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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: $-0.3 \pm 2.0$, ranging from +1.75 to $-3.5$D; mean cylinder: $-0.50 \pm 0.35$) were corrected by means of trials lenses or subject's own contact lenses for subject S5 (sphere: $-3.5$D). 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 ($\lambda$ = 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 ($\lambda$ = 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, Nattick, 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

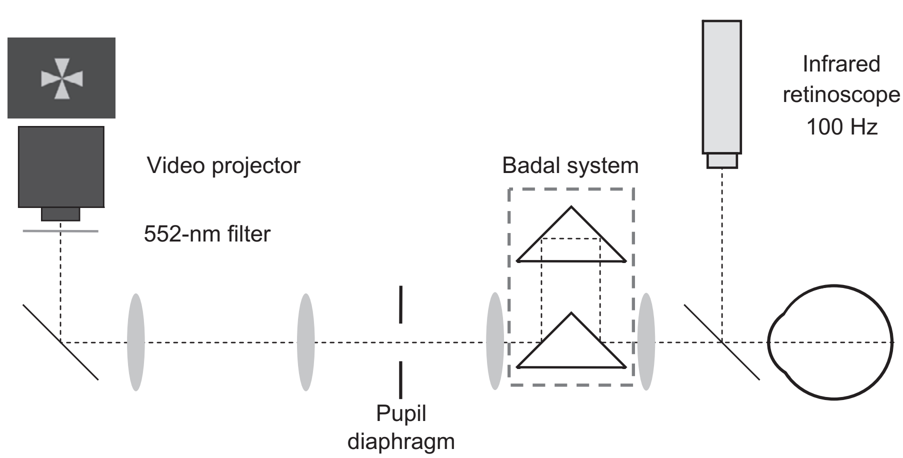


**Fig. 1.** Experimental set-up: the target is presented on the micro-mirror display of a video projector and its vergence (Zernike defocus) modified by means of a Badal optometer. Dynamic accommodation was recorded at 100 Hz with an infrared retinoscope.

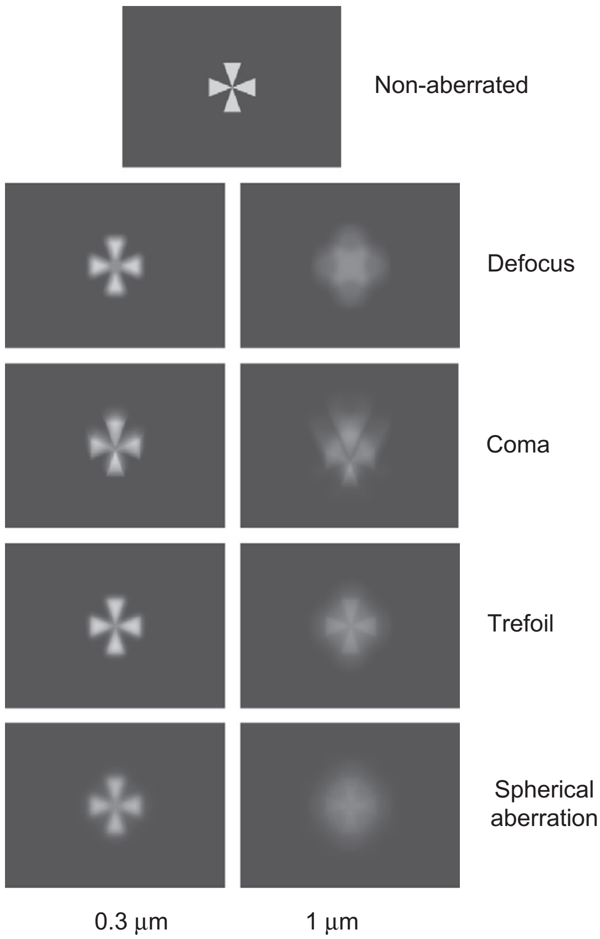


**Fig. 2.** Images of the nine targets used in this study. The non-aberrated Maltese cross is convolved with the PSF corresponding to 0.3 μm and 1 μm of defocus, vertical coma, vertical trefoil and spherical aberration (for a pupil of 3 mm).

original image was reduced to 0.9 in order to work in the linear range of the gamma correction curve.

The nine conditions were randomly repeated six times for every subject.

### *2.4. Experimental protocols*

During every experimental trial, the subject was positioned in front of the apparatus on a chin and forehead rest, which kept the subject still. The left eye of each subject was tested and the right eye was patched. The stimulus vergence varied sinusoidally from 1D to 3D with a frequency of 0.195 Hz during trials lasting 40.96 s. To minimize the subject's fatigue, the 54 trials were run in four experimental sessions of 1 h of duration on different days. If the subject had not followed the stimulus in some of the trials properly, these trials were repeated at the end of the session.

### *2.5. Data processing*

Data were collected and analyzed using custom software. Blinks were removed manually from each accommodation trial before analysis and replaced with a linear interpolation between the pre- and post-blink values. Trials with more than 14.65% blinks were discarded (Kruger, Stark, & Nguyen, 2004). Temporal responses were processed using a fast Fourier transform to extract dynamic gain and temporal phase lag at the stimulus frequency (0.195 Hz). To reduce spectral leakage in the FFT, the mean and linear trend were subtracted from the data before analysis, and a Hamming window was applied. Gain is defined as the ratio between the amplitude of the response at 0.195 Hz and the amplitude of the stimulus (1D). Phase lag is defined as the phase difference between the accommodative stimulus sinusoid and the subject's response. Data from the six trials for each of the nine conditions were averaged for each condition.

An ANOVA Bonferroni T2 test (SPSS 15.0 for Windows) was performed to determine statistical differences in gain and phase lag across experimental conditions.

## 3. Results

Fig. 3 shows some examples of the dynamic response of subject 1, an experienced subject with a very high gain, for the different experimental conditions: (a) the non-aberrated target, the original stimulus blurred with (b) 0.3 μm and (c) 1 μm of spherical aberration, and blurred with (d) 0.3 μm and (e) 1 μm of vertical coma. The gain decreased when the stimulus was blurred, especially for the higher amounts of aberrations and for spherical aberration.

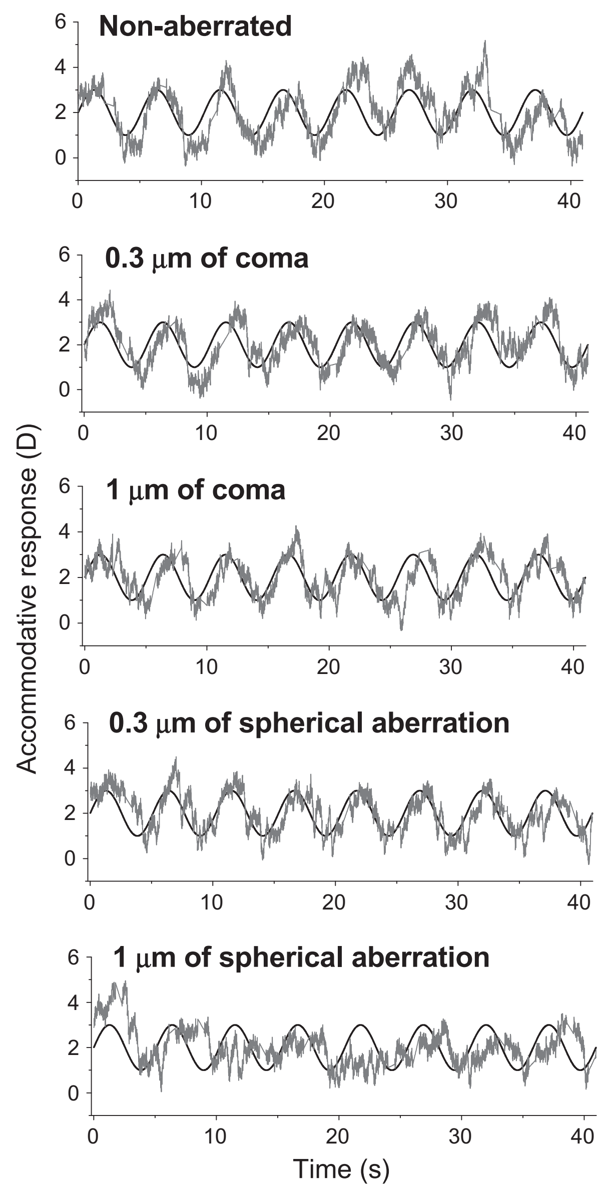


**Fig. 3.** Examples of dynamic accommodative responses of subject 1 to the non-aberrated stimulus and 0.3 μm and 1 μm of spherical aberration and coma. The accommodative stimulus is shown in black.

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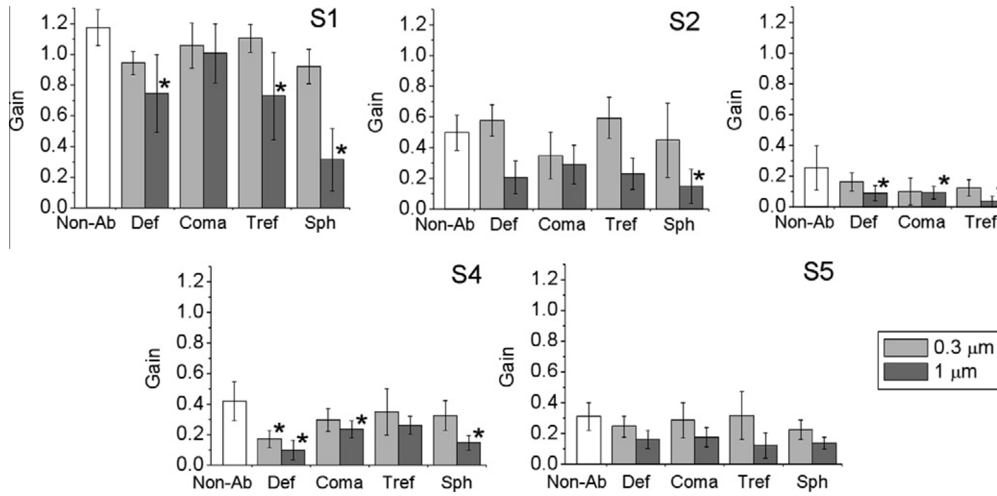


**Fig. 4.** Mean absolute gain across conditions for every subject. Error bars are the standard deviation of the gain for every subject and condition. *Gain is significantly different from the non-aberrated condition (ANOVA, Bonferroni T2).

For the latter condition the subject experienced some problems in tracking the stimulus.

Fig. 4 shows the mean gain across conditions for every subject. As expected, the gain was lower when the stimulus was blurred with the higher amount of aberrations. The aberration type that most affected the dynamic response varied slightly across subjects, although trefoil tended to produce the lowest decrease in gain and defocus and spherical aberration the highest. *Absolute* gain also depends on the subject. We have defined the *relative* gain as the gain for each condition divided by the gain for the non-aberrated condition. Relative gain averaged across subjects was lower when the stimulus was blurred with the higher amount of aberrations (see Fig. 5A). Defocus, and especially spherical aberration, decreases the gain more than coma and trefoil. The drop in the gain is statistically significant ($p < 0.002$) for all aberration types when 1 µm was induced and only for spherical aberration when 0.3 µm of spherical aberration was induced (ANOVA, Bonferroni T2).

The mean phase lag increased in the presence of blur (Fig. 5B), although the change was not statistically significant because of the large standard deviation of the mean values.

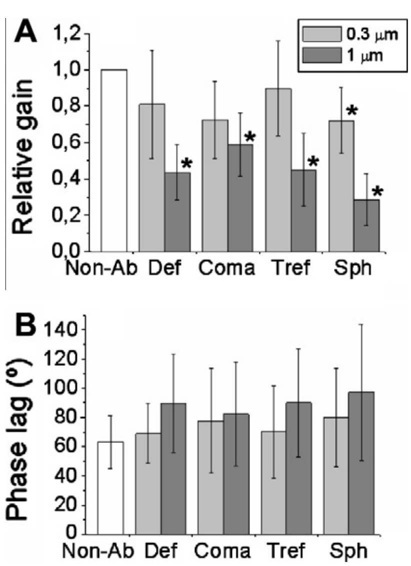


**Fig. 5.** Relative gain (A) and phase lag (B) averaged across subjects. Error bars are the standard deviation of the mean values for the five subjects. *Relative gain is significantly different from 1 (ANOVA, Bonferroni T2).

In most subjects, differences in the relative gain across conditions are quite consistent with the apparent degradation of the simulated targets (Fig. 2), as it is well known that the same amount of aberration (expressed in Zernike weights) produces different amount of image blur, depending on the Zernike order and frequency (Applegate, Ballentine, Gross, Sarver, & Sarver, 2003). To quantify these differences in blur across conditions, we have calculated the modulation transfer functions corresponding to the aberration patterns used to simulate the blurred targets, and used the volume under the MTF (within a certain frequency range) as a retinal image quality metric.

As Mathews and Kruger (1994) showed that frequencies around 3–5 c/deg are more important for accommodation, we have looked at the volume under the MTF in that frequency range, for all cases.

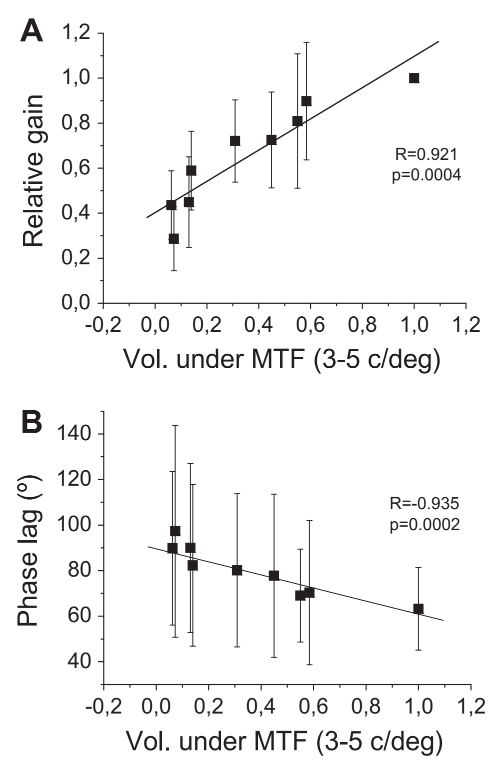


**Fig. 6.** Correlation between the relative gain (A) and the phase lag (B) averaged across subjects and the volume under the MTF between 3 and 5 c/deg.

Fig. 6A shows that there is a high correlation ($p = 0.0004$) between relative gain and the volume under the MTF between 3 and 5 c/deg (normalized to the non-aberrated value). Temporal phase lag is also highly correlated ($p < 0.0002$) with the volume under the MTF between 3 and 5 c/deg (Fig. 6B). The correlation between relative gain and the volume under the MTF (cut-off at 100 c/deg) did not reach statistical significance ($p = 0.076$).

## 4. Discussion

We have shown that the blur induced by HOA impairs dynamic accommodation, proportionally to the amount of blur, due to the contrast degradation produced in the target. As the blur is imposed directly on the target (and not on the eye) the effects of potential interactions of the imposed aberrations with the natural aberrations of the eye are discarded. The inaccuracy of the accommodative response with aberrated targets seems to result from improper contrast content in the image, and the higher tolerance to defocus with blurred targets. The results support the findings obtained in previous studies that manipulated directly the phase, either inducing aberrations with contact lenses (López-Gil et al., 2007; Theagarayan et al., 2009) or correcting or inducing aberrations with adaptive optics (Gambra et al., 2009).

Although interactions between the imposed aberrations and the natural aberrations of the eye may play a role in the final accommodative response (Gambra et al., 2009) the results of the current study support the conclusion that a major effect of increased aberrations (or in general, degraded retinal image quality) is a decrease in accommodative gain.

Our results show high intersubject variability in the absolute gain (even for the non-aberrated condition), which could arise from different sources. First, although the effect of the subjects' own natural aberrations was minimized by the use of a 3-mm pupil, there are some residual high order aberrations, which varied across subjects. However, we did not find a correlation between the absolute gain and the amount of natural aberrations of the subjects. Some other potential sources include: the experience of the subjects (S1 is highly experienced and S2 is moderately experienced) which could explain the highest performance of S1 and the relative good performance of S2, despite his relatively high amount of HOA; cues arising from the presence of specific HOA; and also the absence of other accommodative cues (such as longitudinal chromatic aberration, Lee et al., 1999) that could be more important for some subjects than for others.

We found that the deleterious effects of blur on the accommodative response are only significant for amounts of aberrations much higher than typical values. This suggests that the effects of high order aberrations on gain and phase of dynamic accommodation is small and only present in subjects with an abnormally high amount of aberrations – such as keratoconic patients (Barbero, Marcos, Merayo-Lloves, & Moreno-Barriuso, 2002). These results are consistent with those found by López-Gil et al. (2007), Stark et al. (2009) and Chen et al. (2006).

Nevertheless, although the effect may not to be important even in patients with increased spherical aberration after standard refractive surgery (Marcos, Barbero, Llorente, & Merayo-Lloves, 2001), previous studies showed that the presence positive spherical aberration could be detrimental for accommodation due to a pupil constriction effect (Gambra et al., 2009).

In our study, we found the largest effects to be caused by symmetric aberrations (defocus and spherical aberrations), which for the same amount of aberration produced the largest amount of image blur. The impact of those aberrations when induced optically would highly depend on the sign of the aberration (i.e. vergence of the wavefront), as coupling of defocus and spherical aberration (which also changes with accommodation) will modulate the induced aberration. These data are of importance when prescribing the newest refraction/presbyopia correction alternatives that modify the natural aberration pattern of the eye (either inducing or correcting aberrations).

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