrounding night-myopia, we examined the importance of stimulus configuration when measuring ocular refractive state. We found that under photopic conditions the eye's refractive state is significantly more myopic when the eye's focus is optimized for detecting a point source on a dark background compared to the focus needed to optimize legibility of black letters on a white background. Since isolated point sources are more likely encountered at night, whereas extended objects are more likely encountered in the daytime, our results suggest that a significant part of the night myopia phenomenon is determined by the nature of the visual stimulus and the visual task used to assess ocular refractive state.

Methods

Subjects

Seventeen emmetropic subjects (spherical equivalent refractive error $< \pm 0.375$ D) and two myopic patients corrected with contact lenses were evaluated. Age range was 21.9 ± 4.6 years, and astigmatism (less than 0.75 D of cylindrical power as determined by subjective refraction) was left uncorrected. Informed consent was obtained from all subjects and the tenets of the Declaration of Helsinki were followed.

Apparatus

An open-field optometer (Grand Seiko WAM5500, Hiroshima, Japan) was used to measure objectively the eye's paraxial refractive state over the central 2.5 mm of the eye's pupil (Sheppard & Davies, 2010). Measurements were recorded continuously with a resolution of 0.10 D for the tested eye while the fellow eye was occluded. The same instrument also measured pupil diameter. When aligned to the instrument the observer has an unobstructed view of visual stimuli through a hot mirror that reflected infrared light (850 nm) to the optometer. As illustrated in Figure 1, a Badal lens was placed after the hot mirror and a moving lens (L) behind it enabled the subject to adjust the stimulus vergence (Atchison, Bradley, Thibos, & Smith, 1995) to maximize perceived quality. The resolution of the

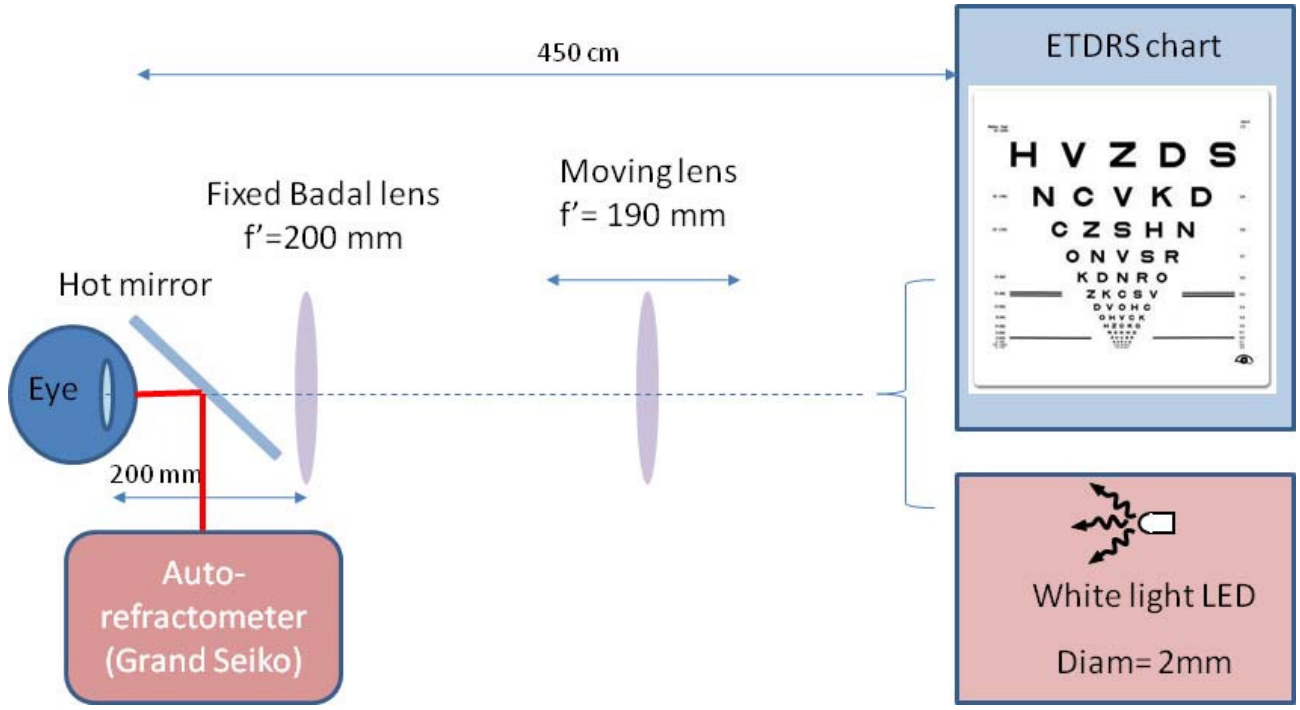

Figure 1. Experimental setup. The subject views a visual stimulus of variable vergence while the optometer monitors refractive state.

optimum target vergence measurements was 0.20 diopters.

The visual stimulus was either a point source (a white light-emitting diode (LED), angular subtense 0.86 arcmin, intensity 70 mcd), or a trans-illuminated ETDRS letter chart displaying high-contrast, black letters on a white background (background luminance = 200 cd/m^2). The luminance spectra of the LED and the letter chart were similar, which suggests negligible chromatic refractive shift between the two stimuli. During data collection the room was darkened to simulate night viewing conditions with a naturally dilated pupil.

At the conclusion of the experiments, the higher-order aberrations of the subject's eye with relaxed accommodation were measured with the Irx3 Hartman-Shack wavefront based aberrometer (Imagine Eyes, France). Coefficients were estimated for a 5 mm pupil diameter to enable comparison of Zernike aberration coefficients for eyes with different pupil sizes (always larger than 5 mm).

Procedures

The subject was instructed to adjust stimulus vergence by moving L (Figure 1) to optimize the perceived quality of the visual stimulus using the following criteria. For the LED stimulus, the point source should appear small and bright whereas for the ETDRS chart the letters on the 20/25 line should be maximally legible. Five settings were recorded for each stimulus. Each setting was accompanied by an objective measurement of refractive state and pupil diameter using the optometer. For a fixed state of accommodation and pupil diameter, the refractive state of the eye may be defined as the stimulus vergence that maximizes retinal image quality (Lopez-Gil & Fernandez-Sanchez, 2010; Tarrant, Roorda, & Wildsoet, 2010). When the crystalline lens accommodates to variations in stimulus vergence, the aberration structure of the eye changes (Young, 1801; Ivanoff, 1947). Moreover, the effect of ocular aberrations on retinal image quality changes when the accommodative reflex causes the pupil to change size. Thus by allowing the subject to accommodate freely in the search for maximum perceived image quality, the subjective determination of optimum target vergence may be interpreted as the eye's optimum refractive state. Our primary outcome measure was the difference in optimum refractive state for the point and letter stimuli, which was compared with objectively measured differences in paraxial refractive state reported by the optometer.

Results

Optimum refractive state (indicated by optimum stimulus vergence) for all eyes was more myopic (i.e., the eye had larger equivalent power) for the LED

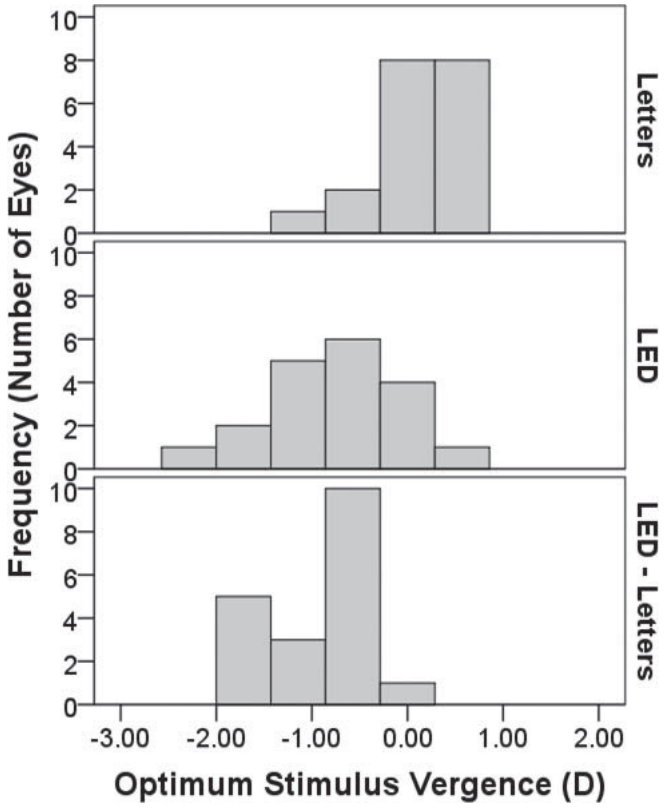

Figure 2. Frequency histogram of the optimum stimulus vergence measured subjectively with a Badal optometer for letters (top), LED (middle) and the difference between them (bottom).

stimulus than for the letter chart (Figure 2). Only one eye showed a similar refractive state for the two stimuli. Although our subject population was nominally emmetropic by clinical standards, the population mean of optimum refractive state was slightly hypermetropic (0.09 D, $SD = 0.46$) for the letter stimulus and significantly myopic (−0.81 D, $SD = 0.64$) for the point stimulus. To factor out individual differences in refractive errors for the population, we computed for each eye the difference between optimum refractive states for these two stimuli. The mean difference was 0.91 D ($SD = 0.52$) more myopic for the point stimulus compared to the letters. Figure 2 displays the frequency histogram for these values. In other words, the refractive state of the average eye in our test population was significantly more myopic when perceived quality was optimized for the point stimulus compared to the letter stimulus.

Objective refractometry in the paraxial zone revealed that most of the eyes were slightly accommodating when perceived quality of the LED was optimized . The population mean of difference values measured objectively by the Grand Seiko was 0.41 D ($SD = 0.34$), more myopic for the point stimulus compared to the letters (Figure 3). Thus, approximately half of the shift in optimum refractive state reported in Figure 2 could be accounted for by changes in accommodation as measured objectively with the Grand Seiko. The remainder of the effect is presumably due to changes in other optical factors such as pupil size and higher-order aberrations (see Discussion).

We evaluated pupil size as a contributing factor by comparing the measured pupil size when perceived image quality was maximized for the two stimuli. The mean pupil diameter when observing the point source (5.65 ± 0.81 mm) was 0.4 mm smaller than when viewing letters (6.08 ± 0.70 mm), which was consistent with a larger accommodative response for the point source compared to letters. However, this small difference was not statistically significant (paired sample t test, $p = 0.51$).

The difference in optimum refractive state for the two stimuli was significantly correlated with ocular SA measured in the relaxed state of accommodation as shown in Figure 4. Eyes with larger amounts of positive SA were more likely to exhibit a myopic shift in optimum refractive state for point sources relative to letters. Surprisingly, some patients with negative or neutral SA still showed some degree of myopic shift in optimum refractive state when viewing the LED compared to the letter stimuli. This result suggests that in some eyes additional, unknown factors besides SA are also contributing to the difference in refractive state measured for the two stimuli.

Discussion

Our study has demonstrated the importance of visual stimulus configuration and criterion when determining the optimum refractive state for maximizing perceived retinal image quality in the accommodating eye. When a point source is judged to be optimally focused (according to the criteria of minimum image size and maximum contrast) its vergence will be more negative than the vergence of an optimally focused letter chart (according to the criterion of letter legibility). We conclude from this result that the eye's optimum refractive state for point sources is myopic relative to the optimum refractive state for letters under the conditions of our experiment. To the extent that our experimental design mimicked the conditions that elicit the night myopia phenomenon, we may infer that part of the night myopia phenomenon can be explained if the optimum daytime refractive state is determined by letter chart legibility whereas the optimum nighttime refractive state is determined by point sources.

Light from objects at night is different from light from daytime objects. In particular, contrast values and maximum luminance of self-luminous objects at night

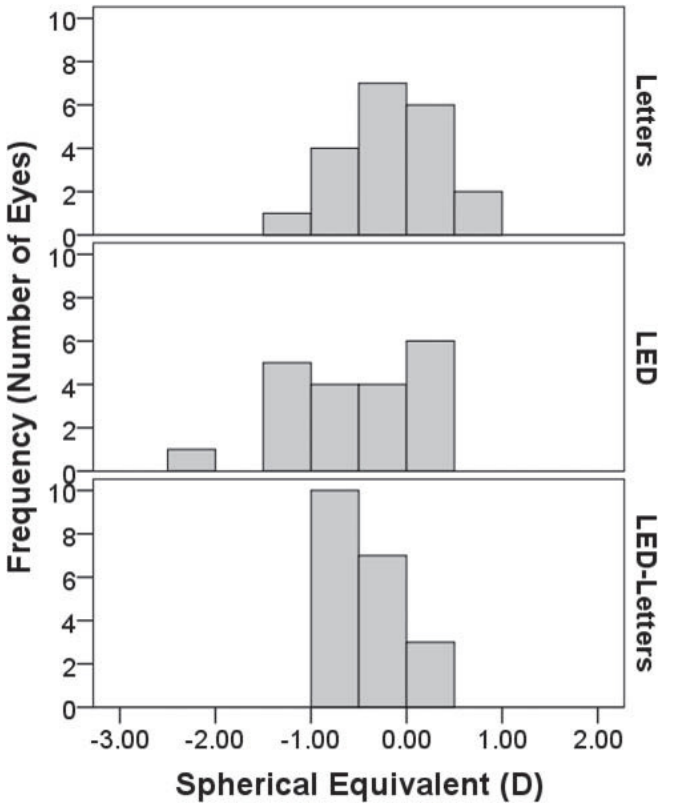

Figure 3. Frequency histogram of spherical equivalent refractive state measured objectively with a Grand Seiko optometer for letters (top), LED (middle) and the difference between them (bottom).

(such as LEDs, car lights, etc.) are much higher than most of the objects seen during the day. Moreover, tails of the light distribution for point sources can be much more visible with a dark background because of increased contrast. Thus, we can expect high-order aberrations, such us spherical aberration, to play a more important role at night than during the day, not only because of larger pupil diameter, but also because of larger retinal contrast. For example, the reader could look at a distant point source such an LED from an electronic device (TV, computer, etc.) in a relatively dark room through a +2 D lens added to a distance prescription. The LED point should be seen as a relatively large and round defocused spot with a certain structure with bright and dark zones. Then, if the room light is suddenly switched on, the large blur circle will decrease, leaving a much smaller defocused visualization of the LED. The effect is appreciated from the very first moment before the pupil has time to constrict, but the same effect can be appreciated with a mydriatic pupil. The larger contrast in a dark room makes the effect of the high-order aberrations much more visible than under daylight conditions when contrast is reduced. As suggested by Otero and Duran (1943)

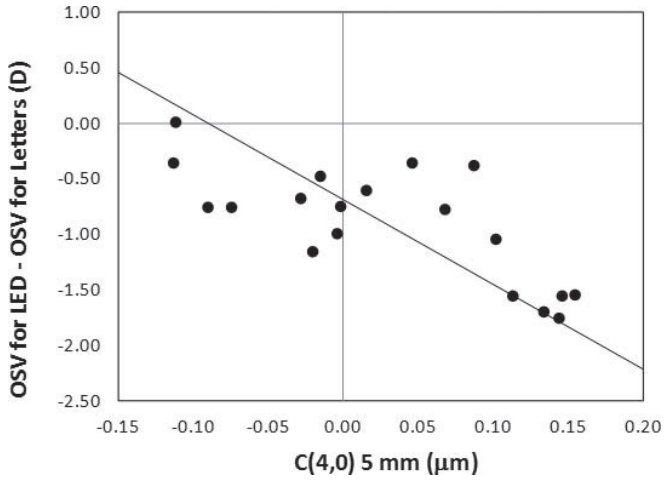

Figure 4. Correlation between the difference in optimum stimulus vergence (OSV) for two visual stimuli (point source and letters) and the fourth order spherical aberration coefficient for a 5 mm pupil size. The straight line represents the orthogonal least-squares regression: $y = -7.64x - 0.683$ ($r^2 = 0.5504$; $p = 0.00028$).

and by Ivanoff (1947), a reasonable strategy for optimizing retinal image quality at night is for the eye to reduce its spherical aberrations by accommodating, assuming the defocus generated by accommodation can be compensated by an external focusing system (such as a telescope, spectacles, etc.).

In our experiments, approximately half of the myopic shift in optimum refractive state for point sources relative to eye charts may be attributed to changes in paraxial power associated with different states of accommodation (Figure 2). To account for the other half of the effect, we examine next the possible role of spherical aberration in determining the optimum target vergence.

Theoretical simulations

The correlation between SA of the relaxed eye and the magnitude of the myopic shift for point sources revealed in Figure 3 suggests a possible causal relationship. To evaluate this possibility theoretically, we computed retinal image quality as a function of defocus and SA in an eye model with 6 mm pupil that is otherwise free of monochromatic aberrations. To capture the difference between the two visual stimuli and their corresponding optimum vergence, we computed two metrics of image quality for each configuration of the model. The first metric, called RMSs, is defined as the root-mean-squared value of wavefront slopes over the domain of the eye's pupil (Thibos, Hong, Bradley, & Applegate, 2004). This metric represents the size of the image of a point source according to geometrical optics. The second metric is

called visual Strehl ratio computed in frequency domain (VSOTF), which is defined as the volume under the visually weighted optical transfer function of the aberrated model, normalized by the volume under the visually weighted optical transfer function of the ideal, diffraction-limited model. This metric is known to accurately predict the legibility of letter stimuli and visual acuity (Cheng, Bradley, & Thibos, 2004; Martin, Vasudevan, Himebaugh, Bradley, & Thibos, 2011).

In a diffraction-limited optical system, both metrics of retinal image quality change equally for equal amounts of positive and negative defocus. However, when positive SA is introduced into the model, the minimum size of the image of a point (as specified by metric RMSs) occurs when the eye model views through a defocusing lens with negative power (–0.2 D) as shown in Figure 5 and therefore the eye model would be characterized as myopic. The opposite behavior occurs for the image quality metric VSOTF that is appropriate for letter stimuli. The maximum value of metric VSOTF occurs when the eye model views through a defocusing lens with positive power (+0.5 D) as shown in Figure 5, and therefore the eye model would be characterized as hyperopic. Thus for this eye model, there is a significant difference of refractive state (0.7 D) for the two visual stimuli according to appropriate metrics of image quality, with point sources yielding the more myopic state.

The refractive state of the eye model for the two metrics RMSs and VSOTF varies with the amount of spherical aberration as shown in Figure 6. The difference in refractive state predicted for the two metrics grows increasingly larger as the magnitude of spherial aberration increases, and the relative sign of this difference in refractive state depends on the sign of the spherical aberration.

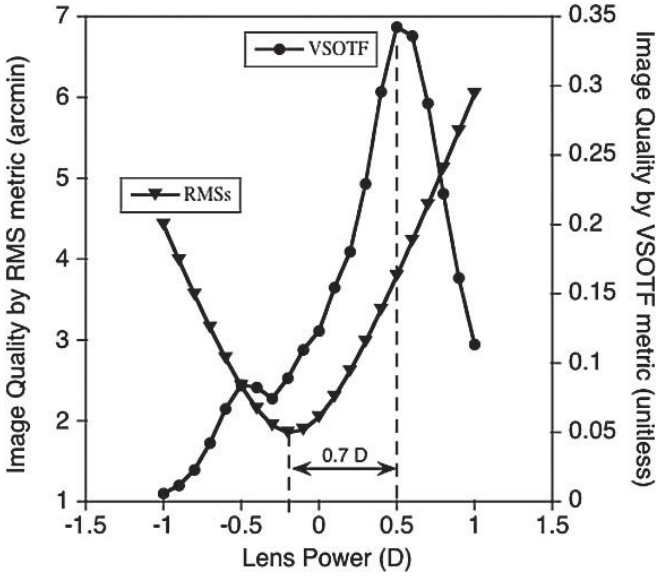

Figure 5. Effect of defocus on optical quality of a theoretical eye model containing only positive spherical aberration ($C_4^0 = 0.3$ microns, 6 mm pupil diameter). Refractive state is the lens power that maximizes image quality (e.g., minimizes metric RMSs or maximizes metric VSOTF). The difference in refractive states for these two metrics is 0.7 D for this eye model.

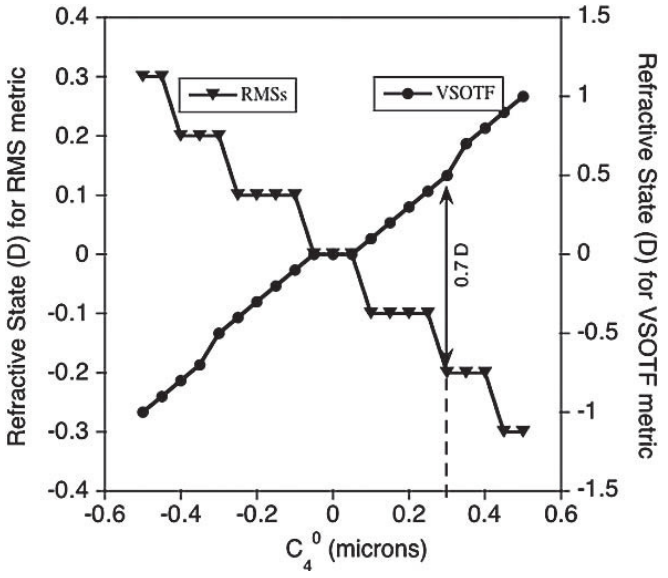

Figure 6. Effect of spherical aberration on optimum refractive state as determined by two different metrics of retinal image quality. Each symbol represents the optimum stimulus vergence obtained from a through-focus graph of the kind shown in Figure 5. Amount of spherical aberration is specified by Zernike coefficient C_4^0.

To interpret these optical calculations in the context of our experiment, consider an eye with relaxed accommodation for which spherical aberration is maximally positive. Had the observer's eye failed to accommodate to changes in stimulus vergence, then we would have expected the observer to adjust the Badal stimulator to provide additional negative vergence when viewing a point source but provide additional positive vergence when viewing a letter chart. That prediction is consistent with the sign of the results obtained experimentally (Figure 2). However, we know that the observers' eyes accommodated to some degree (Figure 3), so according to Figure 6, the difference in optimum refractive state obtained for the two stimuli is less than would have been obtained in the absence of accommodation. Indeed, had our observers accommodated sufficiently to eliminate spherical aberration entirely, the optical model predicts zero difference in optimum refractive states for the two stimuli. This argument suggests our observers accommodated less than would have been needed to completely eliminate the spherical aberration of their eyes. Our experimental results indicated about half of the 0.9 D difference in refractive state measured for the two visual stimuli

could be accounted for by accommodation. The remaining half attributed to the effects of spherical aberration is of the same order as the difference in refractive state predicted by the eye model (Figure 6) for levels of spherical aberration encountered in our population of eyes (Figure 4).

To gain an intuitive understanding of why the optimum refractive state should depend on the visual stimulus, consider the slightly myopic astronomer viewing a bright star through a telescope focused on infinity. If a normally aberrated eye has positive spherical aberration, the retinal image will have a starburst appearance with a central core and radiating tails that are visible against a dark background. These tails are a perceptual cue that the image is not well focused, which prompts an adjustment of the focus of the telescope to eliminate the tails. Adding negative lens power will compensate for the eye's myopia but, according to Figure 6, even more negative power is required when the eye has positive spherical aberration. Thus the eye will appear to have been overcorrected by the telescope, indicating a larger degree of myopia than would have been present without spherical aberration. Now reverse the stimulus contrast by using small dark objects on a bright background, such as black letters on white paper. The tails of individual points of light on the paper produce insufficient contrast to be visible on the light background, but will combine to increase the luminance of the dark letters. This loss of contrast is a perceptual cue that the image is not well focused, which prompts an adjustment of the focus of the telescope to increase contrast. However, the optical calculations summarized in Figure 6 indicate that the adjustment should be less than that required without spherical aberration. The reason is that the increased contrast achieved by adding additional negative lens power is accompanied by contrast reversals and possibly other spatial phase shifts in the image that hamper legibility (Cheng, Bradley, Ravikumar, & Thibos, 2010). Thus the optimum stimulus vergence for dark objects on a light background occurs when the target vergence is less negative than for point sources on a dark background.

In summary, spatial phase shifts induced by defocus in the presence of spherical aberration strongly influence the legibility and perceived quality of high-contrast daytime-objects such as dark letters on a bright background (Cheng et al., 2010; Cheng et al., 2004). When spherical aberration is positive, the under-powered eye is plagued by spatial phase shifts whereas the overpowered eye avoids these phase shifts. Thus, an optimum spectacle correction prescribed for daytime viewing of high contrast letters leaves the eye slightly overpowered (i.e., undercorrected myopia). When the same correction is used at night to view bright sources on a dark background, undercorrection leads to starburst patterns that demand more negative power in the correcting lenses, and thus a tendency for "night myopia."

Present findings are consistent with the night myopia phenomenon described in 1789 by the presbyopic Royal Astronomer Reverend Nevil Maskelyne concerning his observations of distant stars without refractive correction as well as with daytime negative correction and slightly more negative lenses (Levene, 1965; Maskelyne, 1789). Similar observations by Lord Rayleigh in 1883, including difficulties in identifying small objects under bad light conditions, might have included an accommodation component since Rayleigh was only 42 years old. This account assumes that the early astronomers Rayleigh and Maskelyne had eyes with positive spherical aberration, as is typical of the older adult population.

Conclusions

Subjective refractive error is influenced by luminance stimulus configuration. Stimuli typically encountered at night leave the eye in a more myopic state compared to daytime targets.

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