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Dynamic accommodation without feedback does not respond to isolated blur cues

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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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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

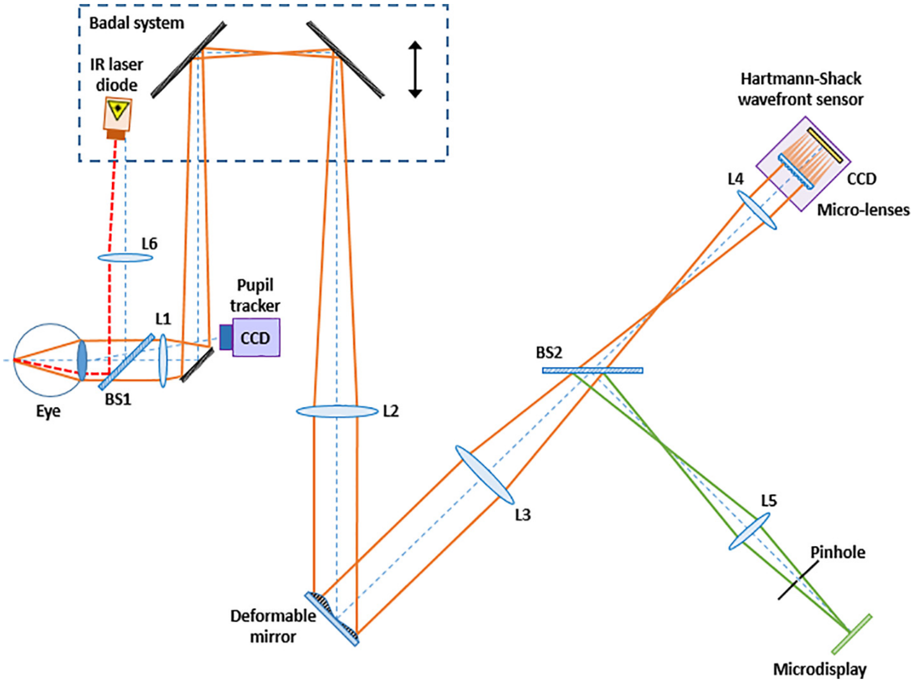

Fig. 1. Sketch of the custom-made optical system. All lenses, except for L5 and L6, are achromatic doublets; BS1 is a pellicle beam-splitter; BS2 is a hot mirror; the pinhole is conjugate with the pupil of the eye. The red dashed line shows the optical path of light for the measurement infrared (IR) laser diode; orange lines show the optical path for the wavefront sensor, while green lines show the optical path for the microdisplay.

were unable to use trial-and-error changes in defocus blur to bring the image into focus. The only cues available to the eye during the measurements were the changes in the simulated video images.

To generate the simulated images for the video stimuli, wavefront aberration data were recorded for each subject at different levels of accommodative demand. Aberrations profiles were measured with the Hartmann-Shack sensor for stimulus-vergence demand that varied from 0.0 D to −5.0 D, in 0.5 D steps. To fully characterize changes in the aberration pattern as a function of the accommodative response, three wavefront aberration measurements were averaged to calculate each stimulus demand, and a linear regression fit was applied to each Zernike coefficient, up to the 6th order. The manipulations to the Maltese cross target were simulated using custom software developed in MATLAB based on the Fourier Optics Calculator (Thibos, Hong, Bradley, & Applegate, 2004). The video stimuli therefore consisted of blurred images of a Maltese cross that simulated movement towards and away from the eye in a sinusoidal motion pattern at 0.2 Hz and 1.0 D of amplitude. Four tests were carried out, one with each of the stimulus conditions described above.

2.4. Procedure

Six trials were run for each of the four experimental conditions, presented in random order, for a total of 24 trials per subject. The initial direction of the sinusoidal movement was also randomized. Each trial lasted 25 s. To obtain the AR values, we used the minimum root mean square (RMS) refraction from the recorded Zernike aberrations (Thibos et al., 2004). The AR was calculated for each of the 24 trials for each subject. Participants were instructed to try to keep the target clear as if they were reading a book. These instructions were based on the findings by van der Wildt, Bouman, and Kraats (1974), who showed that careful instructions influence the AR. Before starting the measurements, subjects were asked to find their eye's far point without accommodating. For this purpose, the subject changed the vergence of the target stimulus—i.e., the dioptric demand—by moving the Badal optical system using a computer mouse. Participants were instructed to start with a vergence beyond their far point to avoid unintentional use of their accommodation, and to move the image of the target slowly towards the eye until it first became clear. This procedure was repeated three times and the average reading was taken as the subject's far point.

2.5. Data analysis

The dynamic AR was characterized by the amplitude and temporal phase lag of the measurements. For each trial, both parameters were obtained by fitting a sinusoidal function with the same temporal frequency as the simulated accommodative demand to the recorded AR over time. Accommodation gain—i.e., the ratio between the amplitude of the AR and that of the accommodative demand—was calculated for each trial. The temporal phase lag is defined as the time shift (delay) between the response and the demand, i.e., the difference (in seconds) between the stimulus peak and the AR peak. If this difference is positive, this implies that a phase lag exists in the response with respect to the demand, which is the most common type of response. Fig. 2 illustrates graphically the gain and phase of a particular (simulated) sinusoidal response with respect to a sinusoidal accommodative demand.

Each recruited subject had to pass a screening test to be enrolled in the study. As part of the inclusion criteria, subjects had to be able to accommodate with a gain greater than 0.2 to a monochromatic target (550 ± 5 nm) that moved sinusoidally towards and away from the eye, changing its dioptric demand between 1.0 D and 3.0 D. The targets were presented under normal closed-loop conditions with feedback from accommodation, no pinhole, and viewed through a 4-mm pupil. This control experiment was used to ensure that subjects were able to accommodate under the monochromatic light used in our experiment (Del Águila-Carrasco et al., 2017). The results of these control trials are reported in the Results section.

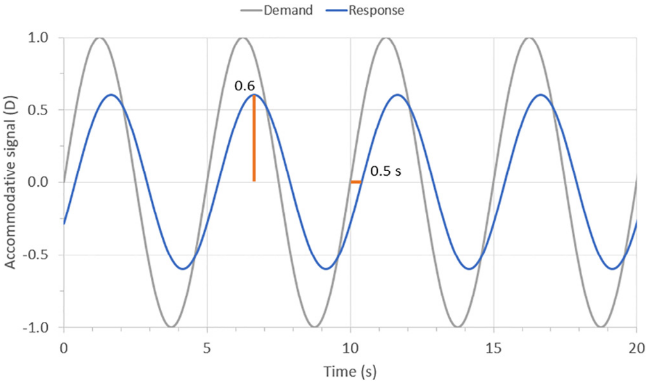

Fig. 2. Meaning of the gain and the phase for a sinusoidal AR. The grey curve represents the accommodative demand; the blue curve is a typical hypothetical accommodative response. The orange vertical line shows the amplitude of the response (0.6 D), which corresponds to a gain of 0.6 (since the amplitude of the demand is 1 D). The orange horizontal line indicates the phase lag, 0.5 s; that is, the time span between the peaks of the two signals.

For each subject, gain and phase lag were compared across the four conditions so as to identify any differences in their AR pattern. A repeated measures analysis of variance (rANOVA) was performed after applying the Greenhouse-Geisser correction (Box, 1965) for lack of sphericity if required, as determined with the Mauchly's sphericity test. The normality of all data sets was evaluated by means of the Shapiro-Wilk test. The ANOVA procedure based on the F statistic is robust under the breach of the normality assumption, provided that the data samples have no important asymmetries or similar distribution shapes (Tan, 1982). The Bonferroni procedure was used as a post-hoc test for comparisons between data groups when the rANOVA revealed significant differences between measurements. All tests were performed at a 0.05 significance level. The results were evaluated using SPSS software v.22 (IBM Corp., Armonk, NY, USA) and MATLAB.

3. Results

Fig. 3 shows changes in measured accommodative responses under the control condition (grey dots) and under the natural-aberrations condition (black dots), and the simulated accommodative demand (red dashed line) for three different subjects. These subjects serve as an example to show the different kinds of responses that we found in our experiment: subjects with no accommodation activity under the experimental conditions (top panel in Fig. 3), subjects with little activity (middle panel), and subjects with a high amount of activity but who were nevertheless unable to follow the stimulus (bottom panel). Note that in the control condition, all three subjects were able to follow the sinusoidally moving target with accommodation gains between 0.5 and 0.8 and phase-lags of 0.5–1.0 s.

For all subjects and all experimental conditions, the AR worsened significantly for all the experimental blur simulations conditions compared to the control condition. Three subjects showed no response, with a flat AR, to any of the experimental conditions (represented in the top panel of Fig. 3). For these three subjects, the mean accommodation gain ranged from 0.02 to 0.05, and the mean temporal phase lag ranged between 0.2 and 1.1 s. Four other subjects showed small changes in AR during the experimental trials (represented in the middle panel of Fig. 3). For these four subjects, the mean accommodation gain ranged from 0.03 to 0.10, and the mean temporal phase lag ranged between 0.03 and 0.90 s. The remaining two subjects showed high activity in AR responses for each of the four conditions tested (represented in the bottom panel of Fig. 3). For these two subjects, the mean accommodation gain values ranged from 0.23 to 0.46 and the mean temporal phase lags were in the range 0.4 to 1.0 s. These two subjects did not seem to follow the sinusoidal changes in accommodative demand over time in any of the experimental conditions. In fact, the frequency spectra derived from Fourier analysis for these two subjects did not show 0.2 Hz as a dominant frequency, contrary to what emerged from the control test's frequency spectra. Fig. 4 shows the average frequency spectra resulting from the control experiment (top) and the natural-aberrations condition (bottom) for the two subjects who showed high activity in AR responses. The results of the control condition (top) reveal a clear peak at 0.2 Hz, which reflects the fact that the subjects were able to follow the sinusoidal movement of the stimulus. However, for the experimental runs (bottom) there is no clear peak at 0.2 Hz or at 0.4 Hz, which one would expect if changes in the retinal image due to aberrations triggered correct accommodation.

Fig. 5 shows mean AR gain values obtained from the control and the four experimental conditions for the nine study participants. These results revealed that for all subjects but one, the AR in the control condition were significantly greater than for any of the four experimental conditions. Subjects number #4 and #5 were the individuals that showed the greater variability in their responses, having high activity in AR responses for each of the four conditions (see bottom panel of Fig. 3). Although these subjects demonstrated a higher ability to change their accommodative system when trying to react to the dynamic stimulus, they did not seem to follow the sinusoidal changes in accommodative demand over time. Accommodation gain values obtained for the four experimental conditions were significantly lower than those obtained in the control natural viewing condition for all subjects (rANOVA with Greenhouse-Geisser correction, $F = 45.05$, $p < 0.002$). No statistically significant differences were found between specific experimental conditions (rANOVA with Greenhouse-Geisser correction, $F = 0.06$, $p = 0.87$). With respect to the temporal phase values obtained for the four experimental conditions, there were no significant differences from those obtained in the control natural viewing condition for all subjects (rANOVA with Greenhouse-Geisser correction, $F = 1.19$, $p = 0.34$). Besides, no significant differences were found in temporal phase between all the experimental conditions (rANOVA with Greenhouse-Geisser correction, $F = 0.56$, $p = 0.65$).

4. Discussion

Our results show that in the absence of feedback from accommodation responses, monochromatic retinal image blur does not provide a signal sufficient for the eye to accommodate in the correct direction. Dynamic accommodation responses gain worsened considerably when real changes in target vergence were removed, even when the observed images with simulated blur contained information on defocus and information on the subject's own eye HOAs. This drastic decrease in accommodation gain cannot solely be attributed to the absence of feedback from changes in accommodation, because previous open-loop experiments (Del Águila-Carrasco et al., 2017; Kruger, Mathews, Katz, Aggarwala, & Nowbotsing, 1997; Kruger et al., 1995; Lee, Stark, Cohen, & Kruger, 1999) have shown that accommodation responds strongly even without feedback, especially when the stimulus includes reliable directional cues to the sign of defocus.

Only two of the nine subjects that participated in this study (Fig. 5) showed some accommodation response, but this response did not follow the pattern of the stimuli demand. The responses of these two subjects cannot be explained by the natural accommodation microfluctuations as they were not able to follow the

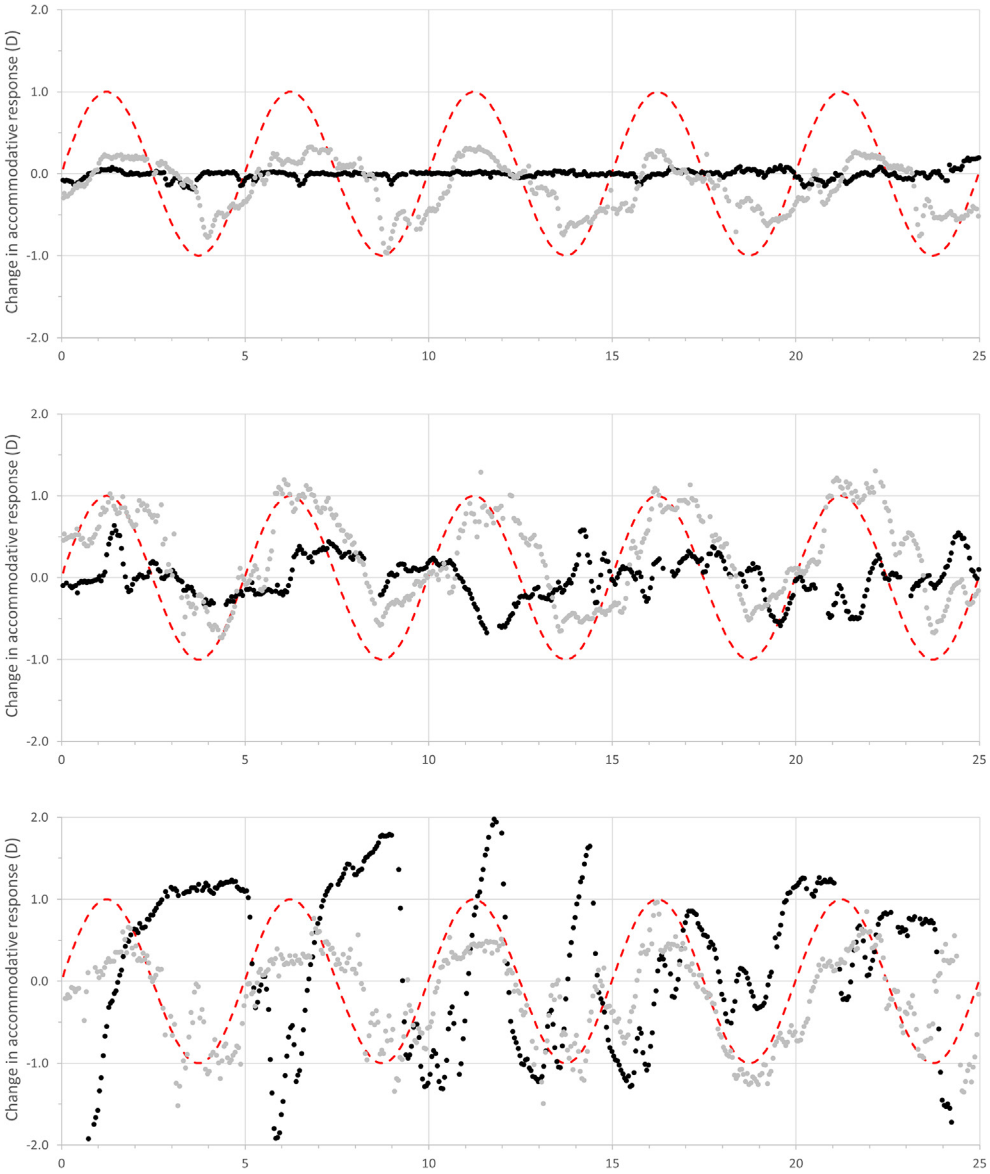

Fig. 3. Changes in measured AR under the control condition (grey dots), under the natural-aberration condition (black dots), and the simulated accommodative demand (red dashed line) for three different subjects. The first subject (top panel) showed no activity; the second subject (middle panel) showed very little activity, similar to normal microfluctuations in accommodation (Charman & Heron, 2015; Metlapally, Tong, Tahir, & Schor, 2014, 2016); whereas the third subject (bottom panel) showed very high activity, and then could not follow the stimulus since the accommodative response was often in counter-phase to the stimulus.

stimulus, and their response was often in counter-phase to the sinusoidal accommodative demand. Indeed, the Fourier analysis of their AR curves (Fig. 4) revealed considerable energy at temporal frequencies other than that tested, probably because the visual system was simply searching unsuccessfully for a reliable directional signal. These two subjects also showed little or no difference in AR across the four experimental conditions.

The average accommodation gain for the experimental conditions was almost a factor of five smaller than the gain for the control natural condition, which emphasizes the importance of real dioptric demand on accommodation responses (Del Águila-Carrasco et al., 2017). No significant differences were observed across the four experimental conditions, either in average gain or in phase lag, so the results appear to be robust to the statistical analysis.

The accommodation temporal phase lag was more variable under experimental conditions compared to the control closed-loop condition. This may be a consequence of the fitting of the function since AR curves with small gains can be fitted to a large number of fitting functions with very different temporal phase lags, with the best fit depending only on small changes in the measured temporal signal. For the same reason, phase lags for the experimental trials always showed greater variability between repetitions than the control trials. Therefore, no significant conclusions may be drawn from the temporal phase lag data reported in this study.

Possible limitations of the study are the subjective way used to determine the individuals' far point, and the fact that the subjects' aberrations used to generate the stimuli in the videos were generated off line, without taking into account possible variations of aberrations that occur in real time (Cheng, Himebaugh, Kollbaum, Thibos, & Bradley, 2004).

Our results are in agreement with previous studies that suggested that accommodation responds primarily to real changes in dioptric demand (vergence of light) (Fincham, 1951; Kruger et al., 1997). Fincham noted in 1951 that small eye movements trigger reflex changes in accommodation. These small eye move-

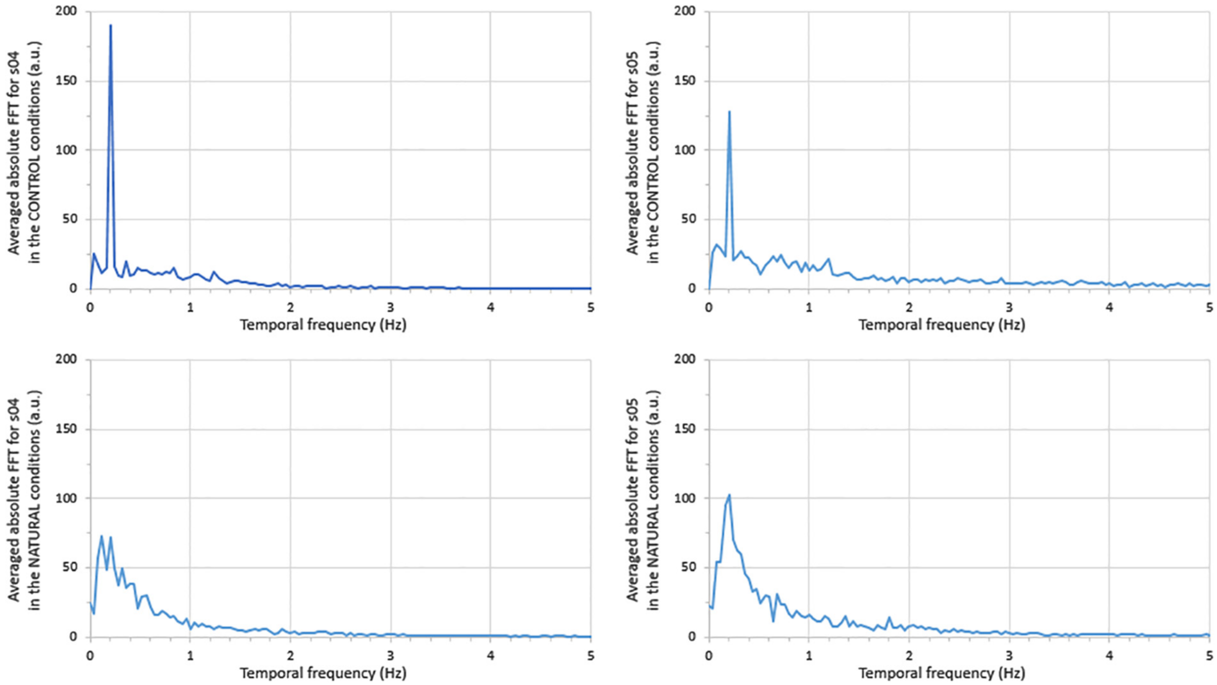

Fig. 4. Average frequency spectra resulting from the control trials (top) and the experimental trials in the natural-aberrations condition (bottom) for subjects s04 (left) and s05 (right).

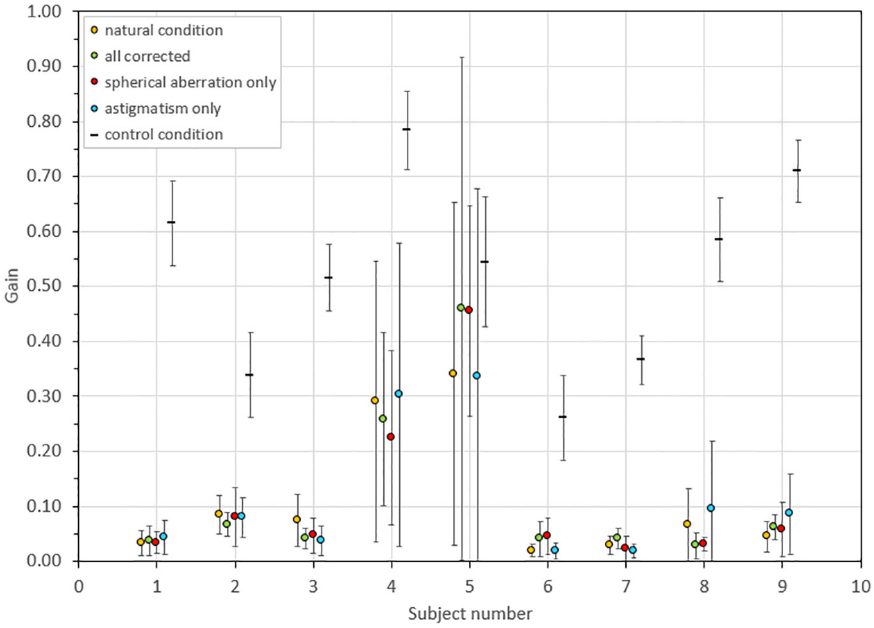

Fig. 5. Mean gain for each subject and condition. Error bars represent ± 1 standard deviation.

ments and the waveguide property of retinal cones results in a brightness difference between the two sides of the retinal blur circle that may allow the eye to detect whether focus changes from behind to in front of the retina (Kruger et al., 1997). Although this hypothesis assumes that the peak of the Stiles-Crawford function is located at the center of the pupil, a similar effect occurs in the absence of off-axis eye movements if the peak of the Stiles-Crawford function is off-center (Westheimer, 1968), more specifically in the nasal direction (Applegate & Lakshminarayanan, 1993; Gorrand & Delori, 1995; Stiles & Crawford, 1933). According to Fincham, this directional reflex response constitutes a significant cue to accommodation, driven by the actual vergence of light, regardless of the real or apparent distance of the object.

In conclusion, we have shown that simulated blur from subject's astigmatism and other HOAs do not provide an effective directional signal for accommodation without feedback from changes in accommodation, thus suggesting that aberration-related blur is not enough to drive accommodation.

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The authors declare no conflict of interest.

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