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Effect of even and odd-order aberrations on the accommodation response

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Abstract

• **AIM:** To investigate the potential effect that odd and even-order monochromatic aberrations may have on the accommodation response of the human eye.

• **METHODS:** Eight healthy subjects with astigmatism below 1 D, best corrected visual acuity 20/20 or better and normal findings in an ophthalmic examination were enrolled. An adaptive optics system was used in order to measure the accommodation response of the subjects' eyes under different conditions: with the natural aberrations being present, and with the odd and even-order aberrations being corrected. Three measurements of accommodation response were monocularly acquired at accommodation demands ranging from 0 to 4 D (0.5 D step).

• **RESULTS:** The accommodative lag was greater for the accommodative demands of 1.5, 3, 3.5 and 4 D for the condition in which the even-order aberrations were corrected, in comparison to that obtained for the natural aberrations and corrected odd-order aberrations for the same accommodation demands. No statistically significant differences were found between the accommodation responses under the three conditions.

• **CONCLUSION:** The odd and even-order aberrations are not helping the visual system to accommodate, because their partial correction do not affect the accommodation performance.

• **KEYWORDS:** accommodation response; monochromatic aberrations; adaptive optics

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INTRODUCTION

It is well known that the eye is capable of changing its power in order to focus on objects that are placed on different distances^[1]. The change in power of the human eye is known as accommodation and it is vital for the improvement of the retinal image quality^[2] and for the appreciation of the details of the objects^[3].

There are several cues that activate the accommodation mechanism of the eye in order to have a proper accommodation response^[4]. These cues can come from the surroundings^[5] (e.g. distance of the object) or from the optics of the eye itself^[6] [e.g. longitudinal chromatic aberration (LCA)], which have an influence on the retinal image quality^[7].

Defocus caused by an incorrect accommodation response can be characterized by a positive or negative sign, which depends on whether the plane of the image is ahead of or behind the retina^[8-9].

It has been demonstrated that LCA provides a directional signal for accommodation^[10-13]. Nevertheless, there have been cases in which the accommodation ability was not lost when the cues of the LCA were artificially removed^[14]. This indicates the co-existence of additional optical cues, which play a role in the accommodation response^[15].

The monochromatic aberrations can be also considered optical cues. More precisely, odd-order aberrations can be considered as signed cues for accommodation, since the images formed at the retina are different whether they are focused in front of or behind it. Moreover, some aberrations have a greater contribution to the accommodation response than others. This is evident in a study conducted by Wilson *et al*^[16] according to which the optical system is capable of differentiating the changes between the point spread function (PSF) of the positively and negatively induced defocus in the presence of monochromatic aberrations. In particular, the even-order aberrations could help to distinguish between the negative and positive defocus, since the image formed when they are present is different whether the light is focused in front of or behind the retina. On the contrary, the odd-order aberrations are not intertwined with such ability^[16-17]. Nonetheless, it is still under research the exact role of the different aberrations in the accommodation response of the eye and whether the even and odd-order aberrations contribute as a signed cue to the direction of defocus or not.

Therefore, the aim of this study to further investigate how the monochromatic aberrations influence on the accommodation response of the eye. To achieve this, an adaptive optics system was used in order to measure the accommodation response of the subjects' eyes under different conditions: with the natural aberrations being present, and with the odd and even-order aberrations being corrected.

SUBJECTS AND METHODS

Subjects Eight young adult subjects (mean age: 31±5.24y, range: 26 to 40y) who could accommodate under monochromatic light conditions participated in the study. The averaged spherical equivalent refractive error was -1.00±2.37 diopters (D). Astigmatism was limited to ≤1.00 D. All subjects had normal corrected visual acuity (20/20 or better) evaluated with the ETDRS chart (Precision Vision, USA), no ocular pathology, no binocular vision anomalies, no previous conducted ocular surgery, and normal clinical amplitudes of accommodation for their ages (at least 4 D). The study followed the Declaration of Helsinki and was approved by the Ethics Committee of the University of Valencia. The subjects were verbally informed about the details and possible consequences of the study, and a signed formal consent was obtained from each subject.

Equipment The crx-1 adaptive optics visual simulator (Imagine Eyes, Orsay, France) was used to measure and correct the wavefront aberrations of each subject's eye (Figure 1). The system is composed of a Hartmann-Shack wavefront sensor and a deformable mirror. The wavefront sensor employs a square array of 1024 microlenses and a near-infrared light source with a wavelength of 850 nm. An internal microdisplay is used to project the target, while the Badal system is employed to change its vergence (in other words, accommodation demand). To control the accommodation process, a monochromatic Maltese cross (550±5 nm) is used as the target. A precise alignment of the subject's pupil is required, and this was achieved with an additional Charge Coupled Device (CCD) camera. Head movements were reduced employing a chin and forehead rest.

Furthermore, the deformable mirror is comprised of 52 independent magnetic actuators, which are used to either correct or modify the wavefront aberrations^[18-20]. Prior to data collection, a customized software based on commercially available routines (Imagine Eyes, Orsay, France) was used to control the deformable mirror and reshape it from its normally flat surface to the desired one.

In this study, the Zernike coefficients of each individual up to and including 6th order were considered and partially corrected to meet the conditions tested (*i.e.* natural aberrations present, odd and even-order aberrations separately corrected).

Experimental Procedure Before starting the experiment, subject's spherical refractive error was corrected using the

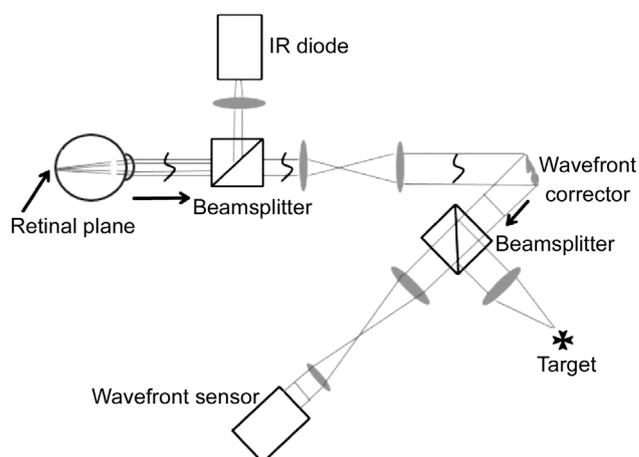


Figure 1 Schematic layout of the crx-1 adaptive optics visual simulator used to measure and correct the wavefront aberrations of the subject's eye.

Badal. The experiment was divided into three conditions, each having different wavefront aberrations present. In the first condition the subject's natural aberrations were present, whereas in the two other conditions the subject's odd and even-order aberrations were respectively corrected. To achieve this, a customized software was made and implemented into the adaptive optics system. This software was further controlling the deformable mirror of the system in order to correct the aberrations corresponding to each condition. In all conditions the measurements were performed monocularly and obtained from the dominant eye of each subject.

The measurements were acquired under three different conditions: 1) natural aberrations were present, 2) odd-order aberrations were corrected, and 3) even-order aberrations were corrected. In each condition, three measurements were acquired at the accommodation demand from 0 to 4 D, with a step of 0.5 D. Thus, 27 wavefront measurements were recorded per condition, with a total of 81 measurements for each eye. The subject was allowed to blink prior recording a measurement, to avoid increased tear film aberration that might otherwise have occurred during an extended inter-blink interval^[21]. Subjects were also allowed to rest between trials.

Data Analysis The wavefront data were exported as Zernike coefficients up to 6th order. To solely identify the accommodation response of the eyes to the accommodation stimuli, the Zernike defocus was used^[22-23]. The accommodation response was estimated in diopters employing the following equation:

$$AR = AD + \frac{C_2^0 4\sqrt{5}}{r^2} \quad (1)$$

where AR is the accommodation response, AD is the accommodation demand, C_2^0 is the second-order Zernike coefficient for defocus in μm and r is the pupil radius in mm^[24].

Data corresponding to each one of the three conditions were fitted to linear models using Matlab 2015b (MathWorks

Natick, MA, USA). For each regression analysis, the intercept, the slope, the determination coefficient, and the *P*-value were obtained. An additional ANCOVA analysis was performed to elucidate whether the slopes of the three different conditions were different. A *P*-value of less than 0.05 was considered to be statistically significant.

RESULTS

To obtain the values of the accommodation response, the second-order Zernike coefficient (defocus) was converted into diopters, employing the previously described formula (Equation 1). Then, the mean of three consecutive measurements was displayed for each condition and accommodation demand considered in this study.

Figure 2 exhibits the mean accommodation response obtained from all eight subjects for each accommodation demand with the natural aberrations being present, starting from 0 D and ending at 4 D of accommodation demand, utilizing a step of 0.5 D. The accommodation responses were acquired when the natural aberrations were present. The dashed line shows the theoretical response of the accommodation process (*i.e.* equal accommodation response for each accommodation demand). In this case, there was a difference towards the same direction between all accommodation responses and the theoretical line, showing accommodative lag for all subjects and accommodation demands.

The mean accommodation responses acquired when the odd and even-order aberrations were removed, are displayed in Figures 3 and 4, respectively. Both figures illustrate the mean accommodation response of all subjects and accommodation demands. In both figures, the obtained accommodation responses are similar indicating a similar accommodative lag for both conditions with reference to the theoretical line. Nevertheless, in Figure 4 the lag of accommodation is greater for the accommodation demands of 1.5, 3, 3.5 and 4.0 D, in comparison to that obtained in Figure 3 for the same accommodation demands.

As already mentioned, a statistical analysis was conducted to analyze whether the measurements obtained for the three different conditions were statistically different or not.

Table 1 summarizes the results obtained for the regression analysis performed for each condition. The referred accommodation demand of 0 D corresponds to the far point of each subject's eye, hence its non-accommodated state. Therefore, this accommodation demand was excluded from the statistical analysis. All the *P*-values for the three linear regression analysis were statistically significant ($P < 0.001$). The minimum determination coefficient (R^2), equal to 0.88, was obtained for the condition in which the even-order aberrations were corrected. The ANCOVA analysis revealed that the slopes of the accommodative responses for the three conditions were not significantly different from each other ($P = 0.26$).

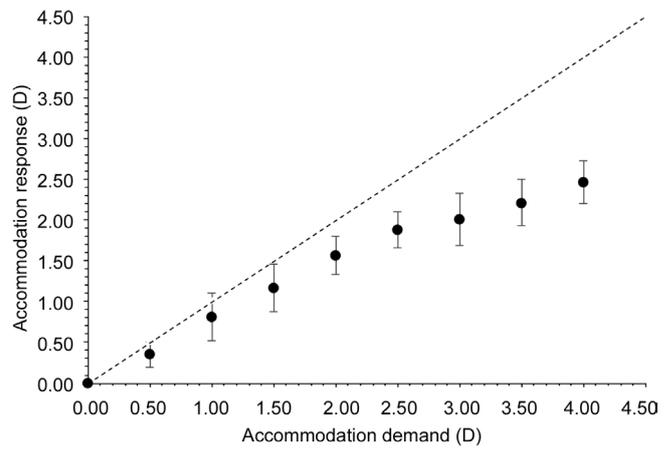


Figure 2 The mean accommodation response obtained with the natural aberrations being present Each data point represents the mean±standard deviation (SD) of each accommodation demand. The dashed line displays the theoretical accommodation response.

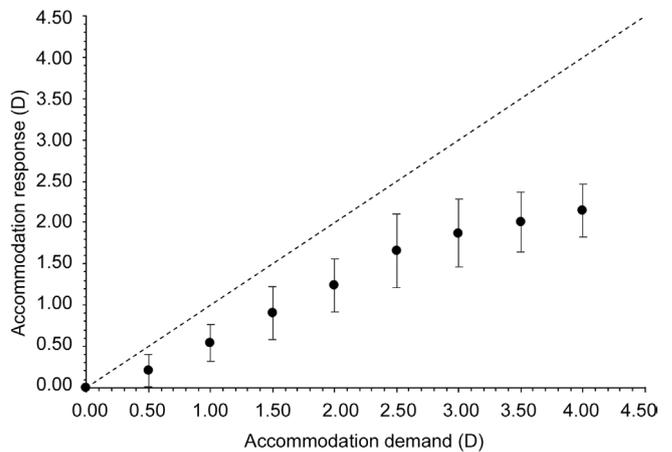


Figure 3 The mean accommodation response obtained with the odd-order aberrations being corrected in the subjects' eyes Each data point represents the mean±standard deviation (SD) of each accommodation demand. The dashed line displays the theoretical accommodation response.

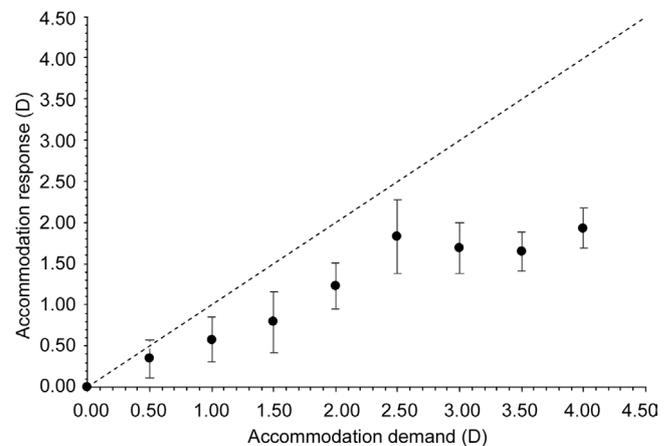


Figure 4 The mean accommodation response obtained with the even-order aberrations being corrected in the subjects' eyes Each data point represents the mean±standard deviation (SD) of each accommodation demand. The dashed line displays the theoretical accommodation response.

Table 1 Results obtained for the regression analysis performed for each condition

Condition	Slope	Intercept (D)	R^2	P
Natural aberrations	0.587	0.237	0.97	<0.001
Odd-order corrected	0.574	0.025	0.97	<0.001
Even-order corrected	0.471	0.195	0.88	<0.001

DISCUSSION

During the past fourteen years, several studies have been conducted to identify the possible use of the high-order aberrations on accommodation^[6-7,16,25]. Nevertheless, all of these studies came up with different results. An additional study conducted by López-Gil *et al*^[26] examined once again the effect of the high-order aberrations, but exclusively the effect of inducing third-order aberrations on the accommodation using customized contact lenses. On the other hand, Gamba *et al*^[27] employed targets, which were blurred with a certain amount of specific high-order aberrations to identify their influence on accommodation. Although, in all of the aforementioned studies there were differences in the methodology employed to perform the different experiments, they all had one common parameter; they all developed their experiments in order to study the dynamic accommodation response. Moreover, the number of participants varied between five to ten among these studies, with one study having only two participants^[6]. Additionally, in two studies, some aspects of latency and speed of the dynamic accommodation response were explored after the partial^[6] and complete^[7] correction of the ocular aberrations using an adaptive optics system, whereas in two other studies the gain and phase of the dynamic accommodation response were examined by inducing ocular aberrations^[26-27]. A fifth study investigated the capability of perceiving changes between the PSF of the positive and negative induced defocus, but it did not record accommodation^[16].

In the present study, we selected a different approach to study the effect of the ocular aberrations on the static accommodation response. This study was designed in this way in order to show the potential of such approach for future research. More specifically, we selected to assess the differences in accommodation with natural aberrations being present in the subjects' eyes and with the odd and even-order aberrations being respectively corrected. This was achieved by employing an adaptive optics visual simulator and several accommodation demands ranging from 0 to 4 D, with a step of 0.5 D. Additionally, we chose to study solely the changes that occurred in defocus when a total of natural, even and odd-high order aberrations were present in the eye. In this way the changes in accommodation response can be adequately assessed for all conditions and accommodation demands.

Our results indicate that in the presence and absence of high-order aberrations, the static accommodation response is not

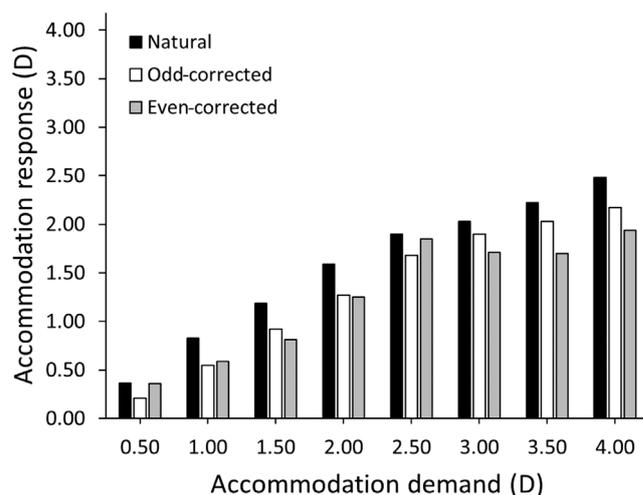


Figure 5 Mean accommodation values for the three conditions and every accommodation demand included in this experiment.

altered. Although, we were expecting that the interactions between the natural and corrected aberrations may play a role in the precision of accommodation, such as worse precision in accommodation in the absence of some ocular normal aberrations; in our study this is not evident. In particular, according to our statistical analysis we found that the obtained accommodation responses were not significantly different between the three conditions. In other words, we would suggest that our results show that the accuracy of accommodation response remains unaffected with the correction of the odd and even-order aberrations. This aspect of our results is in agreement with the corresponding aspect of the results obtained in three previous conducted studies on the dynamic accommodation response^[6-7,26]. Therefore, from these results we conclude that if the higher-order aberrations were helping the visual system to choose the right direction of accommodation, then with their correction the accommodation performance would have been reduced.

Moreover, our results yielded a certain value of accommodation lag for all conditions and accommodation demands (Figure 5). According to previous studies, a general accommodation lag was expected as our subjects were seeing a Maltese cross. Using more demanding stimuli, like small letters, significantly reduces the lag in the accommodation response^[2]. Once again, the differences in accommodation lag between the different conditions were not significantly different for each accommodation demand. Nonetheless, a slightly increased accommodation lag is noticed in the even-order corrected condition for the accommodation demand of 1.5, 3, 3.5 and 4 D in comparison to the lag obtained in the two other conditions for the same accommodation demands.

Furthermore, in this study we used a monochromatic Maltese cross in order to impair the use of the LCA by the accommodation system, as it is well known that commonly it is used as cue for accommodation. This way, we can focus exclusively

in the effect of the correction of the monochromatic aberrations on the accommodation response. We selected only subjects who were able to appropriately accommodate under monochromatic light, despite the great reduction in information provided by the LCA and monochromatic aberrations, respectively. In particular, in their case is indicated that by accommodating in monochromatic light the LCA is not used as a cue of accommodation. Additionally, no difficulties in accommodating were faced in the conditions of correcting the odd and even-order aberrations (in other words, the partial correction of the higher-order aberrations), as it has happened to previous conducted studies^[7].

Overall, neither of the subjects' responses was worse without the odd and even-order aberrations nor it was unchanged. Chen *et al*^[7] suggested that in such case the accommodation response does not improve as it is not affected by the increase in the rate of change in image quality with focus error produced with the removal of the high order aberrations.

In summary, we measured the static accommodation response of the subjects' eyes with the natural aberrations and with the odd and even-order aberrations corrected using an adaptive optics system. Our results indicate that when LCA is eliminated as cue, all of the subjects who are able to accommodate under monochromatic light are capable of accommodating properly despite the elimination of the odd and even high-order aberrations. For all subjects, there is no significant difference in the accommodation response with the natural aberrations or without the odd and even-order aberrations. In our study, we suggest that the odd and even-order aberrations do not provide aid for accommodation, as the accommodation response of all subjects was not affected by the partial correction of these aberrations. Nevertheless, still is under question the actual role of the monochromatic aberrations in the accommodation mechanism. Therefore, further research is needed using a larger number of subjects in order to increase our knowledge in this topic.

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Conflicts of Interest: Moulakaki AI, None; Del Águila-Carrasco AJ, None; Esteve-Taboada JJ, None; Montés-Micó R, None.

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