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Dynamic accommodation without feedback does not respond to isolated blur cues

José J. Esteve-Taboada [a,c,*], Antonio J. Del Águila-Carrasco [a,c], Paula Bernal-Molina [a,c], Norberto López-Gil [b,c], Robert Montés-Micó [a,c], Philip Kruger [d], Iván Marín-Franch [a,c]

[a] Department of Optics and Optometry and Vision Sciences, University of Valencia, 46100 Burjassot, Spain
[b] Instituto Universitario de Investigación en Envejecimiento, University of Murcia, 30100 Murcia, Spain
[c] Interuniversity Laboratory for Research in Vision and Optometry, Mixed Group UVEG-UMU, Valencia-Murcia, Spain
[d] Department of Biological and Vision Sciences, State College of Optometry, State University of New York, USA

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ABSTRACT

The aim of this study was to determine whether dynamic accommodation responds to isolated blur cues without feedback, and without changes in the distance of the object. Nine healthy subjects aged 21–40 years were recruited. Four different aberration patterns were used as stimuli to induce blur with (1) the eye's natural, uncorrected, optical aberrations, (2) all aberrations corrected, (3) spherical aberration only, or (4) astigmatism only. The stimulus was a video animation based on computer-generated images of a monochromatic Maltese cross. Each individual video was generated for each subject off-line, after measuring individual aberrations at different accommodation levels. The video simulated sinusoidal changes in defocus at 0.2 Hz. Dynamic images were observed through a 0.8 mm pinhole placed at a plane conjugated with the eye's pupil, thus effectively removing potential feedback stemming from accommodation changes. Accommodation responses were measured with a Hartmann-Shack aberrometer for the four different aberration patterns. The results showed that seven out of nine subjects did not respond to any stimuli, whereas the response of the other two subjects was erratic and they seemed to be searching rather than following the stimulus. A significant reduction in average accommodative gain (from 0.52 to 0.11) was obtained when the dioptric demand cue was removed. No statistically significant differences were found among the experimental conditions used. We conclude that aberration related blur does not drive the accommodation response in the absence of feedback from accommodation.

1. Introduction

Accommodation is the change that occurs in the power of the crystalline lens as a result of ciliary muscle contraction, which allows the human eye to focus on near objects (Schiffman, 1989; Toates, 1972). Accommodation is thought to respond to signals (cues) that are either environmental or inherent to the eye. Some of the signals inherent to the physiology of the human eye that may affect accommodation responses are: retinal image blur from monochromatic (Campbell & Westheimer, 1960; Stark & Takahashi, 1965; Tucker & Charman, 1979), and chromatic aberrations (Kruger, Mathews, Aggarwala, & Sanchez, 1993; Kruger & Pola, 1986), and microfluctuations in accommodation (Charman & Heron, 1988, 2015). Some of the environmental signals are luminance, interposition, perceived distance, and apparent size (Ittelson & Ames, 1950; Johnson, 1976; Kotulak & Morse, 1995; Kruger & Pola, 1987; Toates, 1972).

Among the monocular optical cues to accommodation, monochromatic retinal blur is thought to be the most important cue. Retinal image blur can result from factors such as defocus blur and other natural aberrations of the eye, and diffraction (Fry, 1955; Kruger & Pola, 1986). Defocus blur is considered to be the primary stimulus for monocular accommodation (Kruger & Pola, 1986). It has been proposed that retinal focus is dynamically controlled by a closed negative-feedback loop so as to reduce blurring and increase contrast of the retinal image (Ciuffreda, 1991). However, under monochromatic conditions, in an aberration-free eye, the same point-spread function (PSF) results from over-accommodation as from under-accommodation. If defocus blur were a sufficient cue to drive accommodation, the human eye would have to respond by trial and error to reduce defocus blur under monochromatic conditions. Nevertheless, the eye presents

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* Corresponding author at: Department of Optics and Optometry and Vision Sciences, University of Valencia, 46100 Burjassot, Spain.

E-mail address: josejuan.esteve@uv.es (J.J. Esteve-Taboada).

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different types of monochromatic aberrations in addition to defocus blur that may add directional information to the non-directional defocus signal (Fincham, 1951; Kruger & Pola, 1986).

The aim of this study was to determine whether accommodation responds to the image blur cues when there are no changes to the dioptric demand of the image and no feedback from accommodation, in monochromatic conditions. We designed an open-loop configuration to measure accommodation responses in which a small pinhole pupil was used to remove feedback from changes in accommodation. This open-loop experiment enabled us to isolate various signals that may control accommodation and assess their effect in the accommodation response while removing feedback from voluntary changes of accommodation, trial-and-error changes in focus, or microfluctuations in accommodation.

In the present experiment, accommodation is expected to respond correctly if blur from the subject's own monochromatic aberrations provides a reliable directional cue without feedback; but there should be no response if blur from monochromatic aberrations does not provide a signed cue per se. In a previous experiment (Kruger, Mathews, Aggarwala, Yager, & Kruger, 1995) where a pinhole pupil was used to provide an open-loop condition, subjects accommodated strongly in the correct direction when a directional blur cue from chromatic aberration was included in the simulation, but not when the directional cue was absent. Thus accommodation should respond correctly only if blur from monochromatic aberrations provides a reliable directional signal for accommodation.

2. Methods

The methodology used in the present experiment follows the same approach as Stark and colleagues' study (Lee et al., 1999), where a stationary target was simulated at near and far distances. In our experimental design, we simulated sinusoidal dynamic patterns where the video stimulus moved towards and away from the eye. The dynamic accommodative response (AR) of each subject was assessed monocularly under monochromatic light. The stimulus presented to the subjects was a video animation based on computer-generated images prepared off line for each subject taking into account their own optical aberrations. The stimulus was viewed through a 0.8-mm pinhole placed in the stimulus optical path at a plane conjugated with the eye's pupil. Thus, the pinhole effectively removed potential feedback stemming from changes in accommodation. Subjects were therefore not able to directly determine the dioptric demand of the stimulus, even though they still had cues from the aberrated PSFs resulting from the blurred stimulus. If the retinal blur resulting from higher-order aberrations (HOAs) provides an effective directional signal for accommodation, the eye should accurately accommodate when the blur effects of these ocular aberrations are present, but not when they are removed. Conversely, if subjects do not respond to the simulations of image blur that include the effect of aberrations, this would be evidence that image blur itself does not provide a sufficient cue to accommodation.

2.1. Subjects

Nine healthy subjects having a mean age of 27.4 ± 6.2 years (range: 21–40 years) participated in this study (only one 40-year-old subject was included in the study; despite his age, he showed enough accommodation amplitude to respond to the stimulus changes and correctly performed the experiments; the age range without this subject was 21–32 years). Their eye's spherical equivalent ranged between −5.0 and +0.5 diopters (D), and none of them had more than 1 D of astigmatism. Subjects were healthy and had no ocular abnormalities or systemic health conditions that may affect vision, and they all presented clear intraocular media. The present study followed the tenets of the Declaration of Helsinki and all participants gave written informed consent. All the subjects were recruited at the University of Valencia and at the University of Murcia (Spain). The Ethics Committees from both universities approved this study's protocol.

2.2. Experimental setup

A custom-made optical system based on adaptive optics was used to carry out the measurements (see Fig. 1). The system consisted of a Hartmann-Shack aberrometer (Haso4 First, Imagine Eyes, France), which measured the aberration pattern at a rate of 20 Hz, and a 52-actuator deformable mirror (Mirao 52e, Imagine Eyes, France) that corrected the aberrations of the ensemble optical system and the eye before each experimental trial. A Badal optical system mounted onto a motorized linear motion stage (LS-65, Physik Instrumente GmbH, Germany) was used to compensate for the subject's spherical refractive error, to induce 2 D of accommodative demand, and to eliminate spatiotopic depth cues for accommodation. The visual targets and simulation videos were presented on an 800 × 600 pixels microdisplay (DSVGA OLED-XL, eMagin, NY, USA) and viewed through a green interference filter (550 nm, 10 nm bandwidth).

To reduce head movements during the trials, a dental mold was made for each subject to bite on. The right eye viewed the target while the left eye remained patched. The tested eye's pupil was monitored continuously using an infrared camera. All the AR measurements were taken using custom software developed in MATLAB (Mathworks Inc., Natic, MA, USA), based on an analysis and simulation software library and a software development kit (Imagine Eyes, France).

2.3. Stimulus

The stimulus was a video animation made up of computer-generated images of a Maltese cross. Individual videos, pre-recorded according to each subject's ocular aberrations, were presented on the microdisplay through the green interference filter (550 ± 5 nm). In each video, changes in defocus-blur simulated sinusoidal oscillation between +1 D and −1 D at 0.2 Hz. The simulated Maltese cross images included blur due to each eye's specific ocular aberrations (astigmatism and HOAs, measured for a 4-mm pupil) in addition to blur due to defocus. The Maltese cross images presented in the videos were manipulated to provide four different types of stimuli: (1) simulation of the subject's natural ocular aberrations, including astigmatism, (2) simulation of correcting all of the subject's ocular aberrations, (3) simulation of correcting all of the subject's ocular aberrations and inducing 0.2 μm of unbalanced spherical aberration, and (4) simulation of correcting all of the subject's ocular aberrations and inducing 0.1 μm of oblique astigmatism. Ocular aberrations were calculated for a 4-mm pupil. The induced spherical aberration was always unbalanced for each subject, i.e., it was radius dependent only, proportional to r^4 (Cheng, Bradley, Ravikumar, & Thibos, 2010; Xu, Bradley, López Gil, & Thibos, 2015).

The luminance of the microdisplay was about 20 cd/m^2, and the target spanned 1.95 degrees of visual angle. During each measurement, the adaptive optics system compensated for the individual eye aberrations, including astigmatism and HOAs. The stimuli video sequences were viewed through a 0.8-mm pinhole (see Fig. 1) to remove feedback from changes in dioptric demand and from defocus blur due to changes in accommodation. For all subjects, the pinhole had the effect of increasing their depth of focus to more than 2 D (Charman & Whitefoot, 1977). Therefore, subjects