Manuscript title: The effect of retinal illuminance on the subjective amplitude of accommodation

Short title: Retinal illuminance and accommodation

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Abstract

Significance statement: We show that the amplitude of accommodation decreases with target illumination even under photopic reading conditions and a constant pupil size. This result provides a basis for clinical approaches that are not based on an optical explanation.

Purpose: We investigated the effect of retinal illuminance on the amplitude of accommodation while the pupil of the eye remained constant.

Methods: The amplitude of accommodation of 10 young subjects (from 20 to 38 years of age) and 10 presbyopic subjects (from 45 to 54 years of age) were measured subjectively through an artificial pupil of 5 mm using a Badal optometer and for four values of retinal illuminance: 222, 821, 2,138, and 5074 Td. Phenylephrine was instilled to all the subjects to ensure that their natural pupil was greater than the artificial one in all experimental runs. Two-way ANOVAs with age and log luminance as covariates were used to check whether changes in amplitude of accommodation with illumination were statistically significant.

Results: In the range of luminances tested, the amplitude of accommodation decreased on average from 6.34 D to 4.35 D in the young subjects, and from 1.69 D to 1.04 D in the presbyopic subjects. Luminance was associated with the amplitude of accommodation in both young and presbyopic groups, with $p < 0.01$.

Conclusions: The reduction in the amplitude of accommodation with target illumination (a phenomenon named *night presbyopia*) under photopic light conditions is not only due to a reduction in the depth of focus as a consequence of pupil dilation; it is strongly affected by the decrease of retinal illumination.

Keywords: accommodation, luminance, retinal illumination, night myopia, night presbyopia.

Introduction

There has been substantial evidence suggesting that the objective amplitude of accommodation changes with object illumination since the effect was first observed in the 18th century.[1] Maskelyne in 1789[2] and Lord Rayleigh in 1883[3] were the first to describe how their eyes became short-sighted under low illumination conditions. That is, their eyes experienced a myopic shift at night. This now well-known effect is called night myopia. It took some 50 years after Rayleigh for Ferree and Rand[4] to study systematically the changes in the near point caused by changes in light, and 10 more years for Cabello to quantify the effect of illumination on the amplitude of accommodation (distance from the near point to far point) as a whole.[5] Cabello coined the phrase *night presbyopia* to capture the effect of receding near point that occurred at mesopic and scotopic light conditions.[5] Figure 1 (data from Cabello[5] and Otero et al[6]) shows the reduction of the amplitude of accommodation when the target illumination decreases. Otero[6] later demonstrated that, on average, the accommodative range decreases progressively towards the point of tonic accommodation (dark focus)[7–9] when the stimulus gets dimmer.

More recent studies report both a myopic shift in distance refractions[10,11] and reduced accommodation at low light levels.[12,13] However, as in the studies of Cabello and Otero mentioned above,[5,6] most of these changes occur at low mesopic and scotopic light levels, below those typically needed for reading text in the modern world.[14]

Given the fact that the retinal illuminance depends on target's luminance and on the pupil size[15] (also depending on the large-field luminance[16]), the changes in near point and far point may have been affected by pupil miosis occurring as light levels change[17] while accommodation takes place.[18,19] As the pupil dilates, more peripheral optics contribute to the retinal image, and due to the change from positive to negative spherical aberration that accompanies accommodation[20,21] refractive measures that include the peripheral optics will tend to reveal reduced accommodation relative to measures that employ more paraxial optics.[22] However, because of the impact of quantal noise,[1,23,24] neural sensitivity declines as retinal illuminance is lowered (square root law). Because defocus primarily demodulates the higher spatial frequencies,[25] the lowered sensitivity to these high spatial frequencies may also contribute to a failure to accommodate at low light levels.

To separate the optical effects produced by the pupil from the neural effects, we have sought to isolate the neural effect on the depth of focus by studying the impact of retinal illuminance on the subjective amplitude of accommodation for a fixed pupil size. In this study, we constrained the light levels to those typically encountered during reading.[14]

Methods

Participants

Twenty-three subjects ranging from 20 to 54 years of age participated in this study. However, three participants could not finish the experiment due to inability to accommodate, having excessive tearing, or a pupil smaller than 5 mm after the instillation of phenylephrine. The remaining 20 subjects were split into two different groups of 10 each: young subjects with ages ranging from 20 to 38 years and with a mean (±standard deviation) age of 25 (±5.3) years; and 10 presbyopes, with ages ranging from 45 to 54 years and with a mean age of 50 (±3.1) years. Prior to testing, a subjective refraction[26] was performed by the same qualified optometrist at a luminance of 108.9 (±1.7) cd m^{-2}. All subjects had a best-corrected visual acuity of 0.0 logMAR or better. The study was approved by the University of Murcia Ethics Committee. All participants gave written informed consent and the study adhered to the tenets of the Declaration of Helsinki.

Experimental set-up

A custom made Badal optometer with a stimulus controlled by a stepper motor[27] was used to vary target vergence in a range of about +10 D to -18 D. The system consisted of two achromatic doublets; one fixed, whereas the other one could be moved (i.e. Badal lens). With this automated Badal system, subjects adjusted target vergence to find their far point and near point subjectively, using a joystick control. The amplitude of accommodation was defined as the difference in vergence between these two positions. Further details about the optical system and the methodology can be found elsewhere.[28]

The entrance pupil of the eye was chosen as the reference plane for the measurements, so that the amplitude of accommodation can be compared among subjects with different refractive errors.[29] For this purpose, a camera focusing at infinity and a plane mirror were used, so the iris of the participants could be focused. Amplitude of accommodation calculations took into account that target position was fixed and its distance finite with respect to the subject.

Experimental procedure

The left eye of all the participants was measured while the contralateral eye remained occluded. The target was a Bailey-Lovie chart placed at 6.95 m from the subject. The target was inverted to account for the inversion introduced by the Badal system. Participants were told to put their chins on a chin rest, and then their refractive error was compensated by placing the prescription obtained in the subjective refraction in the phoropter, which was placed between the Badal lens and the eye, as close to the later as possible. An artificial pupil with a diameter of 5 mm was placed in the phoropter, approximately at 10 mm from the corneal vertex.

Each participant took as many preliminary training trials as necessary until they felt they were ready. After this, two drops of 10% phenylephrine were instilled on the participants' left eye, with an interval of 5 minutes. Phenylephrine does not significantly affect accommodation.[30,31] The artificial pupil was centered with respect to the natural pupil before it was fully dilated. After 40 minutes, and after making sure that the pupil diameter was greater than 5 mm and not reacting to light, the subjective measurements of the amplitude of accommodation started. Different configurations of room lights and the use of two extra incandescent lamps of 500 W were used to generate four different chart luminance levels (nominally, 11.3, 41.8, 108.9, and 258.4 cd m^{-2}, corresponding to a retinal illuminance of 222, 821, 2138, 5074 Td, respectively.[15]) The sequence of luminance conditions was random for every subject.

Participants were instructed to move the Badal lens up to the furthest possible position in which they were able to see the letters corresponding to 0.0 logMAR visual acuity clearly, following the "objectionable blur" criterion. The specific instructions (given in Spanish) were to search for the farthest point that sustained a "level of blur which you would refuse to tolerate on a full-time basis. The blur has just reached a point at which it is unacceptable."[32] After obtaining the position of the far point, the subjects were instructed to find their near point by bringing the Badal lens as close as possible until they could perceive a maintained and unacceptable blur, with the same criterion as before. Amplitude of accommodation was then obtained by averaging five far point and near point measurements for each subject and luminance condition.

Statistical Analysis

Even though we designed the experiment to have two clearly distinct age groups, young (amplitude of accommodation ≥ 3 D) and presbyopes (amplitude of accommodation < 3 D), the effect of age on amplitude of accommodation was still expected to be very strong within each group, especially on young subjects. We therefore incorporated age as a potential confounder of the effect of illumination on amplitude of accommodation in our models. Therefore, for each age group, a linear mixed-effect model for repeated-measures was performed with amplitude of accommodation as a linear function of age (as confounder), a logarithmic function of luminance (the main explanatory variable) and subject as random effect. We used a logarithmic scale for luminance because its association with the amplitude of accommodation is roughly linear on average (see Results section). The significance level after Bonferroni correction of the repeated measures analyses for both groups was set at 0.025. The package "lme4"[33] for the R statistical environment (https://www.R-project.org) was used to estimate the parameters of the linear mixed models. The *p*-values for the Kenward-Roger modification[34] of the F-statistic (an improved small sample approximation) was obtained with the function "Anova" of the R package "car".[35]

Results

The mean spherical equivalent obtained for the young group was −0.15 D. The standard error of the mean (SEM) multiplied by 1.96 was 0.68 D. For the presbyopic group these values were −0.10 and 1.11 D. The mean amplitude of accommodation (and 1.96 SEM) obtained for the young group were (in descending order of luminance) 6.34 (0.35) D, 5.66 (0.43) D, 5.63 (0.45) D, and 4.35 (0.59) D. Figure 2 shows the amplitude of accommodation for each young subject at all four luminances. Subjects are sorted from younger (top) to older (bottom). Overall, amplitude of accommodation decreases when age increases.

The mean amplitude of accommodation (and 1.96 SEM) obtained for the presbyopic group (Figure 3) under different luminance conditions (in increasing order of age) were 1.69 (0.16) D, 1.36 (0.16) D, 1.24 (0.20) D, and 1.04 (0.21) D. In general, same tendency between amplitude of accommodation and age can be observed in this group.

When averaged among each age group, our results can be summarized in Figure 4. As the illumination increased from 11.3 to 258.4 cd m^{-2}, the far point moved farther away from the eye approximately two times more in the young subjects (0.51 D) than in the presbyopes (0.23 D). In addition, the near point came about three times closer to the eye in young people (1.48 D) than in presbyopes (0.41 D).

For the young group, amplitude of accommodation increased with luminance by 1.36 D / $\log_{10}$ (cd m^{-2}) ($p < 4 \times 10^{-5}$) and decreased with age by 0.13 D / year ($p = 0.07$) as estimated with linear random-effect model for repeated measures. For the presbyope group, the estimated increase of amplitude with log luminance was more than 3 times smaller at 0.45 D / $\log_{10}$ (cd m^{-2}) ($p < 2 \times 10^{-6}$). Amplitude decrease with age was similar at 0.11 D / year ($p = 0.01$).

Discussion

The aim of this study was to assess the effect of changes in luminance on subjective amplitude of accommodation over the range of environmental light levels typically used for reading.[14] By employing a fixed 5-mm pupil diameter, these changes in stimulus luminance altered the neural sensitivity of the visual system,[1] but avoided the confounder of optical changes caused by pupil changes. Thus, the only optical changes experienced by the eye were those happening during accommodation, so differences in perception of the target were due to changes in neural effects produced by changes in retinal illumination. In our Badal system, the retinal illuminance changed slightly during accommodation since the image nodal point of the eye changes its position,[15] but that change is less than 5% even for almost 7 D of accommodation.[36] A limitation of the present study is the lack of objective measurements of the amplitude of accommodation, which would shed some light on whether or not the lack of light affects the response of the ciliary muscle or if it is just a problem of photon noise.

Our results (an approaching far point and receding near point) are in general agreement with previous studies by Cabello,[5] Otero[6] and others[37]. Unlike these previous studies, however, in which light levels and the accommodative response both altered pupil size and therefore the optical characteristics of the image,[38] our use of a fixed pupil diameter (5 mm) isolated the impact of changing neural sensitivity on amplitude of accommodation. Thus, our results show that besides optical effects generated by the change in pupil size, retinal illumination plays a key role in the variation of the amplitude of accommodation.

In addition to the main effect of presbyopia, the differences found in the magnitude of average changes of the far point with luminance could be explained by the greater transmission factor of ocular media in younger subjects producing a larger retinal illumination in the younger than the aged eye for the same object's luminance. Mean transmittance of 50 years old subjects is approximately 79% that of the 25 years old subjects.[39] In relative terms, the effect of the target luminance is similar in both groups, since the younger group accommodated between 3 and 4 times more than the presbyopes, on average.

The mean age of the presbyope group was 50 years and previous studies indicate average subjective amplitude of accommodation of an individual of that age is approximately 1.75 D,[40–42] which is about 0.4 D greater than the one obtained in this study with a target luminance of 108.9 (1.7) cd m^{-2} (similar to that one used in clinical measurements). This difference could be explained by the effect of the depth of focus due to the difference in pupil diameters, since a typical pupil of 50 year olds at these luminance levels is approximately 4 mm,[43] 20% smaller than the artificial 5-mm pupil we used here. A similar tendency was found for the younger subjects as for the older ones. The average amplitude of accommodation for a 30-year-old individual is about 7 D,[40] which is larger than the 5.66 D we observed in our younger sample. Significantly, objective measures of amplitude of accommodation[44] report values of about 6 or 7 D in young adults, and approximately zero in those over 50 years. This discrepancy between the subjective[40,41] and objective[44] measures of amplitude of accommodation in older eyes is presumed to reflect the pseudo-accommodation or subjective depth of focus which is incorporated into subjective measures of amplitude of accommodation as used in the present study. Because of large inter-subject differences,[40,42,45] as well as the sensitivity of subjective accommodation to stimulus and instructions given to subjects,[32,46] the small differences between the current study and earlier reports is perhaps expected.

One main difference between a focused and a defocused image is the amplitude of the high spatial frequency content in the image.[25] As retinal illuminance decreases, higher spatial frequencies are affected more by photon noise.[47] Therefore, the signal indicating defocus[48,49] becomes less visible as retinal illuminance decreases and accommodation tends to its resting state (around -2 D on average, although it varies a lot from subject to subject)[13]. Luminance reduction is far more impactful under scotopic light levels as it is shown in Figure 1 with a larger jump in the transition between mesopic and scotopic ranges. The current study has shown that a decrease in amplitude of accommodation can occur independently of the change of pupil size and is present at low photopic light levels as well, such as those used in reading, [14] which would be in agreemen with Cambell's work on the minimum amount of light required to elicit the accommodation reflex in humans.[12] Campbell stated that "if the luminance of the object is diminished until it approaches the sensory threshold the perception of the less intense blurred edge of the image will become impossible". Therefore, in Campbell's own words "the higher the luminance of the object the easier will be the detection of this out-of-focus blurring, and the greater will become the accommodation response".

Our results highlight the importance of light levels in vision, especially in presbyopic patients, when performing near vision tasks, such as reading. For instance, not having enough light could mean that a presbyopic patient may not be able to read at near distances as a consequence of their near point getting further away from their eye due to dim lightning, even when their addition has been properly calculated at photopic levels. Some presbyopia treatments consist of expanding depth of focus by using an artificial small pupil in contact lenses[50,51] or inside the cornea.[52] However, this methodology causes a decrease in retinal illuminance, which may alter the patient's near point. In a theoretical study, Xu et al.[38] found that, at low light levels, visual function was generally worse when using small-pupil solutions than multifocal solutions.

In conclusion, our results show that the retinal illuminance changes that accompany reductions in target luminance reduce the subjective amplitude of accommodation over the stimulus range commonly encountered with text in the modern environment. It is likely therefore that lowered light levels will exacerbate any age related decline in amplitude of accommodation and therefore lower environmental lighting situations may be driving the onset of clinical presbyopia and the age at which optical aids are required.

Lighting conditions, therefore, should be taken into account in the assessments, diagnostics and prescriptions performed in the daily clinical practice.

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Figure Legends

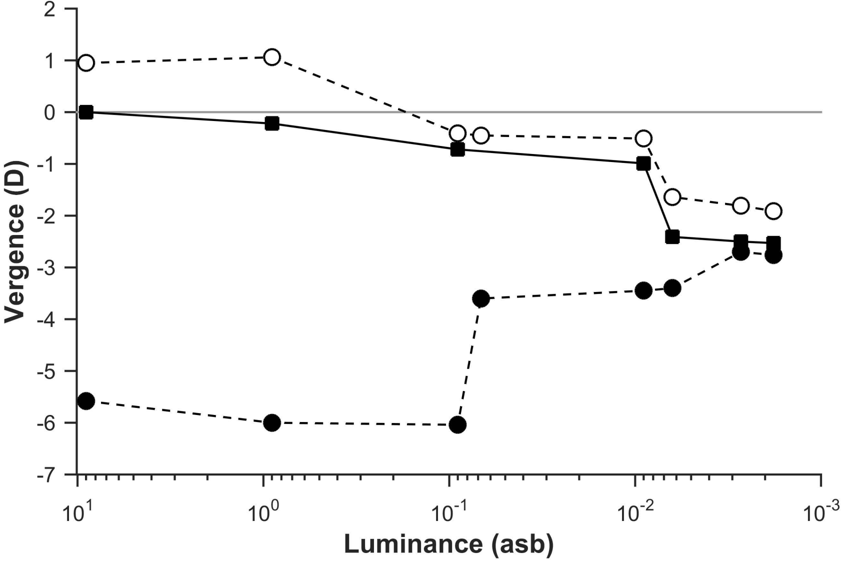
Figure 1. Variation of the subjective far and near points (and thus amplitude of accommodation) as a function of stimulus luminance (open and black circles, respectively). Target vergence producing maximum visual acuity is also plotted (black squares). Luminance is given in Apostilbs (asb), being 1 asb = π^{-1} cd m^{-2}. Scotopic conditions correspond approximately to $\pi \cdot 10^{-3}$ asb; mesopic conditions between $\pi \cdot 10^{-3}$ asb to π asb, and values greater than π abs correspond to photopic conditions. Adapted from Cabello[5] and Otero et al.[6]

Figure 2. Amplitude of accommodation for the young subjects for each retinal illuminance. Subjects are ranked by age with younger on top. The width of the bars indicates the amplitude of accommodation, the left border is the far point and the right border of the bar is the near point of each subject. Red vertical dashed lines show the mean far point and near point among all the young subjects. The left error bars represent the 1.96 SEM of the far point, whereas right error bars represent the 1.96 SEM of the near point. The label M (filled bars) stands for the mean among subjects.

Figure 3. Amplitude of accommodation for the presbyopic subjects for each retinal illuminance. Other details as in Figure 2.

Figure 4. Far point (solid circles) and the near point (empty circles) under different target luminance levels, for young subjects (top left panel) and for presbyopes (top right panel). Bottom panels show the relationship between the logarithm of the luminance and the amplitude of accommodation for young subjects (bottom left panel) and for presbyopes (bottom right panel). The values on the top *x*-axis in the upper panels are the retinal illuminance (in Trolands) corresponding to each log luminance level on the bottom *x*-axis. They were added to allow for direct comparisons with Figures 2 and 3. The length of the error bars represents the Gaussian estimate of the 95% confidence

intervals (±1.96 SEM) around the mean values. Note that in many cases the error bars are so small in length that they are occluded by the symbols themselves.



Vergence (D)
2
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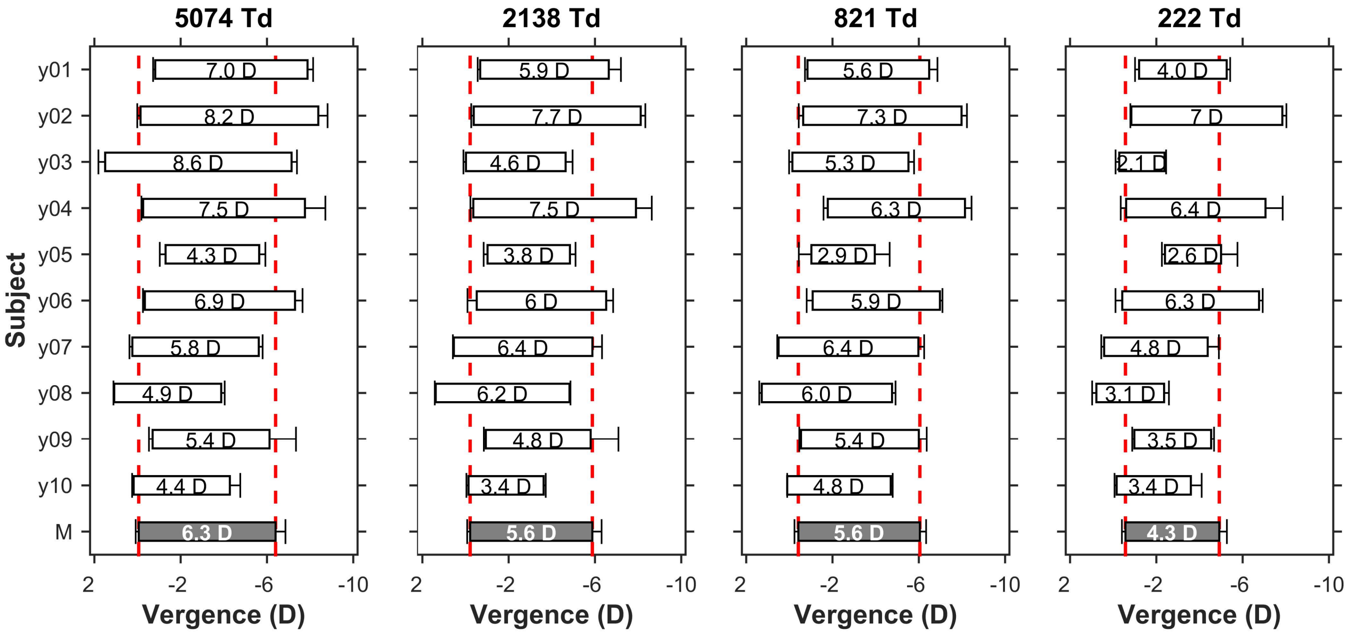
Luminance (asb)



5074 Td
2138 Td
821 Td
222 Td
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6.9 D
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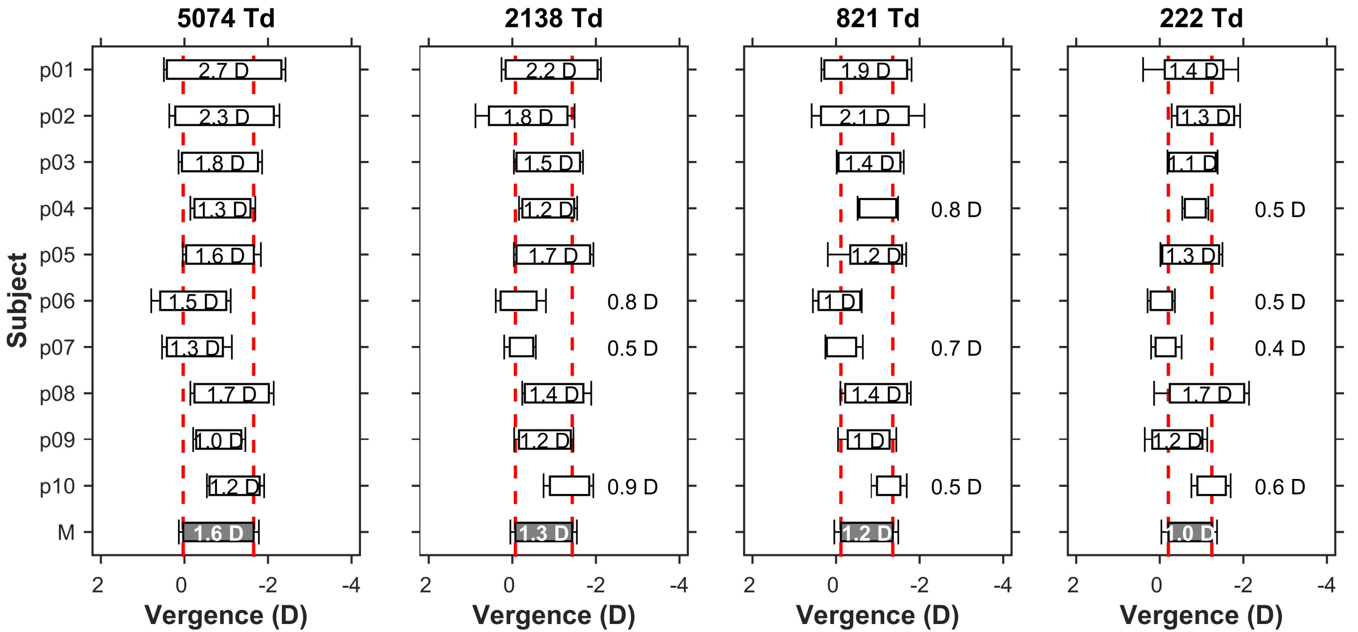
Vergence (D)



5074 Td
2138 Td
821 Td
222 Td
Subject
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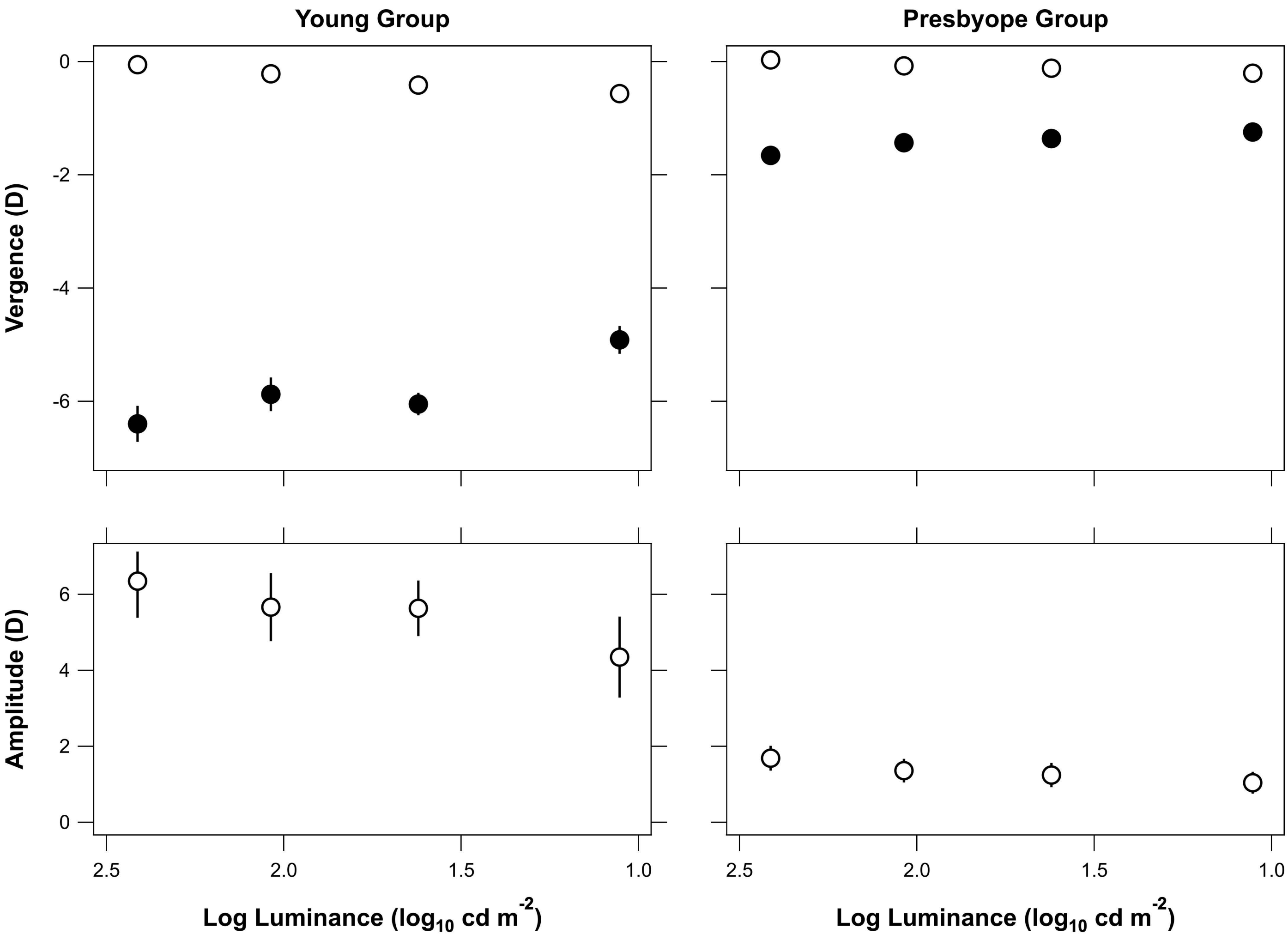
1.4 D
1.2 D
0.9 D
1.3 D
1.9 D
2.1 D
1.4 D
0.8 D
1.2 D
1 D
0.7 D
1.4 D
1 D
0.5 D
1.2 D
1.4 D
1.3 D
1.1 D
0.5 D
1.3 D
0.5 D
0.4 D
1.7 D
1.2 D
0.6 D
1.0 D
2
0
-2
-4
Vergence (D)



Young Group
Presbyope Group
Vergence (D)
0
-2
-4
-6
Amplitude (D)
6
4
2
0
2.5
2.0
1.5
1.0
Log Luminance (log_{10} cd m^{-2})
Log Luminance (log_{10} cd m^{-2})