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Influences of luminance and accommodation stimuli on pupil size and pupil center location

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Abstract

PURPOSE. To investigate effects of luminance and accommodation stimuli on pupil size and pupil center location and their implications for progressive addition lens wear.
METHODS. Participants were young and older adult groups (*n*=20, 22±2 years, age range 18-25 years; *n*=19, 49±4 years, 45-58 years). A wave aberrometer included a relay system to allow a 12.5°x11° background for the internal fixation target. Participants viewed the target under a matrix of conditions with luminance levels 0.01, 3.7, 120 and 6100 cd/m² and with accommodation stimuli up to 6 diopters in 2 diopter steps. Pupil sizes and their centers, relative to limbus centers, were determined from anterior eye images.
RESULTS. With luminance increase, reduction in pupil size was accentuated by increase in accommodation stimulus in the young, but not in the older, group. As luminance increased, pupil center location altered. This was nasally in both groups with an average shift of approximately 0.12mm. Relative to the lowest stimulus condition, the mean of the maximum absolute pupil center shifts was 0.26±0.08mm for both groups with individual shifts up to 0.5mm, findings consistent with previous studies. There was no significant effect of accommodation on pupil center locations for either age group, or evidence that location was influenced by the combination of luminance and accommodation stimulus that resulted in any particular pupil size.
CONCLUSIONS. Variations in luminance and accommodation influence pupil size, but only the former affects pupil center location significantly. Pupil center shifts are too small to be of concern in fitting progressive addition lenses.

Keywords: accommodation, presbyopia, progressive addition lenses, pupil centration, pupil size

INTRODUCTION

The magnitude and the structure of the aberrations of the eye change with pupil diameter, pupil center location and accommodation. Visual performance is closely dependent on these three entities and there are no reports directly quantifying their mutual interactions.

Previous studies have investigated shifts in pupil center location upon changes in pupil size due to illumination changes or to mydriatic drugs.[1-8] Amidst considerable variation between people, generally pupil dilation is accompanied by temporal pupil center shifts. There are different effects between natural and anticholinergic drug-induced dilation[1,4] with the latter showing a tendency for superior shifts, while Porter et al.[5] obtained infero-nasal shifts with the sympathomimetic dilator phenylephrine. The maximum shifts reported are 0.5-0.6 mm. Yang et al.[4] did not find the changes to be related significantly to refraction or to age.

None of these studies considered the effect of accommodation on pupil center location. There are neurological and mechanical influences which might affect pupil center location: pupillary constriction due to accommodation is controlled by area 19 of the visual cortex whereas that due to increase in luminance is controlled by the pretectal nucleus,[9] and during accommodation the crystalline lens thickens and moves forward, causing the iris to be in contact with the protruding anterior lens surface over a greater area.

Pupil position moves inferiorly and nasally relative to a spectacle lens when gaze is shifted from a distant to a near target. Progressive addition lens designs should be optimized for any additional pupil shifts relative to the eye itself. Although likely to be small, such changes influence the eye's optical aberrations and potentially play a significant role in lens acceptability. Mutual interactions between changes in pupil size and center location, optical aberrations and the eye's accommodation will provide important information in understanding the eye's optics and in successful spectacle lens fitting.

This study investigated changes in pupil size and pupil center location due to the influences of luminance and accommodation stimulation, and their implications for progressive addition lens wear.

METHODS

The study complied with the tenets of Declaration of Helsinki and was approved by the University' Human Research Ethics Committee. The participants were staff and students of Queensland University of Technology in good general and ocular health, with tested eyes having best corrected visual acuities ≥ 6/6, subjective spherical equivalent refractions within ±3D, and cylinder ≤ 0.75 D. There were 20 young participants (mean age 22 ± 2 years, age range 18-25 years, spherical equivalent –1.45 D ± 0.94 D) and 19 older participants (mean age 49 ± 4 years, age range 45-58 years, spherical equivalent –1.80 D ± 1.56 D).

The experiment was performed with room lights off and the non-tested eyes occluded. Measurements were done on right eyes, except that left eyes were used when right eye visual acuity was poorer than 6/6 (2 cases) or refraction was < –3 D (1 case). No refractive correction or eye drops were used.

Pupil images and wave aberrations were measured with a modified COAS-HD Hartmann-Shack aberrometer (Wavefront Sciences Inc., USA). In its usual operation, the internal target of the aberrometer is fogged automatically by about 1.5 D. However, the position of the internal target can be controlled manually by changing the "slider" value in the COAS-HD program. In order to estimate the slider value for a given accommodative demand a calibration procedure was performed. A telescope focused for distance by one of the authors was placed with its objective at the usual eye position. Trial lenses ranging from –6.50 D to +8.00 D power in 0.50 D steps were placed in front of the objective and the slider value was adjusted so that the internal target was in focus. The sign of the lens power was then changed to simulate refraction. A second order fit was performed to determine the relationship between the refraction and slider position. The refraction is *mean spherical equivalent refraction – accommodation stimulus*. Mean spherical equivalent refraction was determined from the automatic slider position mode of the instrument, averaging 3 spherical equivalent refractions for a 4 mm pupil, using 2nd and 4th order Zernike aberration terms.

Participants placed their heads on the aberrometer's chin rest and fixated the white internal target through an optical relay system that provided a wide field of view.[10] The internal target provided the accommodative stimulus. There were 4 background luminance levels (level 1 0.01 cd/m², level 2 3.7 cd/m², level 3 120 cd/m² and level 4 6100 cd/m²) and up to 4 accommodation stimulus levels (0, 2, 4 and 6 D). Luminance was measured with a Topcon BM-7A luminance colorimeter (Topcon Corporation, Japan). Internal target luminance was increased as background luminance increased so that the participants were able to focus easily on the internal target in the presence of the glare due to the background. The luminances of the internal target were 0.01, 0.8, 3.7 and 52 cd/m² for luminance levels 1, 2, 3, and 4, respectively.

Powerpoint slides were projected from an LCD projector (Epson EMP-1810) onto a rear projection screen, 1.8 m from the eye, that was viewed though the relay system. The projected slides formed 12.5° horizontal x 11° vertical white backgrounds for the target (Figure 1). Luminance level 1 was produced using the internal target only, luminance level 2 was produced with a Kodak ND-1 gelatin filter in front of the projector, and luminance levels 3 and 4 were produced by altering slide brightness without the filter. To make the internal target visible against the background, a black square of cardboard (2.5° subtense) was placed on the screen.

All luminance levels were used for a given accommodation stimulus before proceeding to a higher accommodation stimulus. Three measurements were taken for each luminance-accommodation stimulus combination. Accommodation stimuli increased until participants reported that the target could no longer be made to appear clear, up to a maximum of 6D.

The eye images were analyzed using ImageJ (developed by Wayne Rasband, National Institutes of Health, available at http://rsbweb.nih.gov/ij/index.html). An algorithm fitted a rotated ellipse using the least squares method to 8 user selected points across each of the limbus and pupillary margins. The algorithm estimated *x*, *y* coordinates of the pupil center relative to the limbus center. Signs of pupil center location were corrected to account for the image rotation due to the relay system and for the left and right eyes. Nasal and superior pupil center locations were taken as positive.

Analysis for the young and older groups was done up to 6 D and 4 D accommodation stimuli, respectively. As two young participants could not see the 6D stimulus clearly and 7 older participants could not see the 4D stimulus clearly, missing value analysis was done using a regression model with IBM SPSS package (IBM Corporation, USA). Repeated measures analysis of variance was used to investigate effects of luminance and accommodation on pupil diameter and pupil center location (separately in horizontal and vertical directions) for each age group. Post-hoc t-tests with Bonferroni correction, to compensate for multiple pairwise comparisons, compared the different luminance or accommodation stimulus conditions.

Apart from absolute shifts, where mean changes in pupil size or pupil center location between conditions are given in the text and figures, these include only participants who could be compared across all conditions i.e. 18/20 and 12/19 participants in the young and older groups, respectively.

RESULTS

Pupil Size

Figure 2 shows pupil diameters at each accommodation stimulus for the 4 luminance levels. The maximum mean changes in pupil diameter across the luminance-accommodation stimulus combinations were 3.8 mm for the young group (comparing luminance level 1 - 0D accommodation stimulus combination with luminance level 4 – 6D accommodation stimulus combination) and 2.6 mm for the older group (comparing luminance level 1 - 0D accommodation stimulus combination with luminance level 4 – 4D accommodation stimulus combination). This shows pupil constriction with increase in luminance ($F_{15, 19} = 236$, $p < 0.001$ for the young group and $F_{11, 18} = 58$, $p < 0.001$ for the older group), with all but one pair-wise comparison of luminance levels being significant. Also, the pupil size became smaller with increase in accommodation stimulus for the young group ($F_{15, 19} = 30$, $p < 0.001$), with all pair-wise comparisons of stimuli being significant. For the older group, there was no significant change of pupil size with accommodation ($p = 0.12$).

Pupil Center Location

Relative to the luminance 1 – 0D accommodation stimulus combination, the mean of the maximum absolute pupil center shifts were 0.20 ± 0.09 mm horizontally and 0.18 ± 0.05 mm vertically for the young group, and 0.17 ± 0.05 mm horizontally and 0.22 ± 0.10 mm vertically for the older group. Combining the horizontal and vertical shifts, the mean of the participants' maximum absolute pupil center shifts were 0.26 ± 0.08 mm for both groups.

Figure 3 shows the pupil center locations at each accommodation stimulus for the 4 luminance levels. The trend is for shift in the nasal direction as luminance increased, with mean shift from the lowest to the highest stimulus combination of +0.11 ± 0.14 mm and 0.12 ± 0.09 mm for the young and older groups, respectively. Luminance affected pupil center location significantly in the horizontal direction only ($F_{15,19} = 20$, $p < 0.001$ for young group and $F_{11, 18} = 15$, $p < 0.001$ for older group), with luminance levels 3 and 4 being significantly different from level 1 for both groups. There was no significant effect of accommodation stimulus for either age group either horizontally or vertically.

Although the mean pupil center shifted little with variations in effects of luminance and accommodation stimulus (Figures 3), there were substantial shifts for some participants. Sixteen of the young participants and thirteen of the older participants had absolute pupil center shifts ≥ 0.2 mm relative to the luminance level 1 - 0D accommodation stimulus combination (Figure 4). One young participant had 0.50 mm nasal and 0.06 mm superior shifts accompanying 2.4 mm pupil constriction from luminance level 1 - accommodation 0D combination to luminance level 4 – accommodation 6D combination (Figure 5).

Pupil size and pupil center interaction

Figure 6 shows pupil center locations as a function of pupil diameter for each participant. Pupil center shifted significantly in the nasal direction (positive shift) with decrease in pupil size, with rates of change of –0.022 mm/mm and –0.039 mm/mm for young and older groups, respectively. The young group also showed significant inferior shift at the rate of –0.013 mm/mm with increase in pupil size.

Figure 7 is similar to Figure 6, but does not distinguish between luminance levels, excludes the participants reporting blur of the highest accommodation stimulus, and has regressions for the different accommodation conditions. Evidence for different interactions of pupil center location with pupil size, at different accommodation conditions, would be shown by different heights or slopes of the regressions. Analysis by t-tests shows no such significance, so it appears that the interactions do not vary with accommodation. This means that the pupil center location for any pupil size does not appear to be influenced by the combination of luminance and accommodation used to produce the pupil size, at least for the conditions of the study.

DISCUSSION

We investigated effects of luminance and accommodation stimulus on pupil size and location. As luminance increased, the expected reduction[11,12] in pupil size occurred. This was accentuated by increase in accommodation stimulus in a young adult group, but not in an older adult group. As luminance increased, the pupil center shifted. This was nasally in both subject groups with an average nasal shift of approximately 0.12 mm and considerable variation between participants with individual shifts up to 0.5 mm, findings consistent with previous studies.[1-5,8] It is interesting that similar nasal shifts occurred for the two groups despite the younger group having a larger range of pupil sizes (e.g. mean range 3.7 mm compared with 2.5 mm for the older group in Figure 2).

New findings are that there was no significant effect of accommodation on pupil center locations for either age group, and that there was no evidence that the location was influenced by the combination of luminance and accommodation stimulus that resulted in any particular pupil size.

It is likely that greater pupil center shifts could have been obtained if we had been able to obtain a larger range of pupil sizes. Smaller pupils could have been achieved by higher luminances or a larger field.[13,14] Watson & Yellott's "unified" pupil size program[12] predicts that pupil size at 6100 cd/m^2 and 22 years decreases from 3.5 mm for a 12° diameter field (mean 3.3±0. mm for our young group for zero accommodation stimulus) to 2.4 mm for a 90° field; the slope of –0.02 mm horizontal decentration/mm change in pupil diameter in Figure 7Aa indicating a further (+) 0.02 mm shift in the nasal direction is likely. Similarly, they predicted pupil size at 6100 cd/m^2 and 49 years decreases from 3.2 mm for a 12° diameter field (3..5 mm for our older group) to 2.3 mm for a 90° field, with the slope of –0.03

mm/mm in Figure 7Ba indicating a further (+)0.03 mm nasal shift. Other studies using natural pupils[2-4,6] were also restricted, at least at the small end of the pupil size range, and otherwise might have shown greater pupil center shifts.

The limited extent to which participants responded to the accommodative stimuli may have been responsible for the limited significant effect of accommodation on pupil size (significant for young group only) and the lack of significance on pupil decentration. Changes in refraction for maximum stimuli level are shown in Figure 8 and it is clear that accommodation response was poor in nearly half the young participants and in all the older participants despite them reporting that the target was clear.

As well as the limitations referred to above concerning the limited ranges of pupil sizes and accommodation responses, the other main limitation of this study was the small number of only older subjects (12/19) reporting being able to see the 4 D stimulus clearly and thus complicating the analyses.

In fitting progressive addition lenses, distance and near reference locations are located. Distance reference points may be measured with the eyes looking straight ahead. The near reference locations are determined from this, usually by assuming them to be at particular settings on the lens relative to the distance reference locations. Alternatively the near reference locations are measured and the distance reference points are derived, or there is some combination of near monocular pupillary distances and distance fitting heights. The measurements are made without any consideration of possible pupil center shifts accompanying luminance and accommodation changes. In the usual clinical setting, lighting levels are likely to be low photopic and without providing a strong stimulus to accommodation. Assuming that both eyes behave similarly with changes in luminance and accommodation, the average effects on pupil center separation under different conditions are likely to be about 0.2 mm, but with the possibility that this might be up to 1.0 mm in a small proportion of cases e.g. 1/39 eyes in our study. It does not seem that pupil center shifts should be of concern in the use of progressive addition lenses.

Acknowledgements

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Figure Captions

Figure 1. Appearance of COAS-HD internal target and background.

Figure 2. Mean pupil diameter with accommodation stimulus as a function of background luminance for (A) young and (B) older groups. This includes only the participants who reported that the target was clear at the highest accommodation stimulus (19 in young group, 12 in older group). The "*" represents significant effect of luminance levels on pupil diameter compared with luminance condition 1. The "#" represents significant effect of accommodation stimulus on pupil diameter compared with O D accommodation stimulus. The error bars are standard deviations. "Acc" represents the accommodation stimulus.

Figure 3. Mean pupil center location with accommodation stimulus as a function of background luminance for (A) young and (B) older groups along the (a) horizontal and (b) vertical meridians for all the luminance accommodation-stimulus combinations. This figure includes only the participants who reported that the target was clear at the highest accommodation stimulus (19 in young group, 12 in older group). Pupil centers are relative to limbus centers, with positive values indicating nasal/superior locations. The "*" represent significant effect of luminance levels on pupil center location compared with luminance condition 1.The error bars are standard deviations.

Figure 4. Pupil center shifts from the lowest luminance-accommodation stimulus combination to the highest luminance-accommodation stimulus combination, for (A) young and (B) older groups. This figure includes only the participants who reported that the target was clear at the highest accommodation stimulus (19 in young group, 12 in older group).

Black crosses show mean pupil center shifts and the other symbols represent individual participants.

Figure 5. Pupil size and pupil center location of one participant’s left eye for (a) luminance level 1 and 0D accommodation stimulus combination, and (b) luminance level 4 and 6D accommodation stimulus combination.

Figure 6. Pupil center location as a function of pupil size for (A) young and (B) older groups along (a) horizontal and (b) vertical meridians. This figure includes all participants. Solid lines are regressions, for which the statistics are given in the legend, and the dotted lines represent 95% confidence intervals of the regressions. Positive values correspond to nasal and superior locations. Symbols represent different accommodation-luminance conditions. L1A0 represents luminance level 1 and 0D accommodation stimulus, and so on.

Figure 7. Pupil center location as a function of pupil size for (A) young and (B) older groups along (a) horizontal and (b) vertical meridians. This figure includes only participants who reported that the target was clear at the highest accommodation stimulus (19 in young group, 12 in older group). Regressions are shown for each accommodation stimulus. For accommodation stimulus 0D, the 95% confidence limits of the regression are also shown.

Figure 8. Accommodation responses for young and older subjects in response to 6 D and 4 D accommodation stimuli, respectively. Response has been determined from differences in spherical equivalent refraction, derived from average defocus aberration coefficients at 3 mm pupils, between 0D accommodation stimulus and the high accommodation stimulus. Luminance level 1 was used for the low accommodation stimulus and luminance level 4 was

used for the high accommodation stimulus. Only participants who reported that the target was clear at these stimuli are included.

Figures

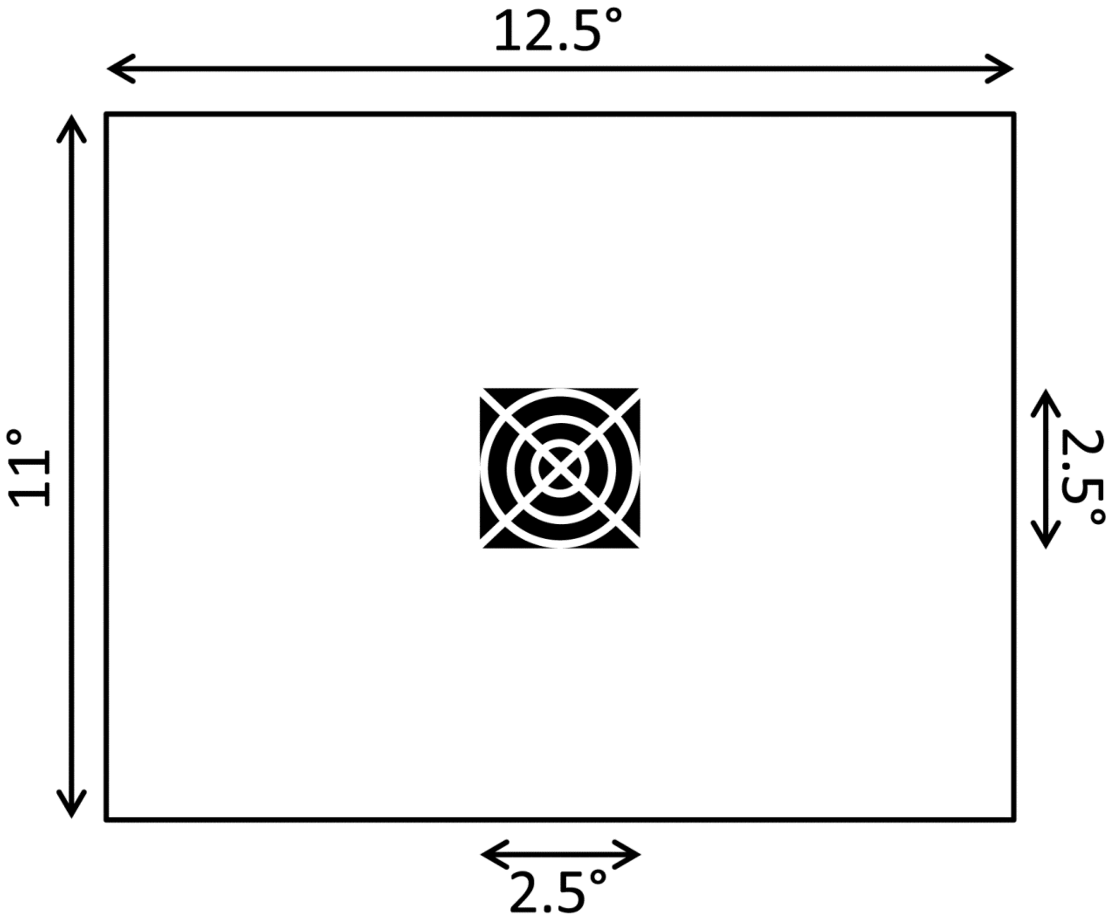

Figure 1

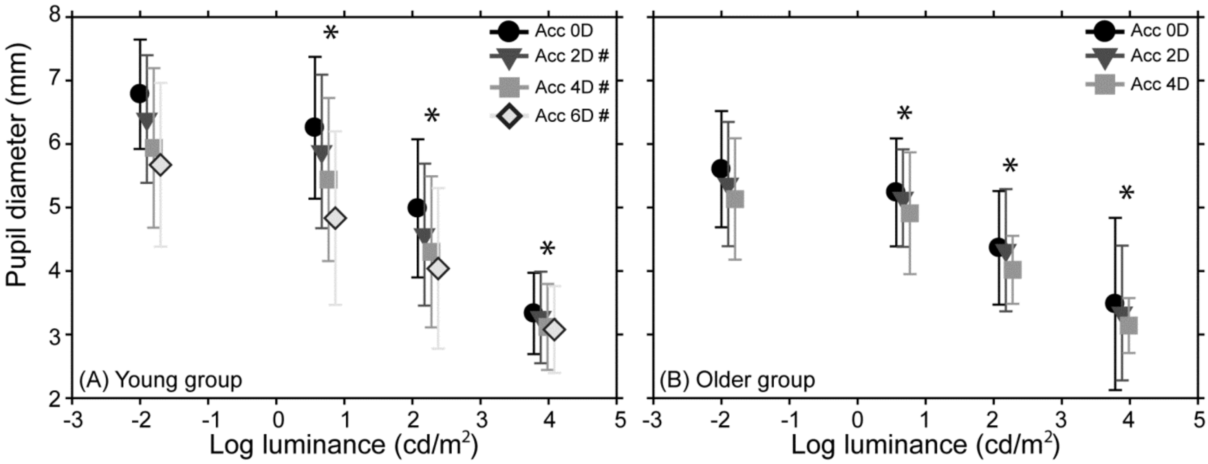

Figure 2.

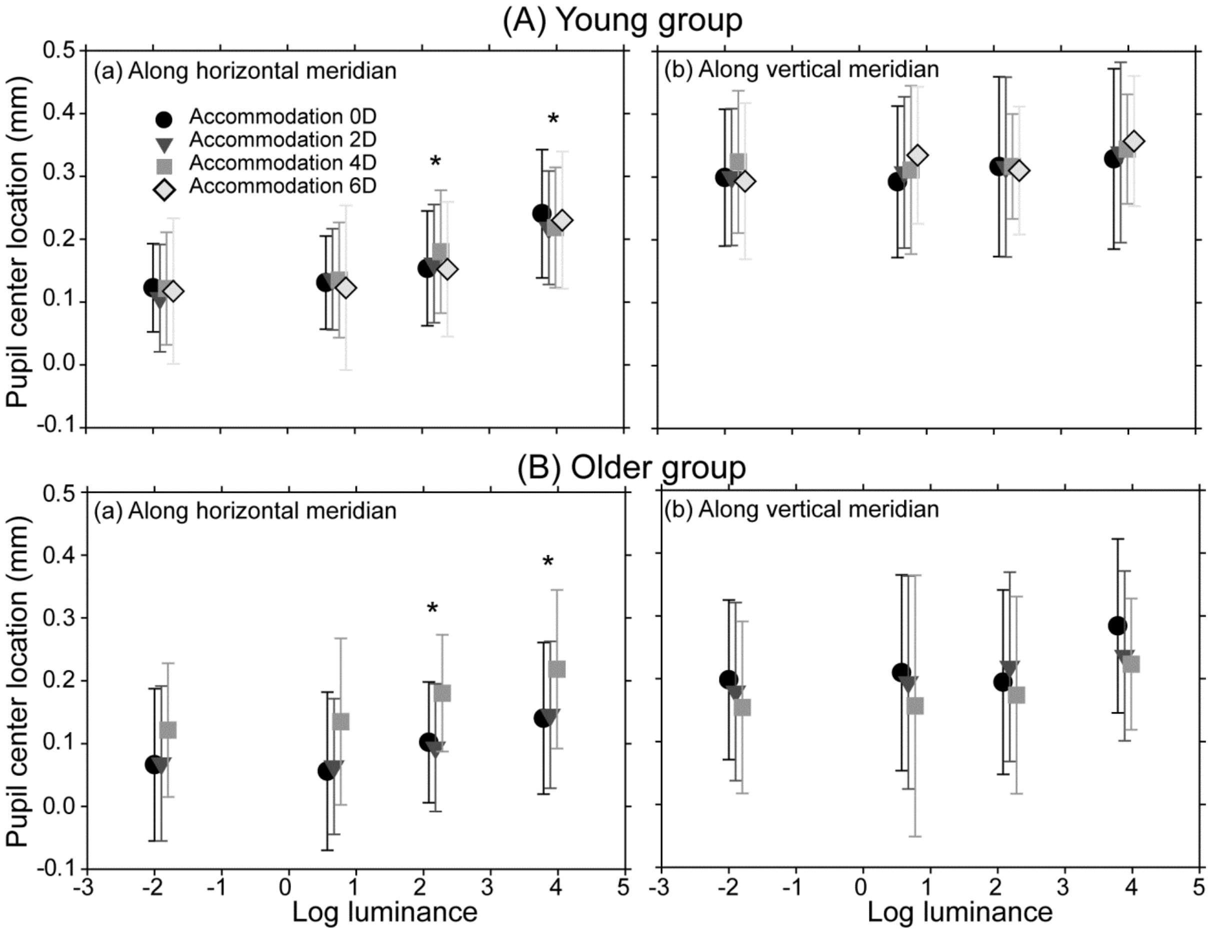

Figure 3

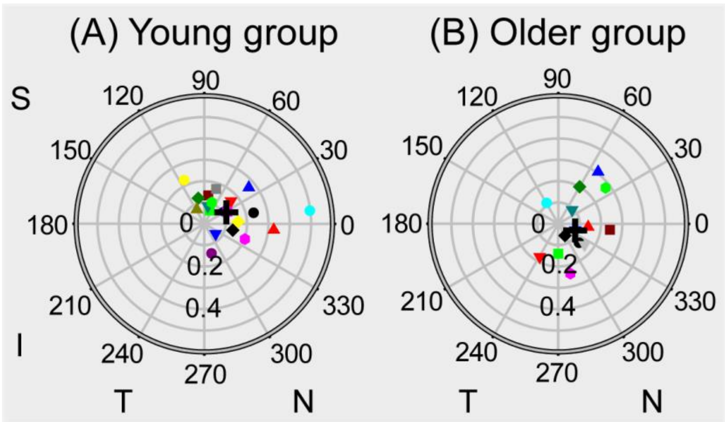

Figure 4

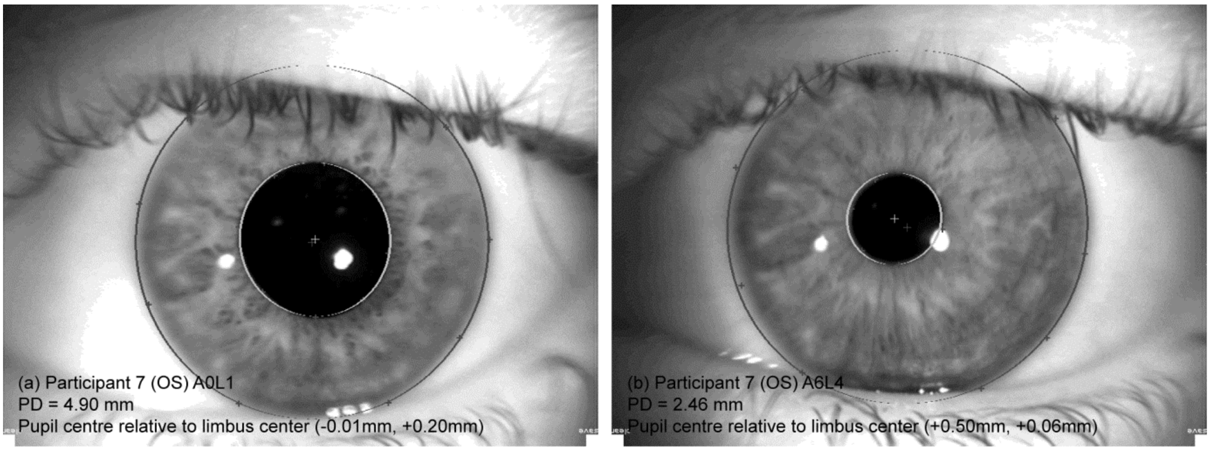

Figure 5

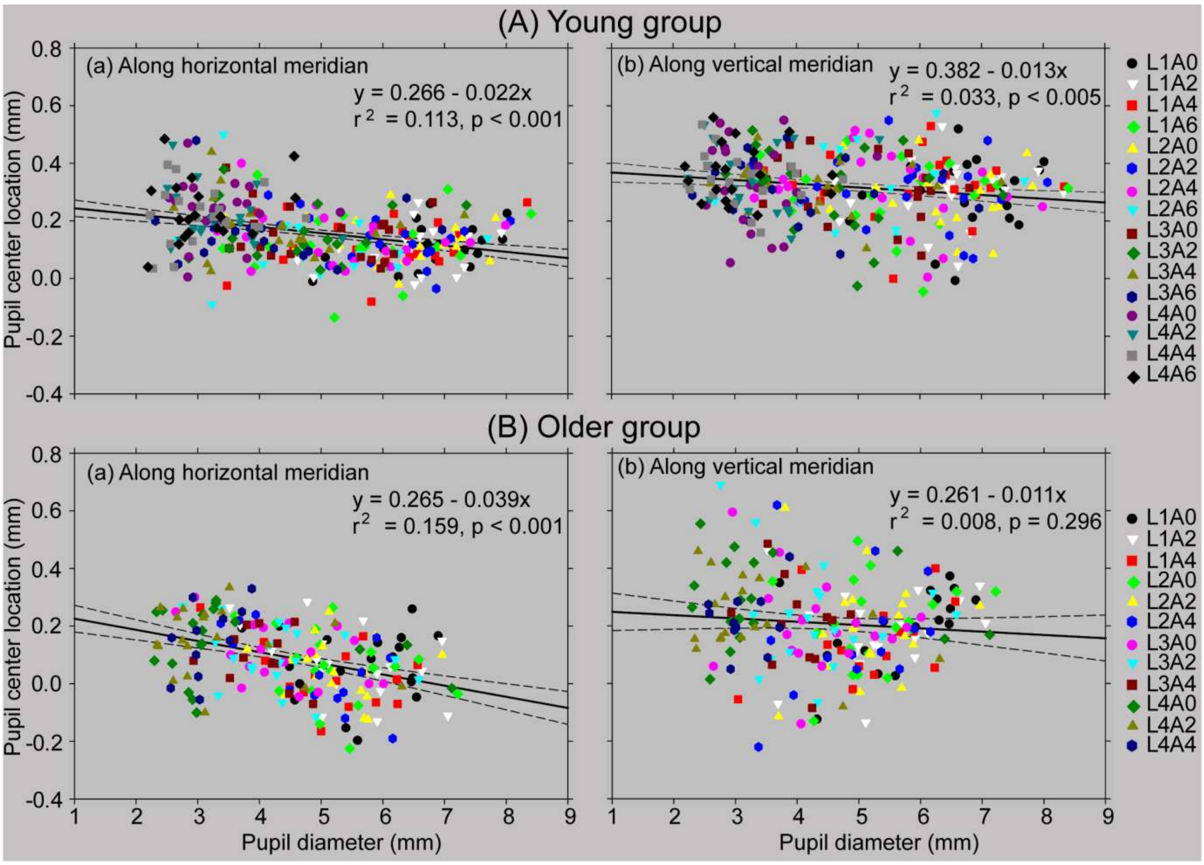

Figure 6

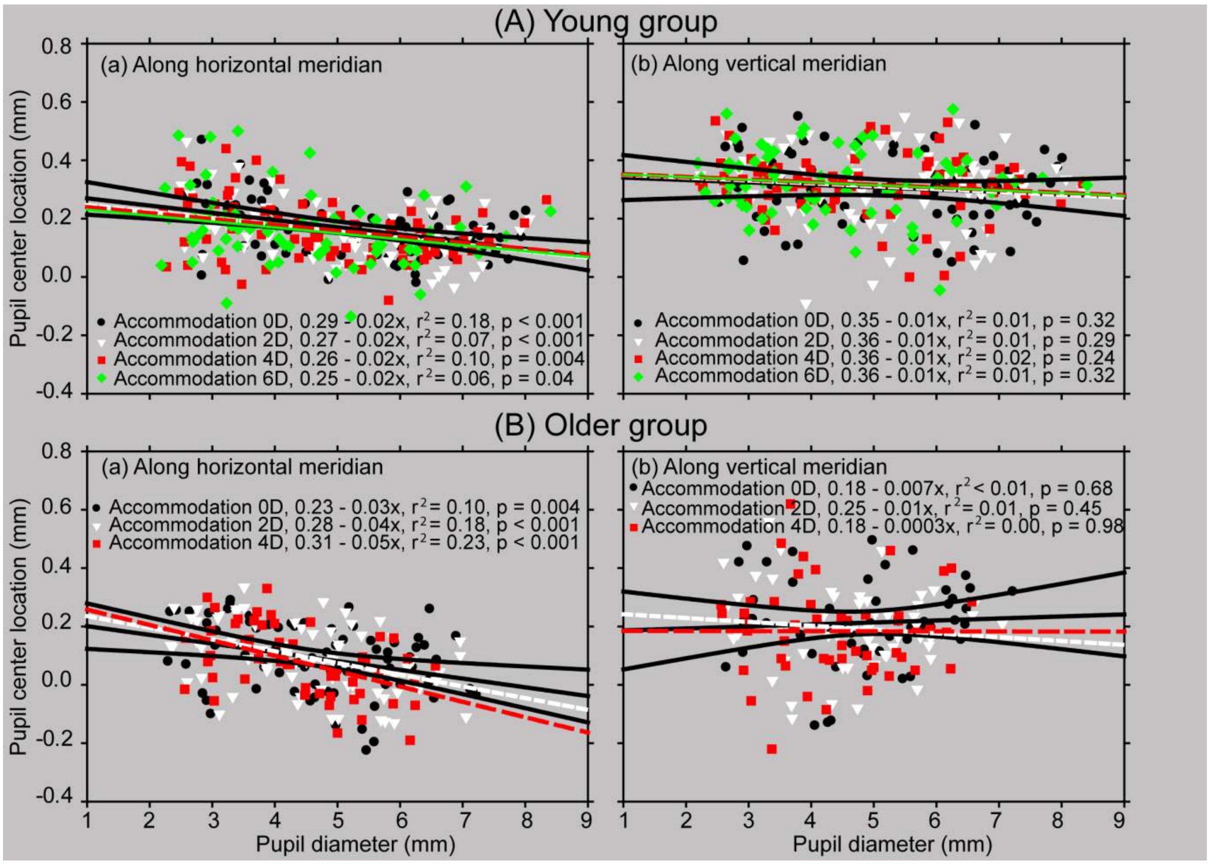

Figure 7

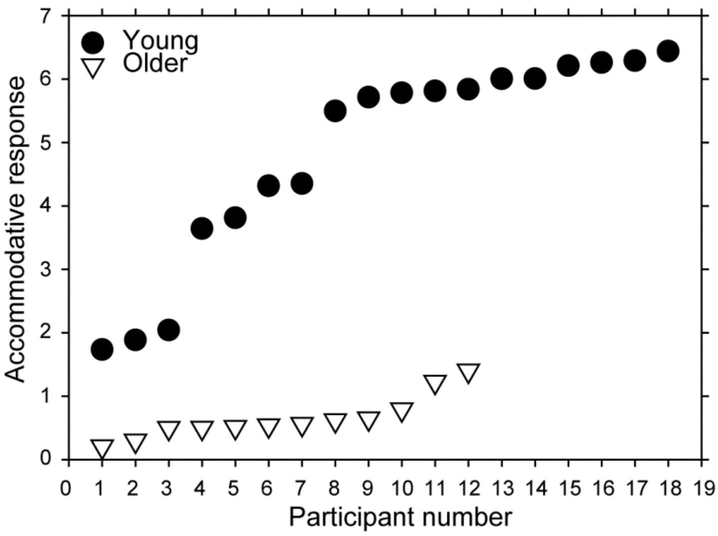

Figure 8