Calibration of the PlusOptix PowerRef 3 with change in viewing distance, adult age and refractive error

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Abstract

Purpose: The PowerRef 3 is frequently used in studying the near triad of accommodation, vergence and pupil responses in normal and clinical populations. Within a range, the defocus measurement of the PowerRef 3 is linearly related to the eye's defocus. While the default factory-calibrated slope of this relation (calibration factor) is 1, it has been shown that the slope can vary across individuals. Here, we addressed the impact of changes in viewing distance, age and defocus of the eye on the calibration factor.

Methods: We manipulated viewing distance (40 cm, 1 m and 6 m) and recruited participants with a range of accommodative capabilities: participants in their 20s, 40s and over 60 years old. To test whether any effect was larger than the range of measurement reliability of the instrument, we collected data for each condition four times: two in the same session, another on the same day, and one on a different day.

Results: The results demonstrated that viewing distance did not affect the calibration factor over the linear range, regardless of age or uncorrected refractive error. The largest proportion of the variance was explained by between-subject differences.

Conclusions: Calibration data for the PowerRef 3 were not sensitive to changes in viewing distance. Nevertheless, our results re-emphasise the relevance of calibration for studies of individual participants.

Introduction

Eccentric photorefraction in combination with Purkinje image eye tracking provides a rapid method for the objective, binocular, simultaneous assessment of refractive error, pupil size, and eye position. The double-pass eccentric photorefraction method estimates refractive state using the slope of reflected light distributed across the pupil with a number of factors known to cause variation in the measurement.[1,2] Additionally, these instruments permit open-field measurements from a typical working distance of 1 m.[3] These features, with a high video sampling rate, make photorefraction a valuable tool in the assessment of typical adults and children, as well as clinical populations.[4–7] Versions of the PowerRefractor instrument[6] have been used to study the near triad of accommodation, vergence and pupil responses in normal and clinical populations.[8,9]

Accurate estimates of refractive state require careful calibration of the photorefraction system. Commercially available photorefractors use an estimate of a population average calibration function to convert the slope of the light distribution across the pupil to an estimate of refractive state.[6,10–12] The Plusoptix PowerRef 3 (www./plusoptix.com) measures gaze position, pupil size and refractive state binocularly at a sampling rate of 50 Hz over a wide dioptric range (+5 D to −7 D). The default photorefraction calibration function used in this instrument is based on a population average and, therefore, is well-suited for studies of experimental manipulations in a group of participants. However, the slope of the relative calibration function, which we define as the calibration factor (CF) for the purposes of this study, can vary in an individual by up to 50% from this default.[13,14] Individual calibration must be performed carefully as a number of optical factors will impact the results.[1,2]

One of the most promising applications of combined eccentric photorefraction and Purkinje image tracking is in simultaneous assessment of dynamic accommodation and vergence responses. Lenses or prisms can be used to drive these responses, but in a naturalistic environment they are typically driven by changes in viewing distance. Previous studies of changes in viewing distance have either relied upon the manufacturer's default instrument calibration or a calibration performed for the individual at a fixed distance.[5,15] Thus, these studies have failed to account for the possible effects of target viewing distance on the calibration function. In addition, they have not included a 6 m viewing distance as an assessment of distance vision. Although a decrease in pupil size with a change to near viewing is typically compensated for in a photorefractor's software, accommodation is more variable when viewing near than far targets[16,17] and it is likely to induce changes in higher order aberrations of the eye.[18] Changes in vergence posture of approximately 13° between a target at 6 m and 25 cm will also change the eccentricity at which measurements are made. These factors, amongst others, could lead to a change in the accuracy or precision of the refractive state calibration function with viewing distance. In particular, a change in the asymmetrical higher-order aberrations of the eye has been shown to impact the relationship between the slope of the distribution of light across the pupil and refractive state.[1]

The goal of this study was to determine the effect of viewing distance on the PowerRef 3 calibration function, for adults of a range of ages with varying accommodative abilities and uncorrected refractive errors. They viewed targets at near (40 cm), medium (1 m) or far (6 m) distance. Given that, in practice, any effects are only important if they are larger than measurement repeatability, the procedure was repeated four times (rounds). In an attempt to understand these effects in naturalistic viewing situations, the data were collected at the highest light level for which the photorefractor was able to measure reliably at all viewing distances for a given participant.

Methods

Participants

Seventeen adult participants with prior experience in psychophysical studies and no clinical ocular disorder beyond refractive error were recruited. One was then excluded because they were unable to perceive the target at 40 cm clearly (due to presbyopia and high hyperopia) and another did not complete the study procedure. Of the 15 remaining adult participants, five were between 20 and 30 years old (T1–T5, in increasing age order), five were between 37 and 50 years old (F1–F5, in increasing age order), and five were above 60 years old (O1–O5, in increasing age order). Participants were recruited over a wide age range to include different levels of accommodative ability. Ethical approval was granted by the Smith-Kettlewell Eye Research Institute Institutional Review Board. Informed consent was obtained from all participants prior to starting the study. The study was conducted in accordance with the Declaration of Helsinki.

Procedure

Participants fixated on an accommodative target at 40 cm, 1 m, and 6 m while their eyes' refractive state and gaze positions were measured with a PlusOptix PowerRef 3. They were instructed to look at the target consisting of a scaled optotype (*Figure* 1). The order of viewing distances was randomised between participants. Data were collected in four rounds: first round (1st); immediately after the first round (Im); the same day as the first round (SD); and on a different day (DD). The study was thus performed over 2 days, with a brief eye examination also performed on the second day. The Im round was performed without change in position of the participant or the photorefractor and was collected within 10 min of the first round. Light level was adjusted for each participant to the highest level for which data collection was reliable at the 40 cm viewing distance.
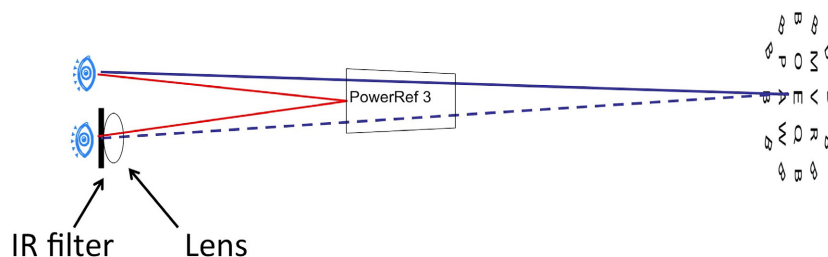

Figure 1. A schematic illustration of the fixation target and the placement of the infrared (IR) filter and lenses in front of the occluded eye for calibration of the PowerRef 3.

Target

The target consisted of a scaled optotype (see *Figure* 1), a central letter 'E' surrounded by two rings of letters. The letters were scaled in size across viewing distance such that they each subtended 0.33 deg; the outer ring diameter was 4 deg. Black letters were printed on white paper.

Viewing

Viewing was monocular while the other eye was occluded with an Acrylite® GP infrared (IR)-pass filter (wavelength bandpass: 750–1600 nm; https://www.acrylite.net/product/acrylite/en/). Data were recorded from both eyes. Spherical trial lenses (+1, +2, +3, +4, −1 and −2 D) were placed in front of the occluded eye in sequence, and in the above order, for at least 3 s each to ensure sufficient data collection. Participants with significant refractive errors who did not have contact lenses participated without optical correction to avoid any possible interference of the optical properties of their spectacle lenses with the measurements.[2] The angle between the photorefractor camera and the participant's gaze was approximately 4 deg, with the camera angled up towards the eye, placing the camera axis close to the axis passing perpendicularly to the cornea through the centre of the pupil.

Design

Viewing distance was a within-subject variable. To determine the reliability of any viewing distance effect, each participant performed the task at each viewing distance (40 cm, 1 m and 6 m) in each of the four rounds.

Data analysis

All of the raw data for which pupil size information was available were included in the analysis. CF was computed using a linear regression of change in measured anisometropia between pre lens placement and during lens placement (100 data points equivalent to 2 s for each sample) as a function of trial lens power. Each period of 2-s was identified subjectively based on the following criteria (1) accommodation seemed stable; (2) gaze position seemed stable; and (3) the time-window was the closest possible to lens placement. To avoid any effect of this subjective judgment on the results, all data were analysed and slopes were calculated over the course of 2 days with the author (SG) being masked to the condition under which a specific data file was collected.

Results

A total of 12 sets of data were collected from each of 15 participants. Five sets of data were not available for analysis as

the data were not stored successfully. Out of a total of 1050 lens-placement trials, data for 18 trials were excluded because the number of data points was insufficient within a 2 s period.

The participants had a range of age, accommodative ability and refractive error. The mean uncorrected refractive errors for the viewing and non-viewing eyes were +0.84 D (S.E.M. = 0.45) and +0.58 D (S.E.M. = 0.41) respectively, ranging from −2 D to +4 D (based on photorefractor measures for the 6 m-target before lens placement). The true baseline refractive state for each viewing distance therefore varied between individuals. The lens power plus uncorrected refractive state might also then shift the refractive state measurement outside the linear range of the instrument.[2] *Figure* 2 presents the mean measured refractive state *during* lens placement (mean of 100 samples collected over 2 s, pooled over four rounds) as a function of the measured refractive state *pre* lens placement (mean of 100 samples
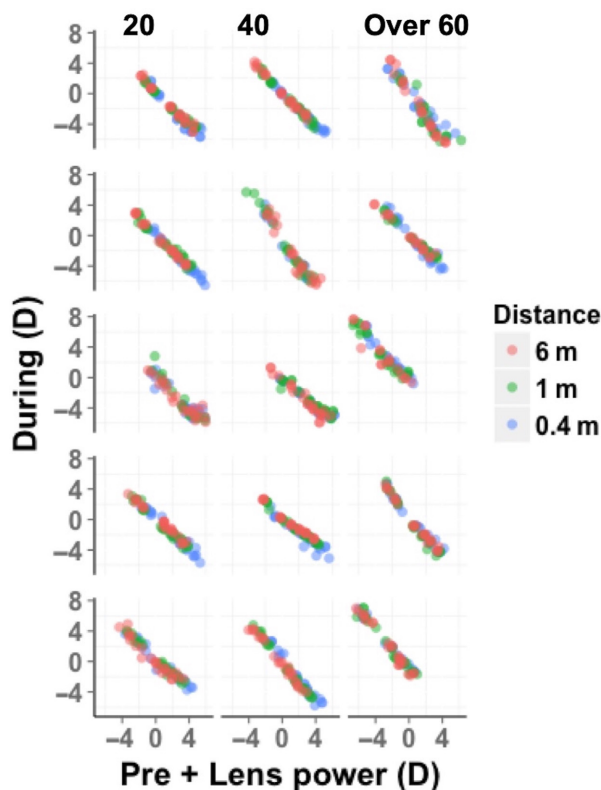

Figure 2. PowerRef 3 measurements from the non-viewing eye during calibration for different viewing distances. The *y*-axis is the measured mean refractive state during lens placement. The *x*-axis is the measured mean refractive state before the lens placement plus the lens power. Data for 15 participants with different accommodative ability are shown (five participants in the twenties T column (20–30 years old); five in the forties F column (37–50 years old); and five in the over 60 O column). Data are arranged by age so that the upper-left are data for data T1 and the lower right are data for O5.

collected over 2 s, averaged across four rounds) plus the lens power. For example, if a participant's eye was focused at a viewing distance of 1 m, the measurement might be 1 D of myopia during the pre-lens placement interval (indicating that a −1 D lens would correct the defocus). In this scenario, the eye's defocus relative to infinity is actually +1 D. During the lens placement, if a +2 D lens was then placed in front of the eye, the PowerRef 3 measurement should be 3 D of myopia (with 1 D contributed by the eye's defocus and 2 D contributed by the lens). This example would be plotted in *Figure* 2 with an *x*-value of 3 D (1 + 2) and a *y*-value of −3 D, and therefore, the slopes of the functions in *Figure* 2 are close to −1. In each case, the pre lens refractive state fell within the linear range of the instrument. The data are plotted for the occluded eye only and for the participants grouped into age range (and thus accommodative ability). The panels are ordered based on age so that data for T1 is on the top left and data for O5 is on the bottom right. The data collected from the younger participants at the viewing distance of 40 cm are visible to the right of the data from the other viewing distances, confirming that an accommodative response was generated for this near target.

A linear mixed model fit to the slopes of the functions in *Figure* 2, with 'participant' as a random effect and 'age' and 'viewing distance' as fixed effects, showed no effect of viewing distance ($p = 0.57$), age ($p = 0.16$) or their interaction ($p = 0.35$). *Figure* 2 confirms that the data collected during
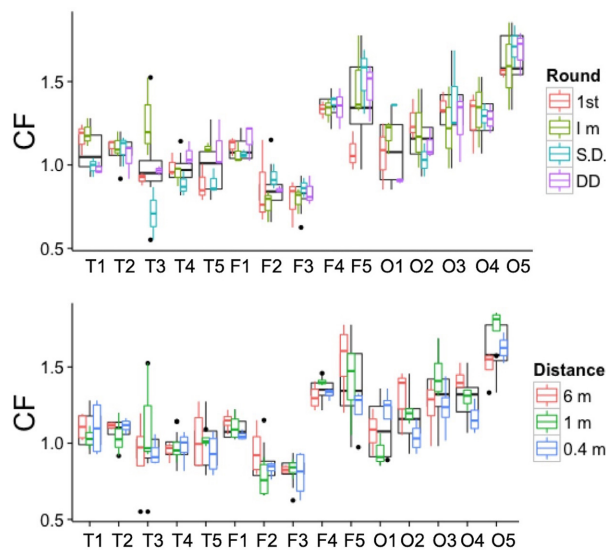

Figure 3. Distribution of calibration factor (CF) for individual participants across round (top panel) and viewing distance (bottom panel). The combined data are shown as black lines. The *x*-axis shows the participants ordered based on age group. Five participants were in their 20s (T1–T5); five were between 37 and 50 (F1–F5); and 5 were over 60 years old (O1–O5). The upper and lower whiskers show the 95% confidence intervals for medians. The dots show outliers.

lens placement fell in the linear range of the instrument and demonstrates that data for different viewing distances fall along the same linear function supporting no effect of baseline refractive state or viewing distance on the slope. In addition, we measured anisometropia during the pre-lens placement interval (for the 6 m-viewing distance), which ranged from −1.2 D to 1.2 D (viewing-nonviewing eye). The average anisometropia was −0.12 D (S.E.M. = 0.19). We conclude that the observed anisometropia was not large enough to impact CF.[19]

The CF for each dataset was then computed. The instrument generates its refractive state measurement based on a group average conversion factor for light distribution in the pupil to corrective lens in dioptres. A participant with the same conversion factor would generate calibration data with a slope of 1, as the instrument's calibration would be appropriate for that individual. Any shift from a value of 1 in the slope of the function relating refractive state measurement to true refractive state indicates an individual difference from the group average conversion factor. The individual calibration factor estimates were computed using a linear regression of change in measured anisometropia, between pre lens placement and during lens placement (median of 100 anisometropia samples collected over 2 s), as a function of trial lens power (from −2 D to +4 D). Anisometropia was used to eliminate the impact of any shift in consensual accommodation between lens placements. The mean R^2 for the regression goodness of fit was 0.98, with a minimum of 0.76.

The upper panel of *Figure* 3 shows boxplots of CF as a function of round, with the combined data shown as a black line. The lower panel shows the boxplots rearranged as a function of viewing distance. Data are plotted separately for each participant: five participants in their 20s (T1–T5); five between 37 and 50 (F1–F5); and five over 60 (O1–O5). The overall distribution of calibration factor was normal (Mean = 1.13, S.D. = 0.2) based on the Shapiro-Wilk test ($p = 0.57$), with a peak somewhat different from the default value of 1 ($t(14) = 2.48$, $p = 0.026$).

Figure 3 suggests that, for these data, individual differences may have a larger impact on calibration factor than any effect of viewing distance, age or uncorrected refractive state. The effects of viewing distance was determined after individual differences were accounted for as a random effect in a linear mixed model using the R Project for Statistical Computing (www.r-project.org)[20] package lme4.[21]

$$CF = \alpha + \beta(\text{Viewing Distance}) + \text{random effect for participant.} \quad (1)$$

We compared a model that includes viewing distance as a fixed effect (as in *Equation* 1) with a simpler model that does not include it ($\beta = 0$) using a *chi-squared* test. The

latter simple model assumes a single intercept for the full group and specific intercept for each individual. The former complete model also assumes a fixed effect of viewing distance for the full group.

The effect of viewing distance was not significant in the complete model ($p = 0.26$). The complete model was also not significantly better than the simple model ($p = 0.18$) and the simple model showed that an intercept alone was able to significantly explain the data ($p < 0.001$). The estimated intercept was 1.14 (S.E. = 0.05). This is close to the mean of the CF distribution (1.13), which was, as reported above, significantly larger than 1 ($p = 0.026$) for this sample of participants.

The relationship between CF, pupil size (of the non-viewing eye before lens placement) and age was also examined. We note that the non-viewing eye was occluded with the infrared (IR) filter which could have affected pupil size. *Figure* 4, top-left panel, plots CF as a function of age. A linear mixed model with age (as a continuous covariate) and viewing distance as fixed effects and participant as a random effect showed no effect of viewing distance ($p = 0.13$), age ($p = 0.098$) or their interaction ($p = 0.13$) on CF. Pupil size decreased with age ($p = 0.011$; *Figure* 4 bottom left panel) regardless of viewing distance (no interaction, $p = 0.60$), while CF did not change with pupil size ($p = 0.087$) regardless of viewing distance (no interaction, $p = 0.12$; *Figure* 4 top right panel).
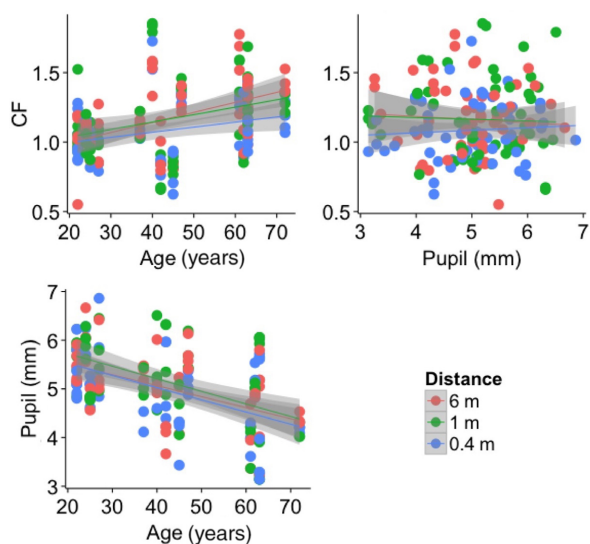

Figure 4. Relationships between calibration factor (CF), age (years) and pupil size (mm). The top panels plot CF as a function of age (top left) and pupil size (top right). The bottom panel plots pupil size as a function of age. Data are broken down for different viewing distances. The shaded area illustrates the 95% confidence interval for the lines that are fit using linear regression to the data for each viewing distance.

Discussion

We measured the calibration factors of adult participants who had prior experience as observers in psychophysical studies. We did not recruit naïve participants because accommodation and vergence responses are more accurate in expert observers[15] and we were interested in any systematic effect of viewing distance on CF. Our study aimed to examine the reliability of the instrument at different distances and not test for naïve vs non-naïve participant effects. We measured CF four times at each viewing distance. The average CF for our population of adults was 1.13 (significantly different from 1). Samples with averages other than 1 have been reported previously[14,15] emphasising the importance of calibration.

We included adult participants across a wide age range to cover a range of accommodative capability and refractive error. Our results did not show an effect of age on the calibration factor. Our participants included a similar range of different ethnicities and skin pigmentation across age, but we did not control for the effect of ethnicity on calibration within our age groups.[22] Although we did not find an effect of age, it is possible that when ethnicity is taken into account, calibration factor could be mediated somewhat by age.

Consistent with previous literature,[23] pupil size reduced with age but was not significantly related to viewing distance. Another way in which age could affect calibration is through accommodative ability. The data presented in *Figure* 2 demonstrated that a change in refractive state resulting from accommodation did not systematically affect the slope of the relationship within the linear operating range of the instrument.

We modulated the defocus of the eyes partly by changing the viewing distance. Using a linear mixed effects model, we assessed the effect of viewing distance on CF. Given that individual differences are reported for CF and observed in our data, we took each individual's mean CF into account as a random factor. In this case there was no reliable systematic effect of viewing distance on CF. The best and simplest significant model included a fixed single value of CF with a random effect of individual, emphasising the importance of considering calibration for each individual. This result is important for studies in which target distance is changed to manipulate accommodation or convergence demand.[5,15]

Data for each viewing distance were collected four times to look at repeatability. Bharadwaj *et al.*[14] looked at the variability of the measured CF across different rounds; the absolute change in CF for both same-day and different-day repetitions had 95% limits of agreement on the order of ±40% of the mean value. This is consistent with the data collected here and, similar to Bharadwaj *et al.*,[14] the range of CF for a given participant did not seem to be related strongly to the average CF for that participant.

In addition to measurement noise across rounds, the measured change in anisometropia could, in theory, be due to real fluctuations in accommodation with a standard deviation of around 0.1–0.3 D[24]; this fluctuation has been noted to increase with accommodative demand.[17,25,26] However, this fluctuation is correlated between the two eyes.[27] Thus, a change in accommodative demand introduced by changing viewing distance should in theory affect fluctuation in accommodation in both eyes similarly. Therefore, accommodative fluctuation should not induce an effect of viewing distance on CF.

In summary, within our experimental paradigm, a calibration function relative to the default calibration of the PowerRef 3 did not seem to be affected by the defocus of the eye, age or target viewing distance, as long as the data were collected within the linear region of PowerRef 3. The results re-emphasise the need for consideration of individual calibration, and also the somewhat limited repeatability of the calibration data.

Acknowledgements

Disclosure

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

References

1. Roorda A, Campbell MC & Bobier WR. Slope-based eccentric photorefraction: theoretical analysis of different light source configurations and effects of ocular aberrations. *J Opt Soc Am A Opt Image Sci Vis* 1997; 14: 2547–2556.

2. Wu Y, Thibos LN & Candy TR. Two-dimensional simulation of eccentric photorefraction images for ametropes: factors influencing the measurement. *Ophthalmic Physiol Opt* 2018; 38: 432–446.

3. Howland HC. Photorefraction of eyes: history and future prospects. *Optom Vis Sci* 2009; 86: 603–606.

4. Anderson HA, Glasser A, Manny RE & Stuebing KK. Age-related changes in accommodative dynamics from preschool to adulthood. *Invest Ophthalmol Vis Sci* 2010; 51: 614–622.

5. Bharadwaj SR & Candy TR. Cues for the control of ocular accommodation and vergence during postnatal human development. *J Vis* 2008; 8: 14.1–16.

6. Choi M, Weiss S, Schaeffel F *et al.* Laboratory, clinical, and kindergarten test of a new eccentric infrared photorefractor (PowerRefractor). *Optom Vis Sci* 2000; 77: 537–548.

7. Horwood AM & Riddell PM. Disparity-driven vs blur-driven models of accommodation and convergence in binocular vision and intermittent strabismus. *J AAPOS* 2014; 18: 576–583.

8. Bharadwaj SR, Wang J & Candy TR. Pupil responses to near visual demand during human visual development. *J Vis* 2011; 11: 6.

9. Horwood AM, Turner JE, Houston SM & Riddell PM. Variations in accommodation and convergence responses in a minimally controlled photorefractive setting. *Optom Vis Sci* 2001; 78: 791–804.

10. Dahlmann-Noor AH, Vrotsou K, Kostakis V *et al.* Vision screening in children by Plusoptix Vision Screener compared with gold-standard orthoptic assessment. *Br J Ophthalmol* 2009; 93: 342–345.

11. Hunt OA, Wolffsohn JS & Gilmartin B. Evaluation of the measurement of refractive error by the PowerRefractor: a remote, continuous and binocular measurement system of oculomotor function. *Br J Ophthalmol* 2003; 87: 1504–1508.

12. Suryakumar R, Kwok D, Fernandez S & Bobier WR. Dynamic photorefraction system: an offline application for the dynamic analysis of ocular focus and pupil size from photorefraction images. *Comput Biol Med* 2009; 39: 195–205.

13. Blade PJ & Candy TR. Validation of the PowerRefractor for measuring human infant refraction. *Optom Vis Sci* 2006; 83: 346–353.

14. Bharadwaj SR, Sravani NG, Little JA *et al.* Empirical variability in the calibration of slope-based eccentric photorefraction. *J Opt Soc Am A Opt Image Sci Vis* 2013; 30: 923–931.

15. Horwood AM & Riddell PM. The use of cues to convergence and accommodation in naive, uninstructed participants. *Vision Res* 2008; 48: 1613–1624.

16. Harb E, Thorn F & Troilo D. Characteristics of accommodative behavior during sustained reading in emmetropes and myopes. *Vision Res* 2006; 46: 2581–2592.

17. Kotulak JC & Schor CM. Temporal variations in accommodation during steady-state conditions. *J Opt Soc Am A* 1986; 3: 223–227.

18. Lopez-Gil N & Fernandez-Sanchez V. The change of spherical aberration during accommodation and its effect on the accommodation response. *J Vis* 2010; 10: 12.

19. Toor S, Horwood AM & Riddell P. Asymmetrical accommodation in hyperopic anisometropic amblyopia. *Br J Ophthalmol* 2018; 102: 772–778.

20. R Development Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing: Vienna, Austria, 2018.

21. Bates D, Machler M, Bolker BM & Walker SC. Fitting linear mixed-effects models using lme4. *J Stat Softw* 2015; 67: 1–48.

22. Sravani NG, Nilagiri VK & Bharadwaj SR. Photorefraction estimates of refractive power varies with the ethnic origin of human eyes. *Sci Rep* 2015; 5: 7976.

23. Birren JE, Casperson RC & Botwinick J. Age changes in pupil size. *J Gerontol* 1950; 5: 216–221.

24. Charman WN & Heron G. Fluctuations in accommodation: a review. *Ophthalmic Physiol Opt* 1988; 8: 153–164.

25. Candy TR & Bharadwaj SR. The stability of steady state accommodation in human infants. *J Vis* 2007; 7: 4.1–16.

26. Miege C & Denieul P. Mean response and oscillations of accommodation for various stimulus vergences in relation to accommodation feedback-control. *Ophthalmic Physiol Opt* 1988; 8: 165–171.

27. Campbell FW. Correlation of accommodation between the 2 eyes. *J Opt Soc Am* 1960; 50: 738.