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Dynamic accommodation with simulated targets blurred with high order aberrations

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ABSTRACT

High order aberrations have been suggested to play a role in determining the direction of accommodation. We have explored the effect of retinal blur induced by high order aberrations on dynamic accommodation by measuring the accommodative response to sinusoidal variations in accommodative demand (1–3D). The targets were blurred with 0.3 and 1 μm (for a 3-mm pupil) of defocus, coma, trefoil and spherical aberration. Accommodative gain decreased significantly when 1-μm of aberration was induced. We found a strong correlation between the relative accommodative gain (and phase lag) and the contrast degradation imposed on the target at relevant spatial frequencies.

1. Introduction

It is well known that the human eye has the ability to focus both near and far targets by changing its crystalline lens geometry. However, the mechanisms that drive accommodation (i.e. how the visual system knows the correct direction to accommodate) are not completely understood. Binocular vision, chromatic light, and subjective cues, such as stimulus size, could explain accommodation in many circumstances but, even in their absence, the human eye is able to accommodate.

The potential role of ocular aberrations as an optical cue to determine the direction of accommodation has been investigated. As different wavelengths are focused in different planes, several works have explored the role of longitudinal chromatic aberration in reflex accommodation (Aggarwala, Kruger, Mathews, & Kruger, 1995; Aggarwala, Nowbotsing, & Kruger, 1995; Fincham, 1951; Kotulak, Morse, & Billock, 1995; Kruger, Aggarwala, Bean, & Mathews, 1997; Kruger, Mathews, Aggarwala, & Sanchez, 1993; Kruger, Nowbotsing, Aggarwala, & Mathews, 1995; Kruger & Pola, 1986; Lee, Stark, Cohen, & Kruger, 1999; Stark, Lee, Kruger, Rucker, & Fan, 2002). Lee et al. (1999) showed that chromatic aberration drives accommodation to both moving and stationary objects. However, Kruger et al. (1997) suggested the existence of other achromatic cues driving reflex accommodation, as some individuals were able to accommodate in the absence of chromatic aberration.

Monochromatic high order aberrations (HOA) have also been suggested to play a role in determining the direction of accommodation (Charman & Tucker, 1977; Walsh & Charman, 1989). Theoretical studies (Wilson, Decker, & Roorda, 2002) demonstrated that the combination of HOA with defocus results in different PSFs depending on the sign of the defocus, suggesting that the visual system could determine the correct direction of focus shift based on those differences. Fernández and Artal (2005), and Chen, Kruger, Hofer, Singer, and Williams (2006) have used Adaptive Optics to correct aberrations and to study how the absence of specific types of aberrations may affect the response time after a small change in vergence. However, inconclusive results have arisen from these experiments: Fernández and Artal (2005) found a significant and systematic increase in two subjects in the accommodation response time and a decrease in response velocity when asymmetric aberrations (astigmatism and third order terms) were corrected in real time. However, Chen et al. (2006) did not find a systematic trend in response time when aberrations were corrected, nor in gain.

Alternatively, other studies tested the accommodative response with induced aberrations. López-Gil et al. (2007) studied the accommodative response in subjects wearing contact lenses that induced low and high values of third order aberrations and found a decrease in gain when around 1 μm (for a 5 mm pupil) of coma or trefoil was induced, which approached but not reached statistical significance, suggesting that 3rd order aberrations may not play a major role in the dynamics of the accommodation response. More recently, Stark et al. (2009) simulated targets using the subject's own monochromatic high order aberrations and Stiles–Crawford apodization functions in combination with positive or negative defocus to assess their potential cue on accommodation. They found that monochromatic aberrations provided a statistically significant but rather small cue to monocular accommodation.

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In a recent study, we used a custom-developed Adaptive Optics system (Gambra, Sawides, Dorronsoro, Llorente, & Marcos, 2007; Marcos, Sawides, Gambra, & Dorronsoro, 2008) to measure the accommodative response (to accommodative demands increasing from 0 to 6D following a staircase function) in young subjects to corrected or induced aberrations (Gambra, Sawides, Dorronsoro, & Marcos, 2009). We found that the absence of HOA made the accommodative response more accurate (less accommodative lag to higher accommodative demands), while inducing HOA such as -2 μm of vertical coma for 6-mm pupil decreased the accommodative response (i.e. increased the accommodative lag). The interactions of the accommodation-induced spherical aberration (He, Burns, & Marcos, 2000) and change of pupil diameter (Kasthurirangan & Glasser, 2005) produced differences in the response to positive (increased lag) or negative (decreased lag) spherical aberration induced by the deformable mirror, as also reported by Theagarayan et al. (2009) using contact lenses to induce spherical aberration.

The observed changes in the accommodative response when aberrations are induced (or corrected) may result from changes in the wavefront vergence, due to optical interaction between the induced aberrations and the subject's own aberrations. Alternatively, the decreased response with induced aberrations (and more accurate response with corrected aberrations) may result from the higher tolerance to blur in the presence of HOA (Marcos, Moreno, & Navarro, 1999). While the use Adaptive Optics or contact lenses inducing aberrations does not allow us to distinguish between the two alternatives, we can eliminate the interaction between aberrations by imposing blur directly on the stimulus and investigate to which extent blur induced by HOA on these simulated targets influences dynamic accommodation.

2. Methods

2.1. Subjects

Five young subjects (age: 26.0 ± 4.4) participated in the study. The protocols were approved by Institutional Review Boards (IRB) and met the tenets of the Declaration of Helsinki. One subject was an investigator and the rest were unaware of the purpose of the study, although one of them was an experienced subject in accommodation studies. All subjects were visually normal and achieved at least a 20/20 visual acuity. Refractive errors (mean sphere: -0.3 ± 2.0, ranging from +1.75 to -3.5D; mean cylinder: -0.50 ± 0.35) were corrected by means of trials lenses or subject's own contact lenses for subject S5 (sphere: -3.5D). Their high order aberrations (3rd order and higher) were measured with a COAS aberrometer (Wavefront Sciences, Albuquerque, New Mexico), resulting in an averaged value of 0.15 ± 0.06 μm, (0.26 μm for subject S2 and the rest ranging from 0.11 to 0.14 μm) for a 3-mm pupil.

Another six subjects were discarded because they did not follow the stimulus properly or their accommodative gain was lower than 0.2 for the non-blurred condition.

2.2. Set up

Fig. 1 shows a diagram of the experimental set-up. The stimuli were presented on the micro-mirror display of a modified high luminance video projector (Sharp NoteVision). An interference filter (λ = 552 nm, BW 10 nm) was used to minimize any polychromatic cue for accommodation. A Badal system was used to change vergence (Zernike defocus) while dynamic accommodation was continuously monitored (100 Hz) with a high-speed infrared optometer (Kruger, 1979). Measurements of accommodation were recorded along the vertical meridian of the eye from a fixed 3 mm diameter area at the center of the subject's natural pupil. The subject's pupil was monitored by a video-camera (30 frames/s), and the image of the pupil was viewed on a video display allowing the experimenter to adjust the position of the subject's eye continuously during the experiment. During the experimental trials, the pupil was monitored and re-centered if necessary.

A pupil diaphragm conjugate to the natural pupil's plane was set to 3-mm in order to reduce the effect of the subject's own aberrations without increasing the depth of focus (Campbell & Gubisch, 1966).

2.3. Accommodative targets

The accommodative target was a quasi monochromatic (λ = 552 nm, BW 10 nm) Maltese cross of 20 cd/m^2 subtending 1°. The Maltese cross was blurred with different types (defocus, vertical coma, vertical trefoil and spherical aberration) and amounts (0.3 μm and 1 μm, for a 3-mm pupil) of aberrations by convolving the original target with the Point Spread Function (PSF) corresponding to every aberrated condition. The blurred stimuli were calculated using a custom routine written in Matlab (Mathworks, Natick, MA).

Fig. 2 shows the nine different conditions that were tested. The video projector was calibrated and the stimulus grayscale was modified in order to take into account the gamma correction of the video projector in the displayed image. The contrast of the

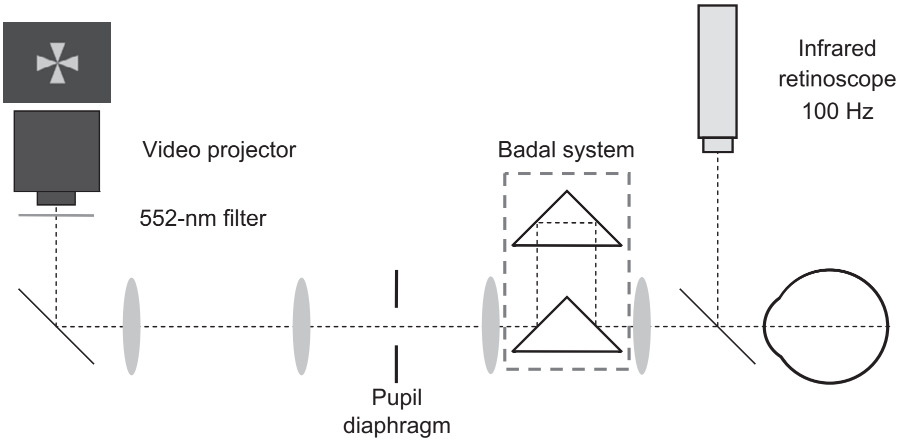

Fig. 1. Experimental set-up: the target is presented on the micro-mirror display of a video projector and its vergence (Zernike defocus) modified by means of a Badal optometer. Dynamic accommodation was recorded at 100 Hz with an infrared retinoscope.