# Accommodation with higher-order monochromatic aberrations corrected with adaptive optics

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Higher-order monochromatic aberrations in the human eye cause a difference in the appearance of stimuli at distances nearer and farther from best focus that could serve as a signed error signal for accommodation. We explored whether higher-order monochromatic aberrations affect the accommodative response to 0.5 D step changes in vergence in experiments in which these aberrations were either present as they normally are or removed with adaptive optics. Of six subjects, one could not accommodate at all for steps in either condition. One subject clearly required higher-order aberrations to accommodate at all. The remaining four subjects could accommodate in the correct direction even when higher-order aberrations were removed. No subjects improved their accommodation when higher-order aberrations were corrected, indicating that the corresponding decrease in the depth of field of the eye did not improve the accommodative response. These results are consistent with previous findings of large individual differences in the ability to accommodate in impoverished conditions. These results suggest that at least some subjects can use monochromatic higher-order aberrations to guide accommodation. They also show that some subjects can accommodate correctly when higher-order monochromatic aberrations as well as established cues to accommodation are greatly reduced. © 2006 Optical Society of America

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## 1. INTRODUCTION

The accommodative mechanism of the eye uses many cues to focus the retinal image of objects at a wide range of viewing distances.[1,2] The natural visual environment is rich in cues, allowing accommodation to respond in the appropriate direction to focus the retinal image with very rare errors. Cues that provide unambiguous information about the appropriate direction of the accommodative response include binocular disparity, familiarity, and a host of other depth cues.[3–5] There is also substantial evidence that many subjects can use the eye's aberrations to accommodate in the correct direction. For example, longitudinal chromatic aberration (LCA) provides an odd-error signal in that it specifies the direction of accommodation that will bring the retinal image into focus.[5–14] However, LCA is not the only stimulus to reflex accommodation. It is well known that many subjects can accommodate to changes in target vergence even when the target is viewed in monochromatic light to eliminate a cue from LCA.[15] Whether or not retinal blur provides an odd-error stimulus with both magnitude and sign of defocus[14] depends on whether the eye is aberrated. When there are no higher-order aberrations and astigmatism at all, a step change of defocus from the focused retinal plane to the front of retina (far step) and the same step change of defocus from the focused retinal plan to the back of retina (near step) produce identical point-spread functions (PSF) on the retina, so that defocus itself does not provide information about the direction of accommodation.

However, the eye suffers from higher-order aberrations besides defocus and astigmatism. Spherical aberration[3,5] and uncorrected astigmatism,[3,16,17] as well as other monochromatic aberrations,[18] provide odd-error cues to accommodation because they cause differences in the appearance of stimuli depending on whether there is a far or a near step of defocus. Wilson *et al.*[18] showed that subjects could see these differences in PSF subjectively, and trained them to use the visible information as a cue to determine whether the light is focused in front of or behind the retina. We set out to determine whether the subject actually uses this visible information when they accommodate.

Another viewpoint suggests that higher-order aberrations in the eye could hinder the accommodation response because the depth of focus is larger when higher-order aberrations are present.[19–22] The effect of correcting higher-order aberrations is to reduce the eye's depth of focus. For objects that lie nearer to or farther from the plane of focus, image quality can actually be worse than it is when aberrations are left uncorrected. If accommodation relies on the rate of change of focus, then the speed and accuracy of the accommodative response could actually be improved when higher-order aberrations are removed.

In this paper, we investigate whether higher-order aberrations affect accommodation in an experiment in which these aberrations were either present as they normally are or greatly reduced with adaptive optics (AO).

## 2. METHODS

### A. Subjects

Accommodation measurements were made on the right eyes of six subjects. The subjects ranged in age from 27 to 37 years old. Refractive error of the subjects ranged from +1 D to −3.5 D and astigmatism was less than 1 D. The subject's head was stabilized with a bite-bar. The AO system used a 6 mm entrance pupil, requiring the dilation of the subject's pupil with phenylephrine hydrochloride (2.5%). This drug was chosen to dilate the pupil while minimizing any effect on accommodation. Each subject's consent was obtained according to the declaration of Helsinki.

### B. Wave Aberration Measurement and Correction

Subjects viewed a stimulus from a digital light projector through the AO system shown in Fig. 1. This system[23] used a Shack–Hartmann wavefront sensor, conjugate with the subject's pupil plane, to make measurements of the eye's wave aberrations at 30 Hz. The Shack–Hartmann wavefront sensor had 221 lenslets in square array that could measure the aberrations for a 6.8 mm pupil up to the tenth radial order. The wave aberration measurements were made at a wavelength of 810 nm. A deformable mirror with 97 lead magnesium niobate actuators, also conjugate with the subject's pupil plane, was used to correct the wave aberrations based on the measurements from the Shack–Hartmann wavefront sensor, also at a frame rate of 30 Hz. The closed-loop bandwidth of the AO control loop was about 1 Hz. Since the stroke of a deformable mirror is not large enough to correct all ab-

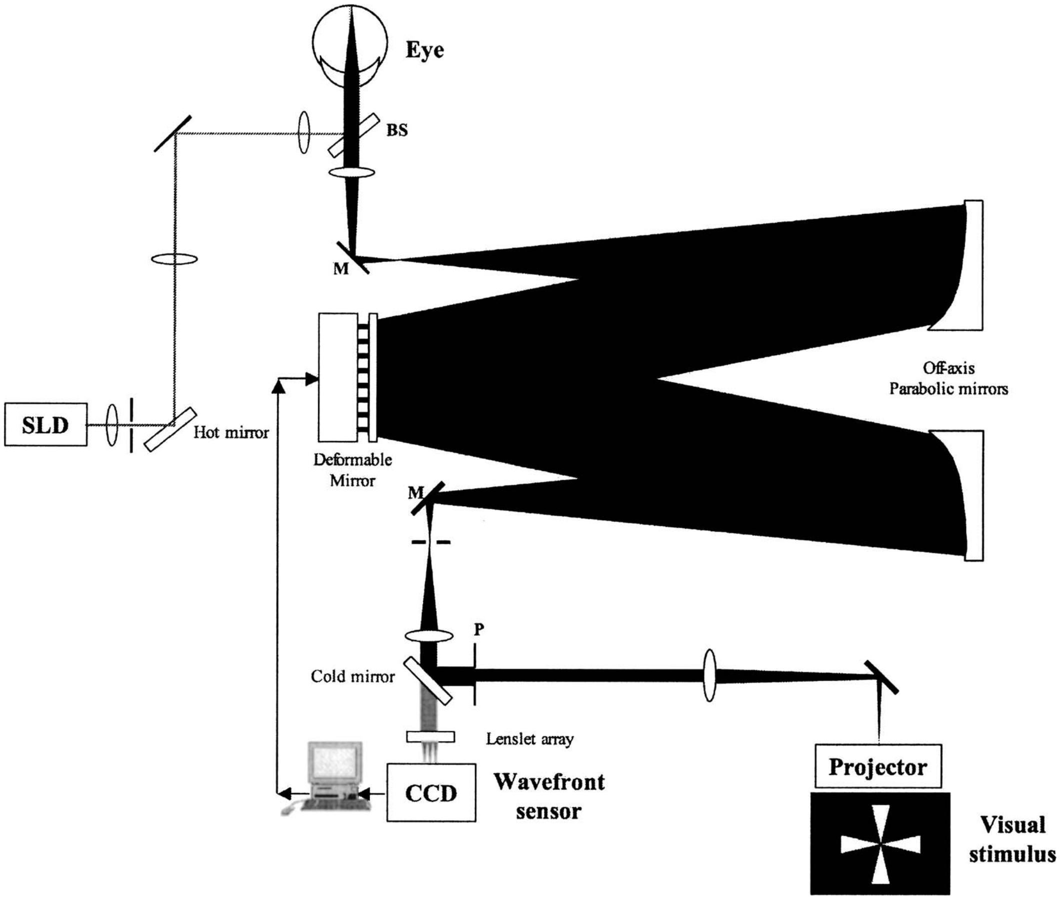


Fig. 1. Schematic diagram of the adaptive optics system for the accommodation experiment. The black path is used to deliver the stimulus image from the projector to the eye. The gray path, overlapped by the black path from the beam splitter (BS) before the eye to the cold mirror, represents the infrared light used for the wave aberration measurement and correction.

errations in some eyes, trial lenses were used to take out most of the low-order aberrations, defocus, and astigmatism. Then the deformable mirror corrected any residual low-order aberrations as well as the higher-order aberrations. Defocus was deliberately left uncorrected so that we could measure the accommodative response.

In all experiments, we used the deformable mirror to correct as many of the aberrations intrinsic to the instrument as the wavefront sensor could detect. Specifically, the static aberrations from the beam splitter (BS) to the wavefront sensor CCD were measured with the wavefront sensor using a reference beam injected into the system at the point where the eye would otherwise reside. These aberrations were small, corresponding to about 0.08 $\mu$m rms. Nonetheless, we could remove their influence by saving the actuator voltages in the deformable mirror required to compensate for them and playing these voltages back to the deformable mirror when the eye was in place. The wavefront sensor cannot detect any aberrations in the system between the cold mirror and the projector (referred to as noncommon-path errors) but calculations and measurements of the optical quality of this part of the path indicated these aberrations were very small and we therefore ignored them.

### C. Defocus Steps Generated with a Deformable Mirror

In addition to removing the higher-order aberrations in the eye on each trial, the deformable mirror also produced a step change in defocus of 0.5 D either from zero to far or from zero to near. Zero was defined as the defocus value producing best image quality for the observer. The aberration correction was done in a closed-loop fashion, so that the AO system was working at a frame rate of 30 Hz to generate the aberrations (or lack thereof) that we wished to present to the eye. The change of stimulus for a far step or a near step produced no change of magnification or target position. On each trial, the direction of the step was either in the far direction or near direction, determined randomly by the computer. The deformable mirror took 33 ms to generate a 0.5 D step change.

### D. Stimulus

Subjects viewed a test field subtending one degree of visual angle through a 6 mm artificial pupil in the adaptive optics system. A −0.75 D trial lens was placed in the pupil plane (denoted by P in Fig. 1) between the cold mirror and the projector, and the lens in front of the projector was repositioned axially to compensate for the −0.85 D chromatic aberration difference between the wavefront-sensing wavelength of 810 nm and the stimulus presentation at 550 nm and 390 td. We used a Maltese cross, shown on the bottom left in Fig. 1, as the stimulus for the accommodation and the fixation stimulus. To eliminate a cue from LCA, subjects viewed the Maltese cross in 550 nm monochromatic light created by filtering the projector output with an interference filter that had a bandwidth of 25 nm.

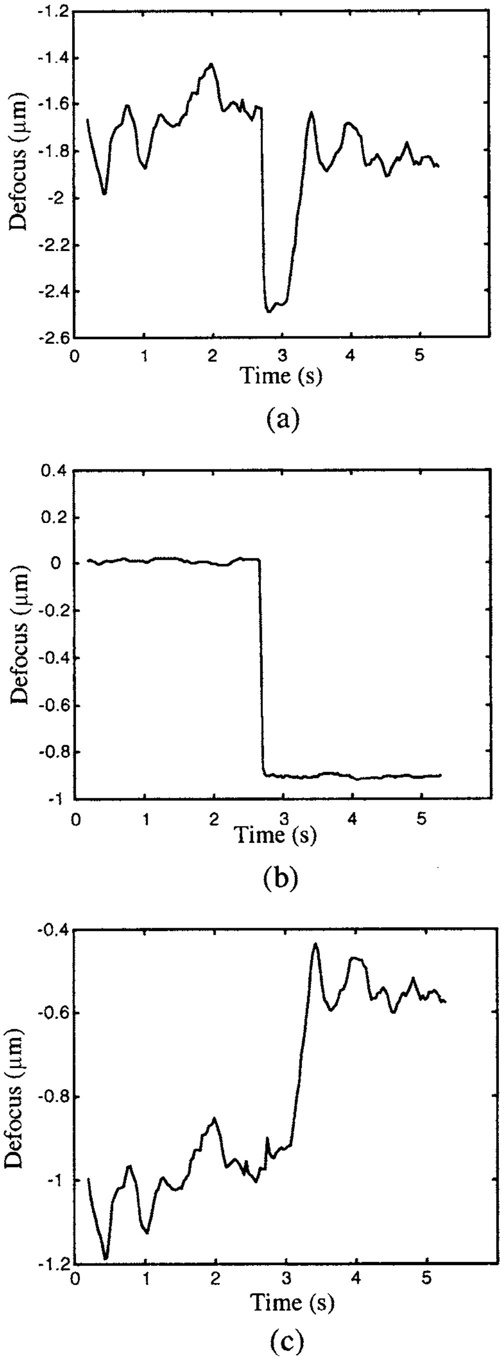


Fig. 2. Accommodation data processing procedure: (a) accommodation measurement with Shack–Hartmann wavefront sensor, (b) the deformable mirror changes in step of defocus measured by wavefront sensor, (c) accommodation response of subject.

### E. Accommodation Measurement with Adaptive Optics

Higher-order aberrations were either presented as they normally would be or removed with AO. We used trial lenses in front of the eye to correct defocus and astigmatism, sometimes supplemented by an additional defocus adjustment provided by moving the eye and the lens closest to the eye as a unit in one direction or the other while keeping the distance between them fixed. The accommodative response was measured with the Shack–Hartmann wavefront sensor at 30 Hz. Responses were measured in two conditions: either with all the normal higher-order monochromatic aberrations present or with these aberrations compensated for with the deformable mirror.

When we measured the subject's accommodation response with higher-order aberrations, on each trial the deformable mirror was shaped to compensate only for the static aberrations of the system itself, leaving the aberrations intrinsic to the eye uncorrected. It also generated a 0.5 D step of defocus either in the far direction or in the near direction 2 s after the trial started. The step lasted 2 s during which the Shack–Hartmann wavefront sensor tracked the change of defocus of the eye. When we measured the subject's accommodation response without higher-order aberrations, the deformable mirror was updated at 30 Hz for continuous correction of all aberrations except defocus on each trial. In addition, it also generated a 0.5 D step of defocus either in the far direction or in the near direction 2 s after the trial started. This step also lasted 2 s during which the Shack–Hartmann wavefront sensor tracked the change of defocus of the eye.

Since we used the deformable mirror to generate the step of defocus, the measurements made by the wavefront sensor also included the defocus generated by the deformable mirror. We developed the following method to separate the subject's accommodation response from the defocus changes produced by the deformable mirror. For every wavefront sensor frame on each trial, we saved the values of the voltages that were used to control the deformable mirror actuators. After the measurements were completed, these voltages were played back on the deformable mirror with an aberration-free, collimated laser beam in place of the subject's eye. To obtain the observer's accommodative response, we subtracted the deformable mirror defocus changes measured with a collimated beam in place of the eye from the wavefront sensor measurements made with the real eye. Figure 2 shows this procedure for analyzing the data.

At least ten trials were averaged to estimate the accommodative response for each subject. From the average accommodative response, we calculated the gain and response time both with and without higher-order aberrations. Response gain was defined as the amplitude of the response to the step divided by the amplitude of the stimulus step. Response time was defined as the time measured from the start of the stimulus to the time when the amplitude of the response reached 63.2% ($1/e$) of the total change.[3,24]

## 3. RESULTS

Figure 3 shows the rms wavefront error of higher-order aberrations with a 6 mm pupil from six subjects before correction and after correction. For a 6 mm pupil, the average correction of higher-order aberrations was reduced from an rms of 0.66 $\mu$m to an rms of 0.033 $\mu$m averaged across the six subjects, corresponding to a 20-fold reduction. This figure shows that the AO system did a good job of removing higher-order aberrations from the real eye.

We measured the accommodation response for six subjects and found different responses depending on the subject. Figure 4 shows that one subject could not accommodate at all for steps in either direction. One subject could not accommodate without higher-order aberrations, though this subject had excellent accommodation under normal conditions. Figure 5 shows data from this subject who accommodated well when higher-order aberrations were present but not when they were removed. This subject apparently uses her higher-order aberrations to accommodate in the correct direction in these viewing conditions.

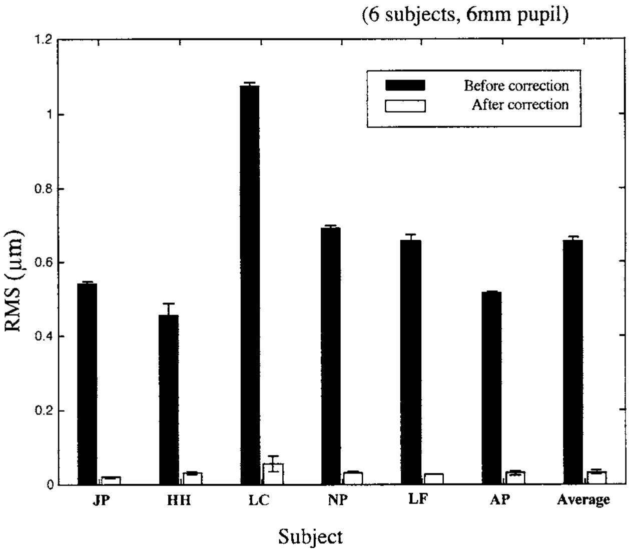


Fig. 3. RMS wavefront error of higher-order aberrations with a 6 mm pupil from six subjects before correction and after correction.

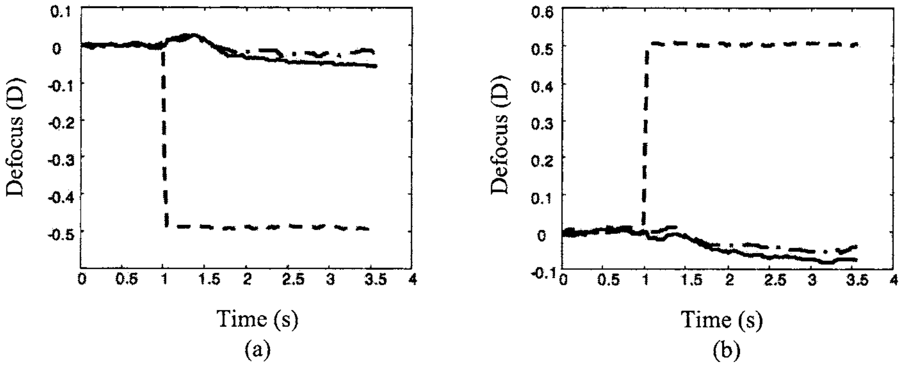


Fig. 4. One subject (AP) could not accommodate at all for steps in either direction. In this figure the dashed curve is the ideal response of accommodation for a 0.5 D step defocus. The solid curve is the accommodation response when higher-order aberrations were presented to the eye, and the dotted-dashed curve is the accommodation response when higher-order aberrations were removed from the eye by AO. (a) Accommodation to far step. (b) Accommodation to near step.

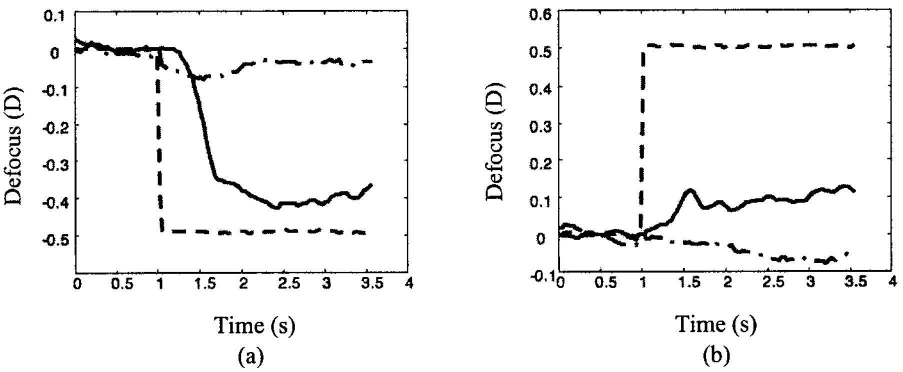


Fig. 5. One subject (LF) could not accommodate without higher-order aberrations (shown as dotted-dashed curve), but could accommodate with higher-order aberrations (shown as solid curve). (a) Accommodation to far step. (b) Accommodation to near step.

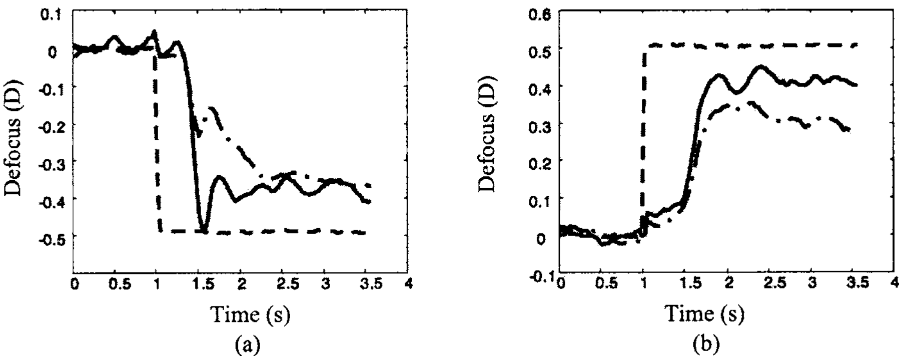


Fig. 6. One subject (JP) could accommodate in the correct direction even when higher-order aberrations were removed. Curves as designated for Fig. 4. (a) Accommodation to far step. (b) Accommodation to near step.

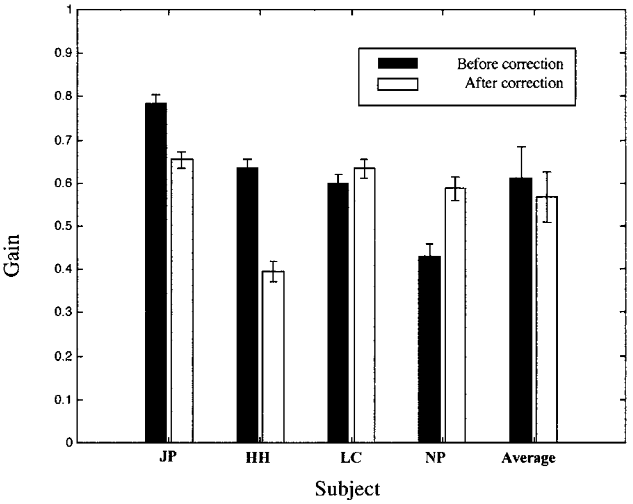


Fig. 7. Accommodation response gain with and without higher-order aberration, for four subjects.

But four out of six subjects could accommodate in the correct direction even when higher-order aberrations were removed. Figure 6 shows the average response of one subject who fell into this category. The behavior of the other three subjects was similar to this.

Figure 7 shows the response gain for the four subjects who could accommodate without higher-order aberrations. We combined the accommodation responses to the far and near steps in this graph. The solid bars correspond to the gain with higher-order aberrations present, while the open bars corresponds to the gain when higher-order aberrations were reduced with AO. When higher-order aberrations were presented to the eye, the average response gain across the four subjects was 0.61±0.14. When higher-order aberrations were removed by AO, the average response gain across the four subjects was 0.56±0.11, which is not significantly different from the

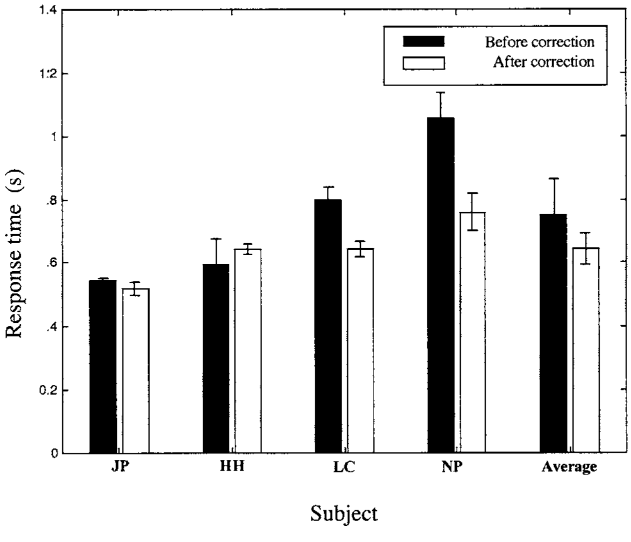


Fig. 8. Accommodation response time with and without higher-order aberration, for four subjects.

gain when higher-order aberrations were present (*t* test, *p* value=0.43). Figure 8 shows the response time for the four subjects who could accommodate with higher-order aberrations reduced. When higher-order aberrations were present in the eye, the average response time across the 4 subjects was 0.75±0.23 s. When higher-order aberrations were removed by AO, the average response time across the four subjects was 0.64±0.10 s. The *t* test result with the large *p* value (0.65) shows that the average response time of these four subjects was not significantly slower without higher-order aberrations compared with the response time when higher-order aberrations were present.

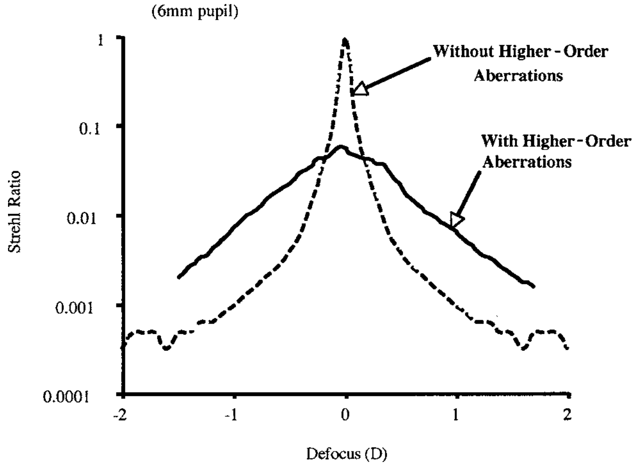
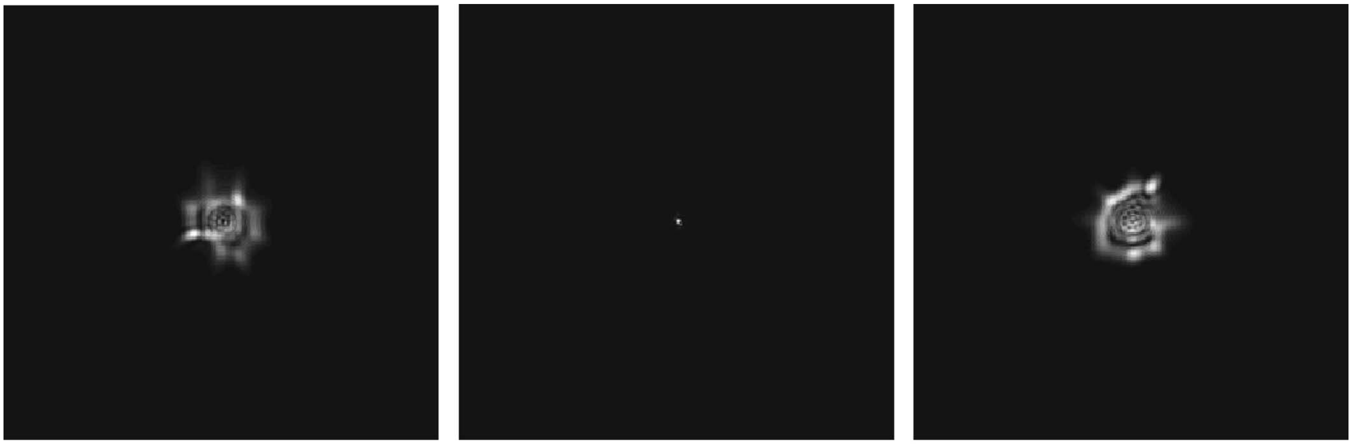


Fig. 9. Decrease in depth of focus when higher-order aberrations are completely corrected. Pupil size was 6 mm. The dashed curve plots the Strehl ratio for an eye suffering only from diffraction and various amounts of defocus. The solid curve is the mean Strehl ratio as a function of defocus calculated from the higher-order aberrations measured with a Shack–Hartmann wavefront sensor in 13 eyes. Different amounts of defocus generate the highest Strehl ratio in different eyes due to the influence of higher-order aberrations, especially spherical aberration. Therefore, we moved each subject's curve along the $x$ axis so that the center of mass lay at 0 D prior to averaging. Higher-order aberrations broaden the curve compared to the diffraction-limited case, resulting in better image quality when the eye is defocused by more than ~0.1 D. Similar calculations on the smaller number of subjects used in this study produced similar results.

## 4. DISCUSSION

The subjects in this experiment showed a wide range of accommodative behaviors. One subject could not accommodate at all in the Badal optical system. The conditions for accommodation were impoverished compared with normal viewing due to the absence of depth cues and LCA. In white light, this subject could accommodate, suggesting that he uses chromatic aberration. But we do not have a good explanation for why this subject differed from the others, who could accommodate in monochromatic light. This subject had among the lowest rms wavefront errors, suggesting that an increased depth of field caused by a large amount of aberrations was not responsible for his failure to accommodate. Another subject accommodated well when higher-order aberrations were present but could not accommodate at all when higher-order aberrations were removed. Finally, four subjects accommodated well both with and without higher-order aberrations. Such wide variation in response among subjects is in line with previous experiments that show wide interindividual variability in response to the effects of defocus and chromatic aberration.[5,9,12,15] It would be of some interest to understand what determines these individual differences. The one subject who could not accommodate without higher-order aberrations did have unusually large amounts of seventh-order aberrations compared with the other subjects, but a study with more subjects would be required to determine whether this had any significance.

Figure 9 shows that the depth of focus is larger when higher-order aberrations are present in the eye. The curves show the average Strehl ratio as a function of defocus based on the wave aberrations of 13 subjects. In averaging the data across the 13 subjects, the curves were first adjusted along the $x$ axis so the center of mass lay at zero D. The correction of higher-order aberrations improves image quality at best focus but reduces image quality for values of defocus away from the maximum, thereby reducing the eye's depth of focus. If accommodation relies on the rate of change of focus, then accommodation could be better when higher-order aberrations are



**Far step 0.5 D** **0 D** **Near step -0.5 D**

Fig. 10. Near and far steps produce quite different point spread functions at 550 nm wavelength with residual aberrations (subject JP); each image corresponds to 1 deg visual angle on a side.

removed from the eye. We did not find any evidence in either the response gain or the response latency that accommodation was improved by removing higher-order aberrations. Either a subject's performance was worse without higher-order aberrations or it was unchanged, but in no case did it improve. Apparently the increase in the rate of change in image quality with focus error produced by removing higher-order aberrations does not improve the accommodative response.

We were surprised to find that four of our six subjects could accommodate essentially normally despite the absence of conventional depth cues as well as the great reduction in information available from chromatic and monochromatic aberrations. The use of a 25-nm bandwidth interference filter should have substantially impaired the use of LCA, while AO reduced higher-order aberrations by about a factor of 20. Our adaptive system had adequate temporal bandwidth to track most of the temporal instability in the higher-order aberrations. Higher-order aberrations are mainly static aberrations, though wavefront sensors record that small-amplitude, temporal instabilities may or may not influence retinal image quality.[24–27] The results in these four subjects depart from those reported by Fernandez,[28] who found that the accommodative response gain and speed were reduced following removal of asymmetric aberrations.

Despite this, it is possible that the residual aberrations that remained may have provided an odd-error signal for the four subjects who retained accommodation. Figure 10 shows the PSFs computed from the residual wave aberration in subject JP for near and far steps. These PSFs are easily distinguished, and some subjects may be able to use this information. An experiment in which the sign of higher-order aberrations were systematically changed at the same time the vergence step were introduced could help clarify the role these small aberrations played. It is also possible that microfluctuations of accommodation provided a signed cue for the accommodative system in our experiment. It is well known that the eye exhibits temporal fluctuations in defocus, with bandwidths less than ~2 Hz.[29–32] It is conceivable that observers can detect the change in retinal image quality caused by microfluctuations after the vergence step to make the correct change in accommodation. Although oscillations of accommodation may have played a role in the present experiment, previous experiments show that the eye continues to accommodate in the correct direction in the absence of feedback from oscillations.[10,11] This suggests that an unknown directional signal may have provided the sign of defocus in the present experiment. Fincham[5] suggested that accommodation responds to the angle of incidence of light reaching the retina, but the results of experiments to test this possibility remain equivocal.[15,33]

## 5. CONCLUSIONS

We measured the accommodation response either with higher-order monochromatic aberrations present in the eye as they normally are or greatly reduced with AO. Our results show that when depth cues and chromatic aberration have been eliminated as cues, most subjects are capable of accommodating in the correct direction despite a reduction in higher-order aberrations. For most subjects, there is no significant difference in the accommodative response with or without higher-order aberrations. For one subject, removing higher-order aberrations prevented accommodation, suggesting that higher-order aberrations can, in at least some eyes, provide the sign of defocus for accommodation. It remains to be clarified what drives different observers to rely on different cues to focus their eyes.

## ACKNOWLEDGMENTS

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## REFERENCES

1. F. M. Toates, "Accommodation function of the human eye," Physiol. Rev. **52**, 828–863 (1972).
2. P. B. Kruger and J. Pola, "Stimuli for accommodation: blur, chromatic aberration and size," Vision Res. **26**, 957–971 (1986).
3. F. W. Campbell and G. Westheimer, "Factors influencing accommodation responses of the human eye," J. Opt. Soc. Am. **49**, 568–571 (1959).
4. G. G. Heath, "Components of accommodation," Am. J. Optom. Arch. Am. Acad. Optom. **33**, 569–579 (1956).
5. E. F. Fincham, "The accommodation reflex and its stimulus," Br. J. Ophthamol. **35**, 381–393 (1951).
6. D. I. Flitcroft, "A neural and computational model for the chromatic control of accommodation," Visual Neurosci. **5**, 547–555 (1990).
7. K. R. Aggarwala, S. Mathews, E. S. Kruger, and P. B. Kruger, "Spectral bandwidth and ocular accommodation," J. Opt. Soc. Am. A **12**, 450–455 (1995).
8. J. C. Kotulak, S. E. Morse, and V. A. Billock, "Red-green opponent channel mediation of control of human ocular accommodation," J. Physiol. (London) **482**, 697–703 (1995).
9. P. B. Kruger, S. Mathews, K. R. Aggarwala, and N. Sanchez, "Chromatic aberration and ocular focus: Fincham revisited," Vision Res. **33**, 1397–1411 (1993).
10. P. B. Kruger, S. Mathews, K. R. Aggarwala, D. Yager, and E. S. Kruger, "Accommodation responds to changing contrast of long, middle and short spectral-waveband components of the retinal image," Vision Res. **35**, 2415–2429 (1995).
11. P. B. Kruger, S. Mathews, M. Katz, K. R. Aggarwala, and S. Nowbotsing, "Accommodation without feedback suggests directional signals specify ocular focus," Vision Res. **37**, 2511–2526 (1997).
12. J. H. Lee, L. R. Stark, S. Cohen, and P. B. Kruger, "Accommodation to static chromatic simulations of blurred retinal images," Ophthalmic Physiol. Opt. **19**, 223–235 (1999).
13. F. J. Rucker and P. B. Kruger, "Accommodation responses to stimuli in cone contrast space," Vision Res. **44**, 2931–2994 (2004).
14. L. W. Stark and Y. Takahashi, "Absence of an odd-error

signal mechanism in human accommodation," IEEE Trans. Biomed. Eng. **BME-12**, 138–146 (1965).

15. P. B. Kruger, L. R. Stark, and H. N. Nguyen, "Small foveal targets for studies of accommodation and the Stiles–Crawford effect," Vision Res. **44**, 2757–2767 (2004).
16. M. J. Allen, "The stimulus to accommodation," Am. J. Optom. Arch. Am. Acad. Optom. **32**, 422–431 (1955).
17. G. Walsh and W. N. Charman, "Visual sensitivity to temporal change in focus and its relevance to the accommodation response," Vision Res. **28**, 1207–1221 (1988).
18. B. J. Wilson, K. E. Decker, and A. Roorda, "Monochromatic aberrations provide an odd-error cue to focus direction," J. Opt. Soc. Am. A **19**, 833–839 (2002).
19. A. Guirao, J. Porter, D. R. Williams, and I. G. Cox, "Calculated impact of higher-order monochromatic aberrations on retinal image quality in a population of human eyes," J. Opt. Soc. Am. A **19**, 1–9 (2002).
20. Y. K. Nio, N. M. Jansonius, V. Fidler, E. Geraghty, S. Norrby, and A. C. Kooijman, "Spherical and irregular aberrations are important for the optimal performance of the human eye," Ophthalmic Physiol. Opt. **22**, 103–112 (2002).
21. P. A. Piers, E. J. Fernández, S. Manzanera, S. Norrby, and P. Artal, "Adaptive optics simulation of intraocular lenses with modified spherical aberration," Invest. Ophthalmol. Visual Sci. **45**, 4601–4610 (2004).
22. X. Cheng, A. Bradley, and L. N. Thibos, "Predicting subjective judgment of best focus with objective image quality metrics," J. Vision **4**, 310–321 (2004).
23. H. Hofer, L. Chen, G. Y. Yoon, Y. Yamauchi, and D. R. Williams, "Improvement in retinal image quality with dynamic correction of the eye's aberration," Opt. Express **8**, 631–643 (2001).
24. S. Phillips, D. Shirachi, and L. Stark, "Analysis of accommodative response times using histogram information," Am. J. Optom. Physiol. Opt. **49**, 389–400 (1972).
25. F. W. Campbell and G. Westheimer, "Dynamics of accommodation responses of the human eye," J. Physiol. (London) **151**, 285–295 (1960).
26. F. W. Campbell, J. G. Robson, and G. Westheimer, "Fluctuations of accommodation under steady viewing conditions," J. Physiol. (London) **145**, 579–594 (1959).
27. W. N. Charman and G. Heron, "Fluctuations in accommodation: a review," Ophthalmic Physiol. Opt. **8**, 153–164 (1988).
28. E. J. Fernandez and P. Artal, "Adaptive-optics correction of asymmetric aberrations degrades accommodation," Invest. Ophthalmol. Visual Sci. **43**, 954 (2002).
29. H. Hofer, P. Artal, B. Singer, J. L. Aragón, and D. R. Williams, "Dynamics of the eye's wave aberration," J. Opt. Soc. Am. A **18**, 497–506 (2001).
30. R. A. Applegate, C. S. Ballentine, and A. Roorda, "Is a bite-bar needed for Shack–Hartmann wavefront sensing?" Invest. Ophthalmol. Visual Sci. **42**, S604 (2001).
31. X. Cheng, N. L. Himebaugh, P. S. Kollbaum, L. N. Thibos, and A. Bradley, "Test–retest reliability of clinical Shack–Hartmann measurements," Invest. Ophthalmol. Visual Sci. **45**, 351–360 (2004).
32. M. Zhu, M. J. Collins, and D. R. Iskander, "Microfluctuations of wavefront aberrations of the eye," Ophthalmic Physiol. Opt. **24**, 562–571 (2004).
33. P. B. Kruger, N. Lopez-Gil, and L. R. Stark, "Accommodation and the Stiles–Crawford effect: Case study and theoretical aspects," Ophthalmic Physiol. Opt. **21**, 338–350 (2001).