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Monocular foveal, parafoveal and perifoveal accommodation response to random defocus step changes

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ABSTRACT

Accommodation of the human eye relies on multiple factors, including – object size, monochromatic and chromatic aberrations, and vergence, and corrects defocus even in monocular conditions. Previous studies have been done to understand whether the retina can decode the sign of defocus as this may play a role for emmetropization and possibly also accommodation. Yet, findings have not been unambiguous and questions remain. Thus, in this study we tried to understand how accommodation makes use of defocus blur to detect the sign of defocus by performing experiments using a fast wavefront sensor in a vision testing system while eliminating other visual cues that may otherwise confound the analysis. A new automated method has been introduced to study monocular accommodation by using a current-driven tunable lens (TL) to induce a random sequence of defocus step changes within the accommodative range of each observer. The response was captured in real time using a Hartmann-Shack wavefront sensor (HS-WFS) operating at 20 Hz while detecting aberrations and Zernike coefficients until 4th radial order across a 3 mm limited pupil. Foveal, parafoveal and perifoveal accommodation has been studied for young emmetropes and myopes to determine until which eccentricity accommodation is triggered. Our findings show that the accommodative range diminishes with eccentricity and at 14° (diameter) and beyond it becomes largely absent.

Keywords: Accommodation, Sign of Defocus, Aberrations, Wavefront sensor, Tunable lens, Emmetropization, Myopia.

1. INTRODUCTION

Accommodation describes changes in optical power of each eye due to changes in thickness and curvature of the crystalline lens when viewing objects at different distances. Within each eye, images are ideally formed in the plane of the retina. When the imaging light is focused in front of the retina, the eye is overpowered resulting in positive defocus (myopic blur). In turn, if the light is focused behind the retina, the eye is underpowered resulting in negative defocus (hyperopic blur). The blur of the point-spread-function (PSF) is symmetric with defocus but yet the eye can accommodate[1]. Understanding the detailed optics related to accommodation is important not only to determine how it operates but also to understand what controls emmetropization of the developing eye where similar or identical optical mechanisms may be involved.

The accommodative response is mainly driven by foveal vision but reacts also to off-foveal stimuli. The macula can be divided into different regions with regard to retinal eccentricity: fovea (central 5° ≈ 1.5 mm), parafovea (8° ≈ 2.5 mm) and perifovea (18° ≈ 5.5 mm). The fovea is a tiny depression in the retina and, within it, the central 1° ≈ 300 μm foveola has the highest density of cones and no rods are present[2]. This region provides the highest visual acuity of the eye. The parafovea and perifovea denote the zones surrounding the fovea. Here, the visual acuity is lower in part due to a reduction in cone density[3] with distance from the fovea. In the parafovea and perifovea, the rod-to-cone ratios change approximately from 4:1 to 130:1. The ganglion cell density increases first with distance from the foveola to reach its highest value of approximately 38,000 ganglion cells/mm^2 (4 ganglion cells per cone) at approximately 5° beyond which it gradually decreases in accord with the density of cones[4]. Outside of the macula the zone is known as the peripheral retina. Previous studies found that the accommodative response have a linear drop-off with higher eccentricities for emmetropes and myopes[5-7] though few facts are still not clear about accommodation response time with higher eccentricities and in which eccentricity the eye totally looses following the correct direction. The study of parafoveal accommodation is not only of fundamental interest but also related to people with central vision loss who are dependent on parafoveal vision[8,9]. Furthermore, peripheral optics of the human eye are believed to play a role in emmetropization of the eye and thus understanding the sensitivity to defocus at different eccentricities, and the corresponding effect on accommodation, may provide vital insight into mechanisms that can stimulate eye growth and myopia[10]. In this study we examine whether human volunteers are capable of accommodating in the correct direction for foveal and off-foveal stimuli in monocular conditions when subject to varying amounts of positive and negative defocus with respect to a fixed viewing distance through a variable focus tunable lens.

2. EXPERIMENTAL SETUP AND METHODS

A monocular vision system has been designed to study foveal, parafoveal and parafoveal accommodation as shown schematically in Figure 1. A current-driven tunable lens (Optotune EL-16-40-TC-VIS-5D-C) was mounted in a conjugate pupil plane to make random changes of negative defocus. The sequence of defocus steps was a random pattern that was chosen to avoid that subjects would memorize the expected response. The same sequence was used for each subject scaled to his/her comfortable accommodative range. Subjects viewed a green Maltese Cross target covering 0.86° of visual angle for most central vision (1°)[11] and annular targets (one at a time) made with nine different diameter of the annular target, viz., 2, 4, 6, 8, 10, 12, 14, 15, and 16° for foveal, parafoveal and perifoveal measurements. In both cases, the targets were displayed on a computer screen placed at 1-meter distance but different lenses were used for 1st and 2nd 4-f system. Measurements were subsequently repeated with green light targets to rule out chromatic clues. The TL was evaluated with the HS-WFS in a single-pass setup separately from the accommodative studies, and it was confirmed that in all cases defocus changes were dominant as other Zernike coefficients (mostly coma and astigmatism) accounted for less than 0.2% of the total change[11].

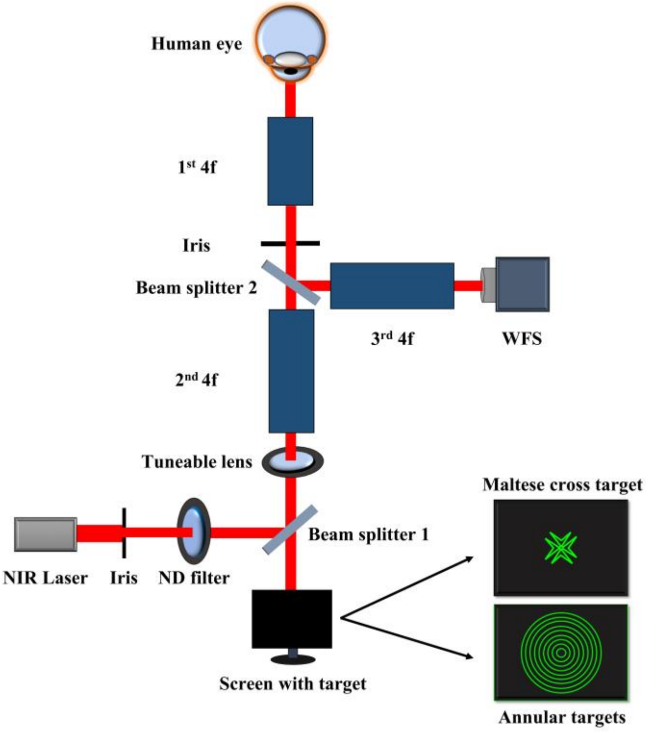

Figure 1. Schematic of the monocular vision system used to measure foveal, parafoveal ad perifoveal accommodative response as a function of defocus. Three 4-f telescopic systems were used to map the iris, HS-WFS and TL onto the pupil plane of the eye. Beam splitter 1 is a hot mirror whereas beam splitter 2 is a 50/50 coated plate.

During measurements, the tunable lens induced random focal changes every 10 sec. within a limited power range (set by the age-dependent accommodative range of each subject) resulting in an accommodative response. The ocular aberrations are sensed with a near-IR (850 nm) laser diode and a Hartmann-Shack wavefront sensor (Thorlabs WFS20-5C) mounted in a conjugate pupil plane operating at approximately 20 Hz. The TL, the iris, and the HS-WFS were all mounted in conjugated pupil planes and the entire system computer controlled via a LabVIEW (National Instruments^{TM}) program. Each data collection session lasted up to 110 sec. The natural pupil size has been truncated by an iris to fixed 3 mm pupil for all cases. The wavefront sensor captures the aberrations up to the 4th Zernike order at 20 Hz. The right eye of 3 emmetropic and 3 myopic subjects aged 23 – 34 years was measured and analyzed, while the left eye was covered with a patch. All had healthy eyes (no known conditions) and myopic subjects wore their spectacle glasses during measurements.

The study has been approved by the UCD Human Research Ethics Committee – Sciences and performed in accordance with the declaration of Helsinki involving human subjects. The subjects were not dilated but the room was dark to ensure a sufficiently large natural pupil. The left eye was occluded with a patch. To limit unwanted head motion, subjects used a bite-bar while gazing in the central direction (guided by the central IR laser dot). The participants took short breaks (5 to 7 min.) between measurement iterations to relax.

3. EXPERIMENTAL RESULTS

In the presented experimental data, blinks were removed numerically by using Matlab^{TM} data processing and the defocus values were calculated from the second-order Zernike coefficient C20. Figure 2(a) and Figure 2(b) shows the recorded accommodative response to the random defocus step changes for emmetropic and myopic subjects #1 and #5, respectively. For all of the observers, the response followed the defocus changes closely during both accommodation and relaxation at foveal vision 2° and 4°. From 6° eccentricity, accommodation and relaxation still followed the correct direction but with a reduced response with higher eccentricities, e.g., 8°, 10 ° and 12° as also reported by others[7,12,13]. At 14° eccentricity and beyond the eye was not able to follow the induced defocus changes anymore and the accommodative response becomes negligible. One extra step (15°) between 14° and 16° eccentricity was taken to monitor the accommodative response closely at the point where the eye looses track on the induced defocus correction.

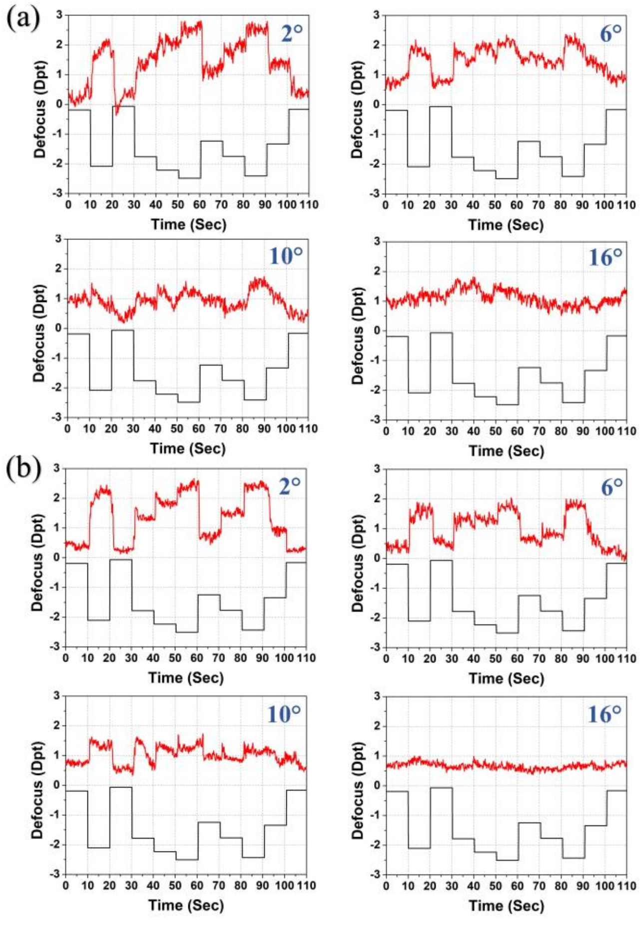

Figure 2. Induced defocus sequence by the TL (black line) and accommodation response of the eye (red line) as a function of time for emmetropic and myopic subject (a) #2 and (b) #5 for increasing eccentricity from 2° to 16° (only selected angles of 2, 6, 10 and 16° are shown).

Figure 3 shows the mean accommodative response determined for the interval 11 - 19 sec. for all subjects as a function of stimuli eccentricity for all subjects. In that time interval, the induced defocus range was between -1.16 and -2.10 diopters depending on the individual. The accommodative response decreases with higher eccentricity, though some variations are noticeable, e.g., for subjects #2 and #3, at 6° eccentricity defocus went up compared to 4° and in case of myopic subject #6, more variations were noticed at 8°, 12° and 15°, which can be due to overshooting of accommodation. It is important to note that the accommodative range is different for each subject, and that the initial starting points are therefore different. Further analysis shows that the accommodation response time increases with eccentricity and that defocus is the most dominant Zernike coefficient whereas the contributions of astigmatism, spherical aberration and coma are largely negligible.

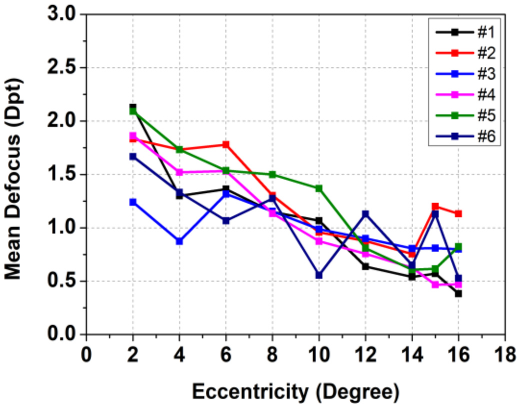

Figure 3. Mean accommodative response as a function of eccentricity for all 6 subjects at time interval 11 – 19 sec. when the induced defocus by the TL was -1.98, -2.08, -1.16, -1.93, -2.10, and -1.87 diopters, respectively, for Subjects #1 – #6.

4. CONCLUSION

This study shows an automated monocular accommodation measurement process with Maltese Cross target projected on the most central (1°) vision and annular stimuli projected on the foveal, parafovea and the perifovea in response to random step defocus changes induced by a current-driven tunable lens. At the fovea, accommodation compensated the induced defocus (almost completely; not shown in the results for 1°) and the amplitude decreased gradually with higher eccentricity and became negligible at 14° diameter distance and beyond. Moreover, it was also found that the accommodative response time increases gradually with increasing eccentricity. For a 3 mm limited eye pupil, defocus was found to be the most dominating Zernike coefficient while no significant contribution from higher-order aberrations were noticed which agrees well with previous findings[11]. It is possible that there is a link between the reduced amplitude of accommodation with increased eccentricity and the reduction in cone density resulting a contrast reduction for the light leakage from the outer segment. There was no significant difference in accommodative response was found between the emmetropes and myopes which agrees with previous studies[14,15] and all 6 subjects showed a similar tendency for the foveal and non-foveal accommodation. We are currently exploring in more depth the optical factors that may trigger or impact the accommodative response for both foveal and parafoveal vision.

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