Monochromatic aberrations provide an odd-error cue to focus direction

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Monochromatic aberrations that exist in the human eye will cause differences in the appearance of the point-spread function (PSF) depending on whether there is positive or negative defocus. We establish whether it is possible to use these differences in the PSF to distinguish the direction of defocus. The monochromatic aberrations of eight subjects were measured with a Hartmann–Shack wave-front sensor. Subjects also performed a forced-choice psychophysical task in which they decided whether a blurred target was defocused in front of or behind the retina. The optical system for the psychophysical task was designed to isolate the blur due to monochromatic aberrations as the only odd-error cue to the direction of defocus. Shack–Hartmann measurements showed that monochromatic aberrations increase as the pupil size increases. On average, the correct/incorrect responses for discriminating differences in the PSF for different directions of defocus were 54/46 for a 1-mm pupil and 83/17 for a 5-mm pupil, representing more than an eight-fold increase in discriminability. This discriminability extended for large amounts of defocus and also for more complex targets, such as letters. Sensitivity to the differences in the PSF for different directions of defocus increased as monochromatic aberrations increased, particularly for the even-order aberrations, which give rise to an odd-error focus cue. It was found that the ability to discriminate PSFs for different directions of defocus varied among individuals but, in general, depended on the magnitude of monochromatic aberrations.

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1. INTRODUCTION

It is well known that humans are able to perceive the shape of blur on the retina that is caused by monochromatic ocular aberrations. In fact, before sophisticated techniques to measure and display aberrations and point-spread functions (PSFs) existed, scientists often described the shape of blur on the retina with hand-drawn sketches.[1–3]

It has since become routinely possible to predict the blur on the retina by using objective techniques that measure aberrations and subsequently compute the PSF of the eye[4] (see Ref. 5 for an extensive collection of papers). Recently Navarro and Losada compared the perceived PSF and the predicted PSF obtained from an objective technique and obtained excellent matches.[6]

The motivation of the current study is to test whether the eye might use the visible information in its PSF as a cue to determine whether the light is focused in front of or behind the retina. The argument is as follows: In an aberration-free optical system an identical shape of blur would be perceived if an object was defocused by the same amount on either side of the retina. With monochromatic aberrations the blur will appear different, depending on whether there is positive or negative defocus (see Fig. 1 below).

Such information can be brought to bear on unanswered questions in vision such as “What are the cues for accommodation” and “What drives emmetropization in the developing eye?” In the absence of the obvious accommodative cues (vergence, scaling, looming, chromatic aberrations, trial and error), the eye still demonstrates an ability to focus in the correct direction.[7–10] There are also unanswered questions about what drives emmetropization. The developing eye can adjust its growth to maintain the surrounding environment in focus.[11] This process of emmetropization requires regulation in the appropriate direction, depending on the sign of defocus. The response in the correct direction has been shown to occur in the absence of accommodative cues such as chromatic aberration and accommodation[12,13] and without sufficient exposure time for a trial-and-error approach to determining the correct sign.[14]

The idea that blur due to monochromatic aberrations provides an odd-error cue is not new. Fincham[7] discussed this odd-error signal after he found that some subjects could accommodate in the correct direction even after chromatic-aberration cues were removed. Campbell and Westheimer[8] found results similar to those of Fincham. To study further the effect of monochromatic aberration, both Fincham and Campbell and Westheimer re-

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peated their experiments, with the subject viewing through an annular pupil in an attempt to eliminate the monochromatic-aberration cue. We now know that this method is not very effective because the eye has more than simple rotationally symmetric spherical aberration.[15] Charman and Tucker[16] and Walsh and Charman[17] concluded that monochromatic aberrations could serve as an odd-error cue for accommodation after the subject looked at the through-focus modulation and phase transfer functions of the eye in the presence of aberrations. However, they concentrated more on gratings, whose effects are observed only in one dimension, thereby failing to produce all the asymmetries that one would observe by looking at a point source or a complex object such as a letter. In the present study, we present point-source stimuli as well as more complex stimuli. We also control the magnitude of aberrations by using different pupil sizes. The small pupil, having relatively low aberrations, is expected to produce a weaker odd-error signal than a larger pupil.

The goal of this paper is to establish that it is possible for humans to use shape information from monochromatic aberrations to detect a difference in the appearance of the PSF between myopic and hyperopic defocus. This study does not address directly the questions of what drives accommodation and emmetropization. Rather, we intend to make the argument that if the odd-error cue in the PSF due to blur from monochromatic aberrations is salient enough to be detected in a psychophysical experiment, then it is conceivable that blur shape can provide a cue to the direction of defocus.

2. METHODS

The experiment involved two parts: an objective measurement of the subjects' monochromatic aberrations and a psychophysical task to test the ability of the subjects to discriminate between PSFs with different directions of defocus. Eight subjects participated in this experiment. The subjects ranged in age from 23 to 35 yr. The subjects' refractive errors ranged from +0.50 diopters (D) to −2.50 D, and astigmatism was always less than −0.25 D. Subjects gave informed consent to the experiments, which were approved and conducted according to the guidelines for experiments involving human subjects by the University of Houston Committee for the Protection of Human Subjects.

A. Aberration Measurement

The subjects' monochromatic aberrations were measured with a Shack–Hartmann wave-front sensor.[4,18] Wave-front sensing with this sensor begins by projecting a small spot of light onto the retina. This spot of light serves as the source of scattered light that emerges from the eye. In the diffraction-limited eye, the wave front emerging from the small spot would be planar. The deviation of the actual wave front from a planar wave front is defined as the wave aberration; it is measured by passing the emerging light through a lenslet array that focuses the light onto a CCD camera as an array of focal points. The wave front is inferred from the deviation of the focal points from where they would be if the eye were perfect. In our particular device, the light source was a 795-nm laser diode, and the lenslet array was composed of a square grid of 0.4-mm-diameter lenslets with 24-mm focal lengths.

The combined root mean square (RMS) of all wave aberrations except defocus was the metric used to quantify the magnitude of the monochromatic aberrations for each subject. Custom Matlab programs were written to generate PSFs for each subject for a range of defocus errors and pupil sizes (see Fig. 1).

B. Psychophysics

Each of the subjects performed a forced-choice psychophysical task in which the subject had to decide whether a blurred target was defocused in front of or behind the retina. An optical system was designed to present a target to the subject with varying amounts of defocus. The target for this psychophysical task was a 10-μm point source formed by a spatial filter (see Fig. 2). The following steps were taken in the experiment to ensure that the only odd-error cue to the direction of defocus was from the monochromatic aberrations of the subject's eye:

- Accommodation was reduced by topically applying one or two drops of cyclopentolate hydrochloride (1%) 30 min before the experiment.
- The target was presented in brief exposures of only 100 ms to eliminate trial-and-error cues from any remaining accommodation. The time constancy also limited the amount of time for viewing the target, thereby preventing the subject from looking at more difficult targets for a longer period.
- A narrow-band target was used to reduce cues from chromatic aberration in the eye. The source was a 658-nm LED with a bandwidth of 40 nm.
- The task was performed monocularly to eliminate binocular vergence cues.
- A Badal optometer was used to keep illuminance and magnification constant for all amounts of defocus.
- Neutral density filters (NDFs) were used to keep retinal illuminance constant for all pupil sizes. No NDF was used for the 1-mm pupil size. For the larger pupil sizes of 2 mm and 5 mm a 0.6 optical density NDF and a 1.4 optical density NDF, respectively, were used. The 1.4 NDF for the 5-mm pupil was a conservative correction, as it would have actually reduced the relative brightness of the PSF in the 5-mm pupil (owing to the Stiles–Crawford effect) and consequently reduced the ability to discriminate between different PSFs.

The procedure for the experiment was as follows: First the subject was aligned with the optical system in the following way. The artificial pupil diameter was set to the smallest possible value (<1 mm). While the subject was fixed to the bite-bar mount, the eye was roughly aligned in the instrument and was then translated horizontally to the point where the subject just lost sight of the point source. This was done in both directions, and the midpoint was determined. The same procedure was done to align the eye in the vertical direction.

Once the eye was aligned with the optical system, we determined the axial position of the point source that appeared in best focus. For the 5- and 2-mm pupils we moved the spatial filter on the optical rail until a best fo-

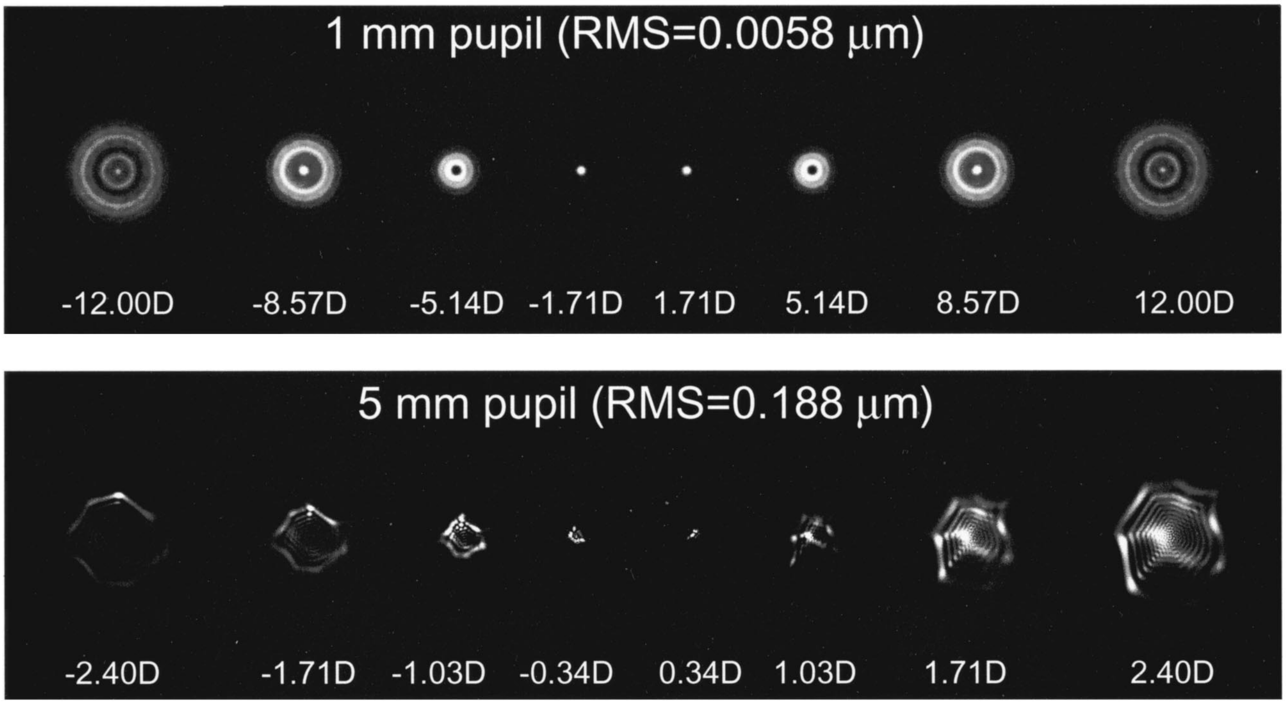

Fig. 1. Simulated PSFs for subject SN, based on his monochromatic aberrations, are shown for a 1-mm and 5-mm pupil. The RMS aberration for all terms except defocus is shown for both pupil sizes. The series of images simulates what this subject would perceive when looking at a point source. The amount of defocus that was used for the simulated defocus is listed below each PSF. The task of the subject was to distinguish between points that were defocused by the same amount but with opposite sign. With this figure it is possible to appreciate the difficulty of distinguishing the sign of defocus with a pupil size of 1 mm, but it is possible to distinguish shape differences with a 5-mm pupil.

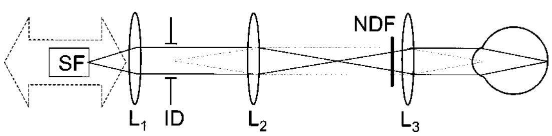

Fig. 2. Schematic of the apparatus. A Badal optometer combined with a telescope was used to present the point source. An adjustable iris diaphragm, ID, was placed at the focal point of a 20-D achromatic lens, L_1. The iris diaphragm was also conjugate to the pupil of the subject's eye through two 10-D achromatic lenses, L_2 and L_3. A neutral density filter, NDF, was placed in the path to control the luminance. The point target was defocused by changing the location of the spatial filter, SF, on an optical rail. The subject's alignment was maintained by a bite bar.

cus was reported. Owing to the large depth of focus with a 1-mm pupil, the best focus was found as the midpoint between the first noticeable diffraction rings in both blur directions. For each pupil size, we trained the subjects before collection of the data by showing them the point source for both hyperopic and myopic defocus of varying amounts and identifying them as being "nearer" and "farther," respectively. The training period was limited to approximately 2 min. During the psychophysical experiment, four defocused PSFs on each side of the subject's best focus were presented. The experiment was done in three blocks. In each block, the defocused PSFs were shown 10 times each in random order, totaling 80 presentations, for a total of 240 presentations for the three blocks at each pupil size. The experiment was split into blocks so we could compute the variability in the response of the subject. The four defocused stimuli on either side of the best focus had mean values that were equally distributed within the range, but the exact amount was varied randomly about the mean to prevent the subject from memorizing one particular shape of the PSF. Each subject performed the task for three different pupil sizes: 5, 2, and 1 mm. The range of defocus for the 1-mm pupil was ± 12 D. The dioptric range for larger pupil sizes was reduced to maintain similar blur sizes at the extents of the defocus range. This was done by dividing the 12-D range by the pupil size: ± 6D for a 2-mm pupil and ± 2.4 D for a 5-mm pupil. The only remaining difference between the tasks for the different pupil sizes was the magnitude of the aberrations of the eye, which was expected to be less for the smaller pupils. One full experimental session lasted approximately 1.5 h.

3. RESULTS

A. Wave Aberration Measurements

Measurements of the monochromatic aberrations for each subject show that monochromatic aberrations increase with increasing pupil size. The magnitude of the monochromatic aberrations is expressed as the RMS of the wave aberration measured with the Shack–Hartmann wave-front sensor. The plot of the RMS as a function of pupil size for all subjects is shown in Fig. 3.

B. Point-Source Stimuli

The data from the psychophysical test were recorded as the fraction of responses that were selected as myopic. For example, if a subject were to correctly identify all 30 presentations of a target with myopic blur, the value for that amount of blur would be 1. If all 30 presentations of a hyperopic blur were correctly identified, the value would be 0. The data were recorded separately for each pupil size. The complete results for one subject, SN, are shown in Fig. 4.

The subject's ability to discriminate between blur directions was quantified by taking the difference in the percent selected as myopic between equal amounts of blur with different signs. Discriminability was defined as the fraction of presentations above chance levels for which the blur direction was correctly differentiated. A discriminability plot is shown in Fig. 5 for subject SN. All three pupil sizes are shown on the same plot, and therefore the amount of defocus is shown on a normalized blur scale.

To reduce the data further, we determined the average discriminability value for each subject by taking the average of the discriminabilities for all myopic and hyperopic blurs for a single pupil size. These values of average discriminability versus pupil size are plotted in Fig. 6 for all eight subjects. The response of the subjects was variable, but for each, the discriminability increased monotonically with pupil size. Therefore it follows that since RMS aberrations also increase with pupil size (see Fig. 3), the discriminability increases as the amount of aberration increases.

C. Extended Range

We postulated that at some amount of dioptric blur, it would become difficult to distinguish odd-error cues because the even-error spherical defocus would begin to dominate and make other cues indistinguishable. To test this, we extended the range for the 5-mm pupil from a maximum blur of 2.4 D to 12 D. The same procedure was repeated, for a total of 240 random presentations of blurred PSFs. Six subjects performed this extended-range psychophysical task. No NDF was used.

The average discriminability for the four different values of blur is shown in Table 1. Discriminability increases as the blur size increases up to 8.57 D and then decreases. Peak performance occurred at 8.57 D. It is not known whether discriminability would continue to decrease toward zero because the full range of our optical instrument was 12 D.

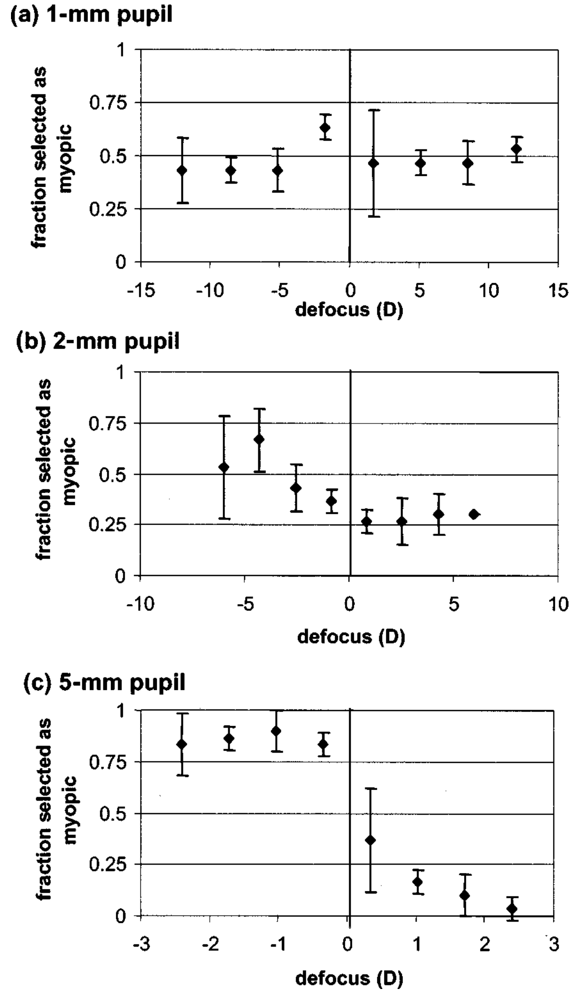

Fig. 4. Complete data for one subject, SN. We plotted the percentage of stimuli that were selected as myopic for each blur condition. For a 1-mm pupil, SN had trouble deciding on the sign of the blur. As the pupil size increased, the aberrations increased and the ability to select the correct sign increased. The error bars are the standard deviations of each value computed from the three separate measurements.

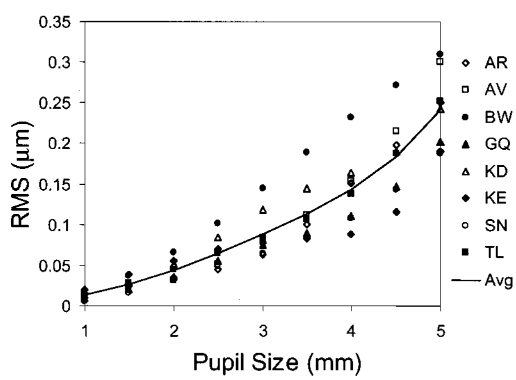

Fig. 3. RMS as a function of pupil size for eight subjects. The RMS was calculated from the wave aberration of the eye measured with the Shack–Hartmann wave-front sensor. A tenth-order Zernike polynomial was fitted to each pupil size (based on the original wave-front measurement above 6 mm) before calculation of the RMS. This was done so that we could remove the residual defocus term for each pupil size.

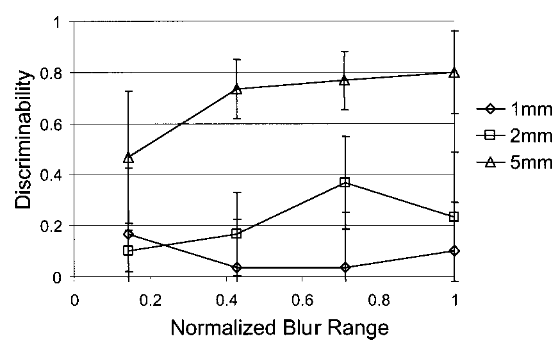

Fig. 5. Discriminability is defined as the fraction of times above chance levels that the subject chose the correct direction of the sign of defocus for a given amount of blur. Discriminability is plotted here for subject SN and is the best for the largest pupil diameter. Error bars are ±1 standard deviation.

D. Complex Stimuli

The psychophysical experiment was repeated with an extended target and the same pupil sizes and defocus levels. The target was a line of five letters. The letter sizes were scaled to a height of 5 arc min, which is the angular subtense of a 20/20 letter. The letters were printed on a clear 35-mm slide with a black background. Five subjects did the psychophysical experiment with letters. First, the subject found a new best-focus position for the complex target, and then we followed the same procedure that was used with the point-source experiments. For this last set of experiments we used tropicamide (1%) rather than cyclopentolate hydrochloride to dilate the pupil and arrest accommodation. While the depth of cycloplegia is expected to be less with tropicamide, we were confident that the short stimulus presentation (100 ms) was sufficient to eliminate any opportunities for accommodative cues.

The results were very similar to those of the point-source tests. All but one of the five subjects showed a monotonic increase in discriminability with pupil size. The results are plotted in Fig. 7.

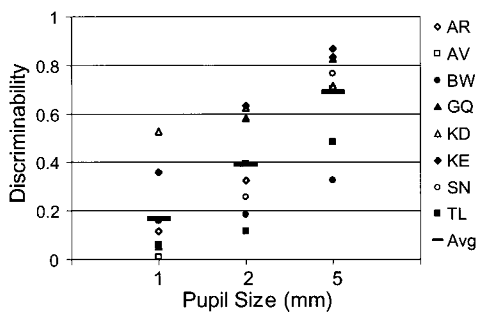

Fig. 6. Average discriminability calculated from all blur sizes on either side of best focus. The plot shows the average discriminability as a function of pupil size for all eight subjects in the experiment. The response varied between subjects, but in all cases the discriminability increased monotonically with pupil size.

Table 1. Summary of Discriminability Values of six Subjects for a 5-mm Pupil over an Extended Dioptric Range

Blur (diopters)	Discriminability						
	TL	GQ	KD	AV	SN	BW	Average
1.71	0	0.9	0.767	0.533	0.5	0.0667	0.461
5.14	0.0333	0.95	0.8337	0.733	0.667	0.233	0.575
8.57	0.0667	0.95	0.933	0.7	0.833	0.467	0.6583
12	0.233	0.75	0.833	0.733	0.8	0.133	0.5806

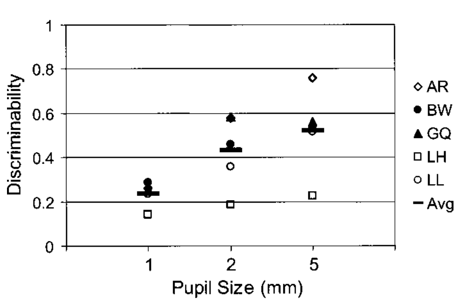

Fig. 7. Average discriminability for 20/20-sized letters rather than a point source. In this plot the average discriminability is calculated from all blur sizes on either side of best focus. The plot shows the average discriminability as a function of pupil size for all five subjects in the experiment. The response varied between subjects, but in all cases but one (GQ) the discriminability increased monotonically with pupil size.

4. DISCUSSION

We found that the ability to discriminate the direction of blur increases as the aberrations increase, but we were interested in the predictive power of the RMS aberration on discriminability. Figure 8 shows a plot of the discriminability versus the RMS aberration. All pupil sizes are shown here, so there are 24 points in the scatterplot. There is a significant increase in discriminability with RMS aberrations, but the R^2 value is low, meaning that the RMS alone cannot adequately explain our results. This is due partly to the fact that RMS does not distinguish among the different types of aberration in the eye, some of which have blurs that are symmetric when combined with positive or negative defocus. Incidentally, it is the asymmetric aberrations (orders 3, 5, 7, etc.), starting with the simple coma terms, that provide no odd-error focus cue. Figures 9(a) and 9(b) show the PSF for subject SN, 0.5 D on either side of best focus when only the even-order aberrations and odd-error aberrations, respectively, are used. All the odd-order aberrations give rise to an even-error cue (therefore no cue) for focus direction. When we replot (Fig. 10) the discriminability versus the RMS for the even-error aberrations alone, we see that there is a slightly greater dependence of discriminability on the aberrations that give rise to the odd-error focus cue. The reason that the dependence of discriminability on the even-order aberrations alone is only slightly greater is that the magnitude of odd-order and even-order aberrations are highly correlated with each other ($R^2 = 0.86$).

Another important result is that the eye can discriminate the sign of the blur even with low amounts of aberration: amounts that are commonly considered to be diffraction limited (Marachel's criterion[19] states that optics are effectively diffraction limited when the RMS aberration is less than λ/14). Such small amounts of aberrations have a negligible effect on image quality, yet the eye still demonstrates an extreme sensitivity for detecting and recognizing the small distortions that these residual aberrations generate,[20] especially when the aberrations are combined with some defocus.

The smallest amount of defocus that we presented was 0.34 D for the 5-mm pupil. The discriminability for this small amount of defocus was usually quite high, which agrees with the results of Campbell *et al.*,[21] who suggest that a sufficient odd-error signal exists in a typical eye for defocus values as small as 0.125 D.

When presented with more complex, defocused targets, the subjects showed discriminability similar to what we measured for the point sources. This implies that these cues should be visible for real-world objects, at least for those that contain components with high spatial frequency and contrast.

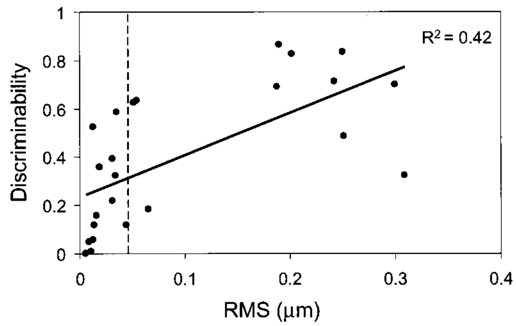

Fig. 8. Discriminability versus RMS wave aberration. The discriminability increases with wave-front error but is weakly dependent on this linear relationship. The relationship between aberrations and discriminability is more complicated. The vertical dashed line indicates the RMS values below which the optics are considered to be diffraction limited.

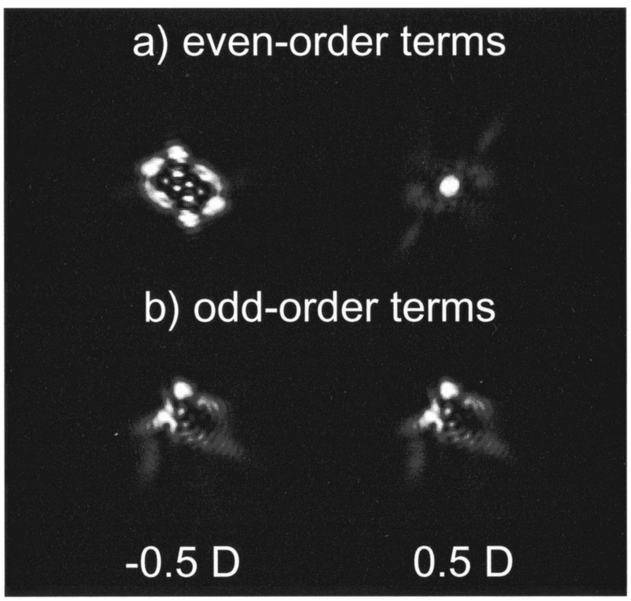

Fig. 9. PSFs for subject SN with −0.5 and +0.5 D of defocus, calculated with (a) even-order aberrations, which give rise to an odd-error focus cue, and (b) odd-order aberrations, which give rise to an even-error focus cue (or no focus cue).

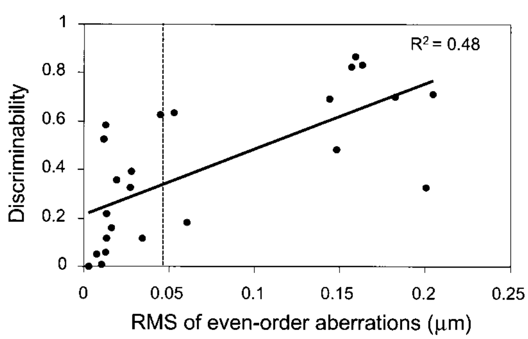

Fig. 10. Discriminability versus RMS aberrations for the even-order aberrations. The even-order aberrations give rise to an odd-error focus cue, and therefore the discriminability is more dependent on these terms. The vertical dashed line indicates the RMS value below which the optics are considered to be diffraction limited for 632-nm light.

It is important to note that the task of the subjects was not to demonstrate an inherent ability to distinguish between myopic and hyperopic blur. Rather, the subjects were instructed only to detect differences between the two defocus directions. These differences were pattern differences caused by the monochromatic aberrations, and the training period was necessary to show the subjects what those differences were. Like Campbell and Westheimer,[8] we found that only a brief training period was necessary before the subject was prepared for the trials. How the direction of defocus was labeled was unimportant; our results would have been the same with different, or even the reverse, labels, e.g., A versus B, nearer versus farther, or farther versus nearer. To test an inherent ability to discriminate the actual sign of blur, future experiments might be devised in which the dynamics of the accommodative response to these blurred stimuli are tested.

Finally, we should add that the amounts of discriminability presented here depended on the exact details of the experiment. Average values might have been higher if, for example, the stimulus had been brighter or if it had been presented for a longer period of time.

5. CONCLUSION

The sensitivity to differences in the PSF for myopic and hyperopic defocus, or discriminability, increases as the monochromatic aberrations increase, particularly for the even-order aberrations, which give rise to an odd-error focus cue. Although the increase in discriminability was variable among the subjects, all eight subjects showed a monotonic increase with increasing aberrations and pupil size.

Subjects are very sensitive to the shape of the PSF. Some discriminability was present for pupil sizes of 1 mm, which by our measures are classified as diffraction-limited (RMS $< \lambda/14$). This demonstrates that even small aberrations give rise to detectable blur changes. Furthermore, the sensitivity to defocus extends to high refractive errors. In the extended-range data, the sensitivity for a 5-mm pupil persisted for dioptric blurs up to 12 D with little decrease in sensitivity.

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