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ORIGINAL ARTICLE

Peripheral refraction under different levels of illuminance

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Abstract

Peripheral refraction is believed to be involved in the development of myopia. The aim of this study was to compare the relative peripheral refraction (RPR) at four different levels of illuminance, ranging from photopic conditions to complete darkness, using an open-field autorefraction method. The RPR was calculated for each eccentricity by subtracting central from peripheral autorefraction measurements. The study included 114 myopic eyes from 114 subjects (mean age of 21.81 ± 1.91 years) and the mean difference in RPR between scotopic and photopic conditions (0 and 300 lux, respectively) was +0.32 D at 30° temporal and +0.37 D at 30° in the nasal visual field (NVF). Statistically significant differences were observed between 0 and 300 lux at 30° in the temporal visual field and at 30° and 20° in the NVF. Our results revealed a significant increase in relative peripheral hyperopia with increasing visual field eccentricity along the horizontal visual field in myopic eyes of young adults. Furthermore, this relative peripheral hyperopia increased as illumination decreased. These findings suggest that an increase in peripheral illuminance may protect against myopic eye growth.

KEYWORDS
illuminance levels, myopia control, peripheral refraction

INTRODUCTION

The incidence of myopia has increased in recent years and it is estimated that 50% of the global population will be myopic by 2050, with 9.8%[1] suffering from high myopia (pathological myopia in which the axial length exceeds 26–27 mm). Pathological myopia can be associated with severe ocular complications, such as retinal detachment, glaucoma and myopic macular degeneration.[1] As such, myopia is considered a global public health problem and its control has become one of the main challenges in the field of vision science in the 21st century.[2]

Myopia is a multifactorial condition and various factors are involved in its development, including genetic predisposition,[3] geography[4] and environmental conditions.[5] Studies in animals have shown that optical defocus at the periphery also affects eye growth and peripheral hyperopic defocus results in an increase in axial length.[6] A longitudinal study of the development of refractive error in 822 children revealed that myopic eyes with relative peripheral hyperopia were elongated and distorted into a prolate shape.[7] Recently, Leighton et al.[8] concluded that myopic children with a more hyperopic relative peripheral refraction (RPR) in the nasal retina exhibited accelerated axial growth over a 12-month period.

Several treatments are currently available to curb the progression of myopia, such as orthokeratology, specially designed soft contact lenses (CLs) and ophthalmic lenses. The aim of these control strategies is to alter the peripheral refraction by inducing myopic defocus, which is thought to slow axial elongation, thus reducing the myopic refractive error. Various clinical studies have looked at the efficacy of CLs and ophthalmic lenses in terms of slowing the progression of myopic refractive error and reducing axial elongation.[9–12] Lam et al.[11] concluded that defocus incorporated multiple segment (DIMS) spectacle lenses reduced myopia progression and axial elongation in myopic children aged 10.15 ± 1.52 years. During the 3-year study, the DIMS group ($n = 65$) exhibited a mean change in spherical equivalent refraction (SER) and the axial length of

−0.52 ± 0.69 D and 0.31 ± 0.26 mm, respectively. By comparison, the control group ($n = 55$) showed a mean change in SER of −0.92 ± 0.81 D and in axial length of 0.57 ± 0.33 mm over the same period. Similarly, Ruiz-Pomeda and Villa-Collar[12] concluded that MiSight (CooperVision) CLs controlled myopia effectively, with 41 children aged 8–12 years who wore MiSight CLs over a 2-year period showing a statistically significant smaller mean change in SER compared to 33 controls with single-vision spectacles (0.45 vs. 0.74 D, $p < 0.001$). Axial elongation was also significantly shorter in the MiSight group compared to the control group (0.28 vs. 0.44 mm, $p < 0.001$). Therefore, it is important to measure peripheral refraction in the control of myopia progression. In addition, evidence from human and animal studies suggests that exposure to ambient light plays an important role in the regulation of eye growth.[13] Several studies have reported that spending less time outdoors is a risk factor for developing myopia.[14–18] Ho et al.[17] conducted a systematic review and meta-analysis to assess the effects of exposure to external light on myopia, and concluded that outdoor light exposure interventions have various benefits, including a 50% reduction in myopia incidence, a 32.9% decrease in spherical equivalent refractive error and a 24.9% reduction in axial elongation for individuals in Asia. He et al.[18] concluded that an extra 40 min of outdoor activity at school compared to usual activity resulted in a lower incidence of myopia over the next 3 years. Moreover, it has been observed that the rates of eye growth and refractive error progression change depending on the season, with slower rates in the summer and faster ones in the winter.[19]

However, changes in peripheral refraction as a function of different illuminance levels have received little attention. Orduna et al.[20] evaluated retinal and optical changes associated with near vision reading for different lighting conditions. A recent study by van Ginkel et al.[21] studied peripheral refraction as a function of accommodation in emmetropic subjects under two different illumination conditions (red and white light). The study concluded that for long wavelength illumination, a significant hyperopic shift at the periphery and a higher accommodative demand were observed.

The aim of this study was to compare the RPR at four different levels of illuminance (300, 150, 30 and 0 lux), ranging from photopic conditions to complete darkness, using an open-field autorefraction method. RPR was measured at seven positions covering the 60° of the visual field, including six at the peripheral retina and one central measurement (foveal vision).

METHODS

Participants

Data collection was carried out according to the tenets of the Declaration of Helsinki. All participants were informed about the nature, risks and possible adverse consequences of the study and signed an informed consent form. The study was approved by the Health Sciences Institute of Aragon local Research Ethics Committee (reference C.P.-C.I.PI20/377).

The participants were European Caucasian subjects from the school of Optics and Optometry of the University of Zaragoza (Spain). Inclusion criteria were 18–29 years old, a myopic refractive error of −0.25 to −12.00 D, refractive astigmatism of −0.75 D or worse and a corrected distance visual acuity with a spherical equivalent (SE) of 0.8 decimal equivalent (6/7.5) or better. Rigid contact lens wearers were excluded. Participants had no prior history of eye injury, surgery, amblyopia or strabismus and were not taking medications that could affect accommodation, pupil size, tear film or refraction. All subjects had natural pupil radii greater than 2.50 mm at all light levels such that the central and peripheral retina could be measured without mydriatic drops.[22] Soft contact lens wearers were asked not to wear their lenses for at least 48 h prior to measurement.

Key points

- The mechanism of myopia remains incompletely understood, but there is evidence of peripheral refraction's role in myopia development.
- Maintaining optimal illumination conditions is critical to prevent the progression of myopia, particularly at the peripheral retina, where relative peripheral hyperopia increases as illumination decreases.
- Results reported here may help prevent myopic eye growth and contribute to the development of new therapeutic modalities for myopia.

Clinical protocol

All measurements were made at the Optometry External Care Practice (Faculty of Sciences, University of Zaragoza) by the same experienced optometrist. Subjective refraction and visual acuity were measured using standard optometry protocols and under an illumination of 300 lux.

Non-cycloplegic central and peripheral refraction and pupil diameter were measured using an open-view autorefractor (Grand-Seiko WAM-5500, Grand-Seiko Co., Ltd., grandseiko.com). Participants looked at seven fixation targets consisting of luminous circles that were illuminated for every lighting condition. The targets were located on a wall 2.28 m from the participants and their size corresponded to a visual acuity of 0.30 logMAR. The targets were placed along the horizontal midline at eccentricities ranging from 30° in the temporal visual field (TVF) to 30° in the nasal visual field (NVF), in 10° increments. We measured seven positions, spanning 60° of the visual field.

Measurements were taken with the eye rotation technique explained by Mathur et al.[23] Participants placed their head against the headrest and held it stationary, then turned their eyes to fixate on the peripheral targets. The instrument's alignment camera was used to check that the pupil of the tested eye was centred with respect to the axis of measurement. This technique ensured better autorefractor–pupil alignment during peripheral refraction.[23,24]

Refraction was measured three times for each fixation target and at each viewing position to obtain an average.[25] The central and peripheral refraction and pupil diameter were measured at four different decreasing illumination levels, 300, 150, 30 and 0 lux (i.e., negligible room illumination). The lighting in the examination room was controlled with a dimmer switch and measured using a lux meter (PCE-174, PCE Instruments, industrial-needs.com). The lux meter was placed in a fixed position close to the patient and beneath the open-view autorefractor to measure the lighting level. The subjects were given 10 min to allow for cone adaptation between different illuminance levels.[26] For the dimmest illuminance condition (scotopic regime), we employed the same dark adaptation period established in a study on night myopia by Chirre et al.,[27] which was set at 30 min.

The same measurement protocol was applied for all participants. For each illuminance level and after measuring central refraction, the peripheral refraction was measured at 10°, 20° and 30° in both the TVF and NVF across the horizontal meridian. The pupil diameter was also measured under each lighting condition.

All measurements were carried out in a single session, which took 60–90 min to complete. Central and peripheral refraction were measured without cycloplegia and therefore under natural viewing conditions. Additionally, both the open-view autorefractor (WAM-5500) and luminous visual targets with low spatial frequency were designed to induce a minimal accommodative response.

Data analysis

All spherocylindrical refractive errors were obtained in standard clinical notation as sphere, negative cylinder and axis, and then converted to vector components: SE (M), with-/against-the-rule astigmatism (J_0) and oblique astigmatism (J_{45}).[28] Only the M component was considered in this study. At each illumination level (300, 150, 30 and 0 lux), the relative peripheral refractive (RPR) error was calculated for each eccentricity as the SER in primary gaze (M_0) subtracted from the SE of peripheral refraction (M_{Exc}), that is, RPR error $= M_{Exc} - M_0$, and defined in terms of visual field.

The statistical analyses were performed and graphs prepared using SigmaPlot 15 software (Systat Software, Inc., systatsoftware.com). Descriptive statistics were used to describe the data and the Shapiro–Wilk test to explore their distribution, which was found to be nonnormal. Therefore, a nonparametric test (the Wilcoxon signed-rank test) was conducted to investigate the differences between mean refraction in primary gaze and the SE of each peripheral refraction. We also aimed to explore the differences between various levels of luminance. Statistical significance was set at $p < 0.05$. Any multiple comparisons were adjusted using the Bonferroni post-hoc test. Spearman's correlation coefficient was used to analyse the relationship between the pupillary diameter and luminance.

RESULTS

A total of 114 eyes from 114 healthy young adult subjects (mean age of 21.81 ± 1.91 years, range: 18–29) were involved in the study. Only one eye per participant (right eye) was measured. The average refraction expressed in SE was −3.47 ± 2.73 D with a range of −0.25 to −12.00 D. As noted above, the right eye was selected with a mean distance corrected visual acuity of −0.11 ± 0.05 logMAR.

Pupil diameter

Table 1 shows the average pupil diameter as a function of illuminance level for the central visual field. As expected, the natural pupil diameter increased with a decreasing level of light. The average pupil diameter was 6.88 ± 1.02 mm at 0 lux and 4.40 ± 0.66 mm at 300 lux. A linear regression analysis showed a significant linear relationship between lighting conditions and pupil diameter ($R = -0.714$ and $p < 0.001$).

RPR across the visual field

Figure 1 shows box plots of the RPR for all data samples as a function of visual field in all lighting conditions: 0 (Figure 1a), 30 (Figure 1b), 150 (Figure 1c) and 300 lux (Figure 1d). Table 2 summarises the mean (and standard deviation) RPR data.

There were no significant differences between RPR, the NVF and TVF for each eccentricity and level of illuminance (all $p > 0.89$, Wilcoxon signed-rank test). In the relative comparison of the foveal and peripheral locations, there were no significant differences between central and both 10° temporal and nasal locations (all $p > 0.10$, Wilcoxon signed-rank test). However, there was a significant difference between 10° and 30° eccentricities in both nasal and temporal locations for each lighting condition (all $p < 0.001$, Wilcoxon signed-rank test).

TABLE 1 Pupil diameter (mean ± standard deviation) as a function of luminance.

Luminance (lux)	0	30	150	300
Pupil diameter (mm)	6.88 ± 1.02	5.48 ± 1.02	4.81 ± 1.20	4.40 ± 0.66

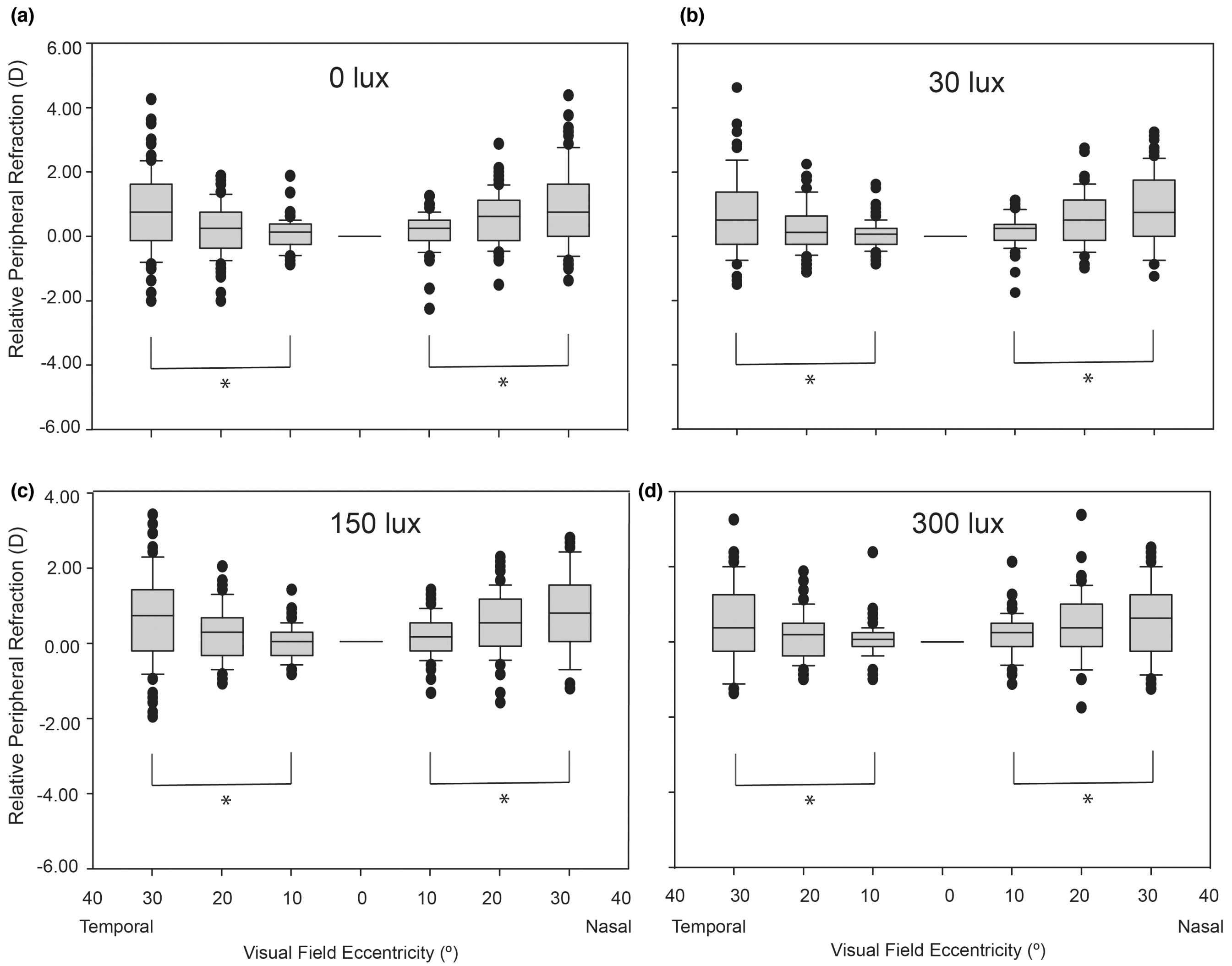

FIGURE 1 Box plots of relative peripheral refraction for each visual field eccentricity and each level of illuminance: (a) 0 lux, (b) 30 lux, (c) 150 lux and (d) 300 lux. The median (central line inside each box), Q1 and Q4 quartiles (lower and higher borders of each box, respectively), and maximum and minimum values (whiskers) are shown for each box. Significant pairwise differences are marked with an asterisk (*).

RPR across the visual field for each lighting condition

Figure 2 shows the mean RPR for all data samples as a function of eccentricity under all examination conditions (0, 30, 150 and 300 lux). The RPR increased with larger eccentricity and lower luminance, leading to a more peripheral hyperopic defocus under these conditions. For completeness, Figure 3 shows the mean difference in RPR between scotopic and photopic conditions (0 and 300 lux) as a function of eccentricity. The mean difference in RPR between scotopic and photopic conditions was +0.32 D at 30° TVF and +0.37 D at 30° in the NVF. In other words, the differences between the RPR under 0 and 300 lux illumination conditions indicate more peripheral hyperopic defocus in all gaze positions. However, this difference depended on the eccentricity value (see Figure 3) and can be fitted experimentally to a parabolic function (Equation 1), as follows:

$$\mathrm{RPR} = 0.003 \bullet \mathrm{Ecc}^2 - 0.0013 \bullet \mathrm{Ecc} + 0.041, \quad (1)$$

where Ecc is the visual field eccentricity.

The Wilcoxon test was used to analyse the differences in mean RPR for different eccentricities, indicating statistically significant differences (p-value < 0.01) for all study conditions, see Table 3. There were statistically significant differences between 0 and 300 lux at 30° in the TVF and at 30° and 20° in the NVF. These differences were also significant between 0 and 150 lux at 30° in the TVF and between 30 and 300 lux at 30° in the TVF and NVF.

DISCUSSION

Myopia is heterogeneous in nature, and a combination of different factors play a role in its onset and progression. Optical defocus at the peripheral retina[29] and

TABLE 2 Relative peripheral refractive error (mean ± standard deviation) for all data samples and for all levels of illuminance across the visual field.

	Visual field (°)						
	Temporal				Nasal		
Light conditions (lux)	30°	20°	10°	0	10°	20°	30°
0	0.83 ± 1.28 D	0.24 ± 0.81 D	0.26 ± 1.62 D	0.00	0.18 ± 0.57 D	0.57 ± 1.02 D	0.85 ± 1.63 D
30	0.76 ± 1.27 D	0.29 ± 0.75 D	0.07 ± 0.44 D	0.00	0.18 ± 0.51 D	0.52 ± 0.96 D	0.76 ± 1.41 D
150	0.65 ± 1.19 D	0.24 ± 0.73 D	−0.02 ± 0.43 D	0.00	0.10 ± 0.69 D	0.44 ± 1.00 D	0.65 ± 1.40 D
300	0.51 ± 1.06 D	0.14 ± 0.63 D	0.07 ± 0.42 D	0.00	0.15 ± 0.65 D	0.37 ± 1.06 D	0.48 ± 1.32 D

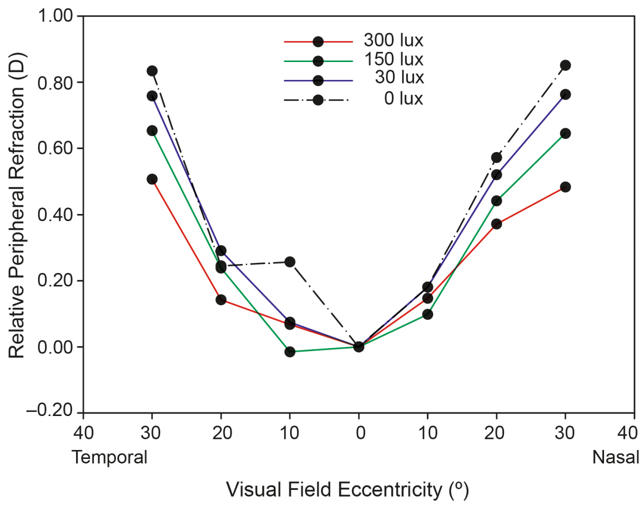

FIGURE 2 Average values of relative peripheral refraction as a function of visual field eccentricity for all levels of illuminance (0, 30, 150 and 300 lux).

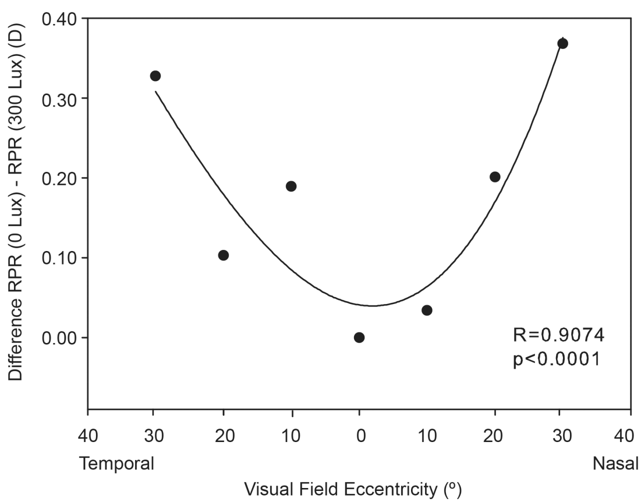

FIGURE 3 Mean difference in relative peripheral refraction between scotopic and photopic (0 and 300 lux) levels of illuminance as a function of visual field eccentricity.

environmental conditions,[30] including lighting conditions or light levels, play an important role in myopia progression. The aim of this study was to examine and compare the RPR error at different eccentricities and under four illumination levels (300, 150, 30 and 0 lux).

With respect to the visual field eccentricity, we observed a hyperopic increase in M in both the TVF and NVF (Figure 2 and Table 2). The magnitude of the hyperopic shift was similar to that reported in other studies.[7,31–33] We found asymmetry between nasal and temporal eccentricities at the same peripheral location for each lighting condition, although the result was not significant (all $p > 0.89$). Marcellán et al.[34] recently reported that the RPR was less hyperopic for the TVF than the NVF, but again, the difference was not statistically significant. Mutti et al.[7] also found a hyperopic (although asymmetric) increase in the temporal and nasal retinas of Caucasian patients. Kang et al.[35] reported differences between moderate myopic East Asians and Caucasians, with the former presenting higher hyperopic defocus at the peripheral retina and nasal–temporal asymmetry. In our relative comparison of foveal and peripheral locations, we did not find any significant differences between central and ±10° temporal and nasal locations (all $p > 0.10$) under each lighting condition. However, there were statistically significant differences between the 10° and 30° eccentricities in both the NVF and TVF for each lighting condition (all $p < 0.001$). Sng et al.[33] found that eyes with low myopia had relative peripheral hyperopia only at 30° in the TVF and NVF, whereas those with moderate and high myopia had relative peripheral hyperopia at all eccentricities. Similar findings were reported by Marcellán et al.[34] They observed a statistically significant, increasing linear trend in RPR measured at 30° eccentricities (nasal and temporal) with respect to the degree of myopia.

Our findings demonstrate that the illumination level has an impact on the RPR error. Under scotopic conditions (0 lux), the RPR exhibited more peripheral hyperopic defocus in all gaze positions. The average difference in RPR between scotopic and photopic conditions (0 and 300 lux) was +0.32 D at 30° TVF and +0.37 D at 30° NVF. These differences in refractive error can be considered clinically significant, as refractive error measurements are commonly taken in 0.25 D increments. However, it is important to note that the magnitude of this difference varies with eccentricity (Figure 3). Statistically significant differences in refractive error were observed for extreme eccentricities (30° TVF and NVF) between 0 and 300 lux, as well as between 30 and 300 lux (Table 2). Van Ginkel et al.[21] found changes in

TABLE 3 Pairwise differences in relative peripheral refraction with eccentricity (degrees) at four levels of illumination.

	p-Values					
	0–30 lux	0–150 lux	0–300 lux	30–150 lux	30–300 lux	150–300 lux
30TVF	x	0.008	0.001	x	0.008	x
20TVF	x	x	x	x	x	x
10TVF	x	x	x	x	x	x
10NVF	x	x	x	x	x	x
20NVF	x	x	0.003	x	x	x
30NVF			0.001		0.000	

Note: A lack of statistical significance is marked with a cross (x). Wilcoxon signed-rank *p*-values are indicated.
Abbreviations: NVF, nasal visual field; TVF, temporal visual field.

various parameters of the lighting conditions, such as the wavelength of the illumination, including a mean difference in *M* between red and white light of −0.28 ± 0.02 and −0.23 ± 0.15 D for accommodative demands of 2.50 and 5.00 D, respectively. Illumination did not, however, have any significant effect on the other refraction vector components (J_0 and J_{45}).

Recent studies have reported that exposure to ambient light is an important environmental factor in the development of myopia.[30,36,37] Several studies have shown that children who spend more time outdoors have a lower prevalence of myopia.[5,13,14] Seasonal differences in myopia progression among myopic children have also been identified, with greater progression observed in winter months.[19,38,39] The authors suggested that this might be due to more near work in the winter months and/or more outdoor activity in the summer. Moreover, animal models of myopia have indicated that elevated light levels can slow the rate of myopia development. For instance, Cohen et al.[40] conducted a study in chicks and found that those exposed to the lowest lighting level became myopic (−2.41 D). The group exposed to medium intensity lighting had a mean refraction of +0.03 D, while chicks in the high intensity group exhibited a stable hyperopic mean of +1.10 D. In a recent study, Cohen et al.[41] examined the non-cycloplegic refraction of preschool children under three different illuminance levels. They found that at low luminance, the children had hyperopia of +0.57 D, under medium conditions the mean refraction was +0.73 D, and at maximum luminance it was +0.89 D. Based on these findings, they concluded that an indoor light intensity of less than 350 lux could be a risk factor for the development of myopia. Further, Hua et al.[42] focused on school-age children and reported that higher ambient light levels in classrooms provided protection against the onset of myopia for non-myopic students and slowed axial growth in both myopic and non-myopic students.

Optical defocus at the periphery is another factor that alters eye growth; specifically, hyperopic peripheral defocus produces an increase in axial length.[43,44] Our findings demonstrate that under low lighting conditions, there was hyperopic defocus at all gaze positions in the periphery, specifically in the scotopic condition (0 lux). Previous research[40,45] indicated that light intensity is an environmental factor that modulates the process of emmetropisation. Bright lighting conditions may increase the synthesis and release of retinal dopamine, which is associated with changes in axial length.

Nevertheless, our study was not devoid of limitations. First, the RPR was only measured at a maximum peripheral eccentricity of 30°. This contrasts with some other investigation that examined higher eccentricities.[46] On the other hand, 30° is considered a good reference value for comparison with other studies.[21,47] Second, we only evaluated the refraction vector component M. However, Ginkel et al.[21] analysed the RPR in terms of vector components *M*, J_0 and J_{45} for two accommodative demands and under two illumination conditions. There was no significant change in J_0 and J_{45} with accommodation, nor between illumination conditions. Third, the central and peripheral refraction were measured without cycloplegia to ensure the eyes were in the most natural condition. As a result, and despite using non-accommodative stimuli and an open-field autorefractor to minimise the participants' accommodative response, it can be argued that our measurements might have been affected by some spurious accommodative 'myopic' noise. However, because all peripheral refractions were relative (through subtraction) to the central refraction, we believe that the effect is negligible.

Future research could explore the RPR as a function of accommodation under different illumination levels or as a function of different illumination conditions (wavelength), such as red light. In addition, data on the biometric changes in near and far vision could provide valuable insight into the alterations occurring in the central and peripheral retina under different levels of illumination.

CONCLUSIONS

Our study revealed a significant increase in relative peripheral hyperopia with increasing visual field eccentricity along the horizontal visual field in myopic eyes of young adults. Furthermore, this relative peripheral hyperopia increased as illumination decreased. These findings suggest that an increase in peripheral illuminance may help prevent myopic eye growth.

AUTHOR CONTRIBUTIONS

Mª Concepción Marcellán: Data curation (equal); investigation (equal); methodology (equal); writing – original draft (equal). **Laura Remón:** Conceptualization (equal); investigation (equal); methodology (equal); project administration (equal); supervision (equal); validation (equal); writing – original draft (equal). **Francisco J. Ávila:** Conceptualization (equal); methodology (equal); project administration (equal); supervision (equal); validation (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data underlying the results presented in this paper are not publicly available but can be obtained from the authors upon request.

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