Dependence of subjective image focus on the magnitude and pattern of high order aberrations

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The image formed by the eye's optics is inherently blurred by aberrations specific to the individual's eyes. We examined to what extent judgments of perceived focus depend on the total magnitude as opposed to the specific pattern of blur introduced by the eye's high order aberrations (HOA). An Adaptive Optics system was used to simultaneously correct each subject's wave aberrations and display natural images blurred by simulated aberrations. To isolate the effects of blur magnitude, images were blurred by pure symmetric defocus, and subjects judged the level of the defocus that subjectively appeared best focused (i.e., neither too blurred nor too sharp). These settings were strongly correlated with the native blur magnitude. To isolate the effect of the HOA pattern, retinal image blur was instead maintained at a constant blur (Strehl Ratio) equal to each subject's natural blur, and subjects judged the best-focused image from pairs of images blurred by different patterns of HOA, one selected from 100 patterns, the other blurred by a reference pattern which included the subject's natural HOA, rotated HOA, or nine other HOA patterns. The percentage of images judged as best focused was not systematically higher when filtered with the subject's own HOA pattern. However, all subjects preferred their own HOA to the rotated version significantly more often (57% versus 45% on average across subjects). The representation of subjective image focus thus appears to be driven primarily by the overall amount of blur and only weakly by HOA blur orientation.

Keywords: adaptive optics, adaptation, blur, orientation, high order aberrations

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Introduction

Images reaching the retina are blurred by the optical aberrations of an individual's eye, which vary widely in magnitude and distribution across the population (Porter, Guirao, Cox, & Williams, 2001; Thibos, Hong, Bradley, & Cheng, 2002). While low order aberrations (LOA) are normally corrected with spectacles or contact lenses, the ultimate challenge is the customization of the correction by compensating for HOA. These are typically uncorrected and thus chronically expose the visual system to optically blurred images. Moreover, certain treatments such as refractive surgery induce significant amounts of optical aberrations (Marcos, Barbero, Llorente, & Merayo-Lloves, 2001), while optical aids such as progressive spectacles produce significant amounts of astigmatism and field distortions (Villegas, Alcon, & Artal, 2006). Thus an important question is how the visual system responds to the blur introduced by HOA and how it might adjust

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to both corrections or induced impairments in the pattern or magnitude of HOA.

Changes in the magnitude of blur introduced by filtering images leads to strong and rapid adaptation in subjective judgments of blur, for example, so that a physically focused image appears too sharp after exposure to blurred images (Webster, Georgeson, & Webster, 2002). This adaptation adjusts spatial sensitivity in response to the blur characteristic of LOA. Furthermore, changes in the orientation of blur introduced by filtering images with astigmatism (vertical to horizontal with constant blur strength) produce aftereffects in the perceived neutral isotropic point, consistent with selective adaptation to the axis of simulated astigmatism, effects which may be at least partly driven by the apparent figural changes that blurring introduces into the retinal image (Sawides, Marcos, Ravikumar, Thibos, Bradley, & Webster, 2010). Astigmatic subjects also rapidly change their neutral isotropic points rapidly upon correction of astigmatism (Viñas, Sawides, de Gracia, & Marcos, 2012). In a previous study, we also showed that subjects can adapt rapidly (short-term) to new amounts and patterns of HOA, either scaled versions of the subjects aberrations or other natural HOA patterns from other subjects (Sawides, de Gracia, Dorronsoro, Webster, & Marcos, 2011a).

Several studies have shown improvements of visual performance after exposure to optical defocus, astigmatism or high order aberrations. For example, visual acuity improved when subjects are exposed for a period of time to optical defocus (Mon-Williams, Tresilian, Strang, Kochhar, & Wann, 1998; George & Rosenfield, 2004). Visual acuity was higher upon induction of astigmatism (with all LOA and HOA corrected with adaptive optics) than nonastigmatic or normally corrected astigmatic subjects (De Gracia, Dorronsoro, Marin, Hernández, & Marcos, 2011). Also, keratoconic patients showed better performance than normal subjects upon induction of keratoconic-like HOA (Sabesan & Yoon, 2010). Visual performance also improved over time after increased aberrations resulting from refractive surgery (Pesudovs, 2005). While these performance improvements could reflect the same mechanisms as blur aftereffects induced by adaptation, they may also depend on some form of perceptual learning to a long-term change in the retinal image.

The extent to which the adaptation can be selective for different patterns of HOA remains uncertain. Studies of this question have become possible through the advent of Adaptive Optics techniques for manipulating the image quality reaching the retina (Roorda, 2011). Retinal blur is either controlled by directly projecting a blurred image obtained by convolution with a point spread function (Sawides, de Gracia et al., 2011a) under full adaptive optics correction of the subject's aberrations or by manipulating the blur pattern using the deformable mirror to recreate different patterns of aberrations (Artal, Chen, Fernandez, Singer, Manzanera, & Williams, 2004). In these cases, subjects are thus generally exposed to the same retinal image blur, and the differences found between subjects must arise from neural components and their internal coding of blur.

In a recent study (Sawides, de Gracia, Dorronsoro, Webster, & Marcos, 2011b), we examined whether vision is adapted (long-term) to the blur produced by the global level of blur produced by HOA of the individual's eyes. Subjects judged the best-perceived focus from a series of images blurred by HOA from real subjects with an extended range of blur. We found that, for most subjects, the blur level deemed as best focused was closely predicted from the magnitude of their native blur, even though the blur in the judged images was not matched to the subjects' blur in terms of the actual orientation of the HOA. This suggested that the codification of their internal blur might depend largely on the overall level of the blur and not on the specific features associated with the asymmetric blur arising from a particular HOA pattern. On the other hand, changes in the orientation of HOAs have been found to significantly influence judgments of image quality. Artal et al. (2004) showed that subjects considered images blurred with their own HOA as sharper than images blurred with rotating versions of their own HOA. Their results thus pointed to an adaptation that was selective for the specific pattern of HOA. Thus, the extent to which the overall magnitude of blur or the actual form of blur drives long-term adaptation to one's aberrations remains unresolved.

To directly answer whether the internal code for blur is biased by magnitude or by orientation, we examined the relative impact of the magnitude versus the pattern of HOA on blur adaptation in two experiments with stimuli that isolated the independent effects of blur level (with no orientation bias) and the effects of blur orientation (with an equal amount of blur) under full Adaptive Optics correction. In the first experiment, we measured the blur level perceived as best focused by subjects when images were blurred only by pure defocus, which allowed us to test the effect of blur magnitude when there were no differences in the orientational features of blur. In the second experiment, we instead held the overall level of blur constant, then compared the perceived focus of images, which varied only in the orientation of the HOA.

Methods

Apparatus and stimuli

We used a custom Adaptive Optics (AO) psychophysical system to test neural adaptation to the subject's ocular

Figure 1. Images used in the experiments. The first image (face) was used in the first experiment. All 10 images were used in the second experiment.

aberrations. The system has been previously described in detail and reported in previous articles (Marcos, Sawides, Gambra, & Dorronsoro, 2008; Gambra, Sawides, Dorronsoro, & Marcos, 2009; De Gracia et al., 2011; Sawides, Gambra, Pascual, Dorronsoro, & Marcos, 2010; Sawides, de Gracia et al., 2011a; Sawides, de Gracia et al., 2011b). The primary components of the AO channel are a Hartmann-Shack wavefront sensor and the electromagnetic deformable mirror (Imagine Eyes, France). A motorized Badal system compensated for the subject's spherical error. A Maltese cross was presented on a minidisplay (12 mm × 9 mm SVGA OLED, LiteEye 400) for fixation during measurement and correction of the subject's aberrations. A 12-inch × 16-inch CRT Monitor, calibrated to provide linear luminance levels and controlled by a ViSaGe psychophysical platform (Cambridge Research System, UK), was used to project the grayscale test images in the psychophysical experiments. The system was controlled using custom routines written in Visual C++ (to control the AO loop and the Badal system) and Matlab to control the ViSaGe psychophysical platform from two computers.

Subjects

Six subjects participated in the first experiment, and their natural Strehl Ratio at best focus varied from 0.103 to 0.356 (for 5-mm pupil diameters). Four experienced subjects participated in the second experiment, and their natural Strehl Ratio varied from 0.042 to 0.1233 (for 5-mm pupil diameters). All the subjects had normal vision as evaluated in clinical ophthalmological examination and were emmetropes or corrected ametropes. Their refractive error (without correction) was −1.5 ± 2.4 D on average. All protocols met the tenets of the Declaration of Helsinki and had been previously approved by Institutional Review Boards.

Generation of optical blur

The original images in both experiments were acquired using a photographic digital camera with an original resolution of 4M pixels and converted to grayscale. The images showed a rich content of spatial frequencies and orientations with the typical power spectra of natural images. In the first experiment, one face image was used (the first image in Figure 1). In the second experiment, the 10 images shown in Figure 1 were used. The images subtended 1.98° on the retina.

Standard Fourier Optics techniques (Goodman, 1996) were used to calculate the Point Spread Function (PSF) corresponding to a given aberration pattern. Image convolutions were performed using routines in Matlab. The PSF was scaled to match the pixel size of the images in a 1.98° window and normalized. All computations were performed for 5-mm pupils. Strehl Ratio (SR) was used as an image metric. Retinal-image-based metrics are preferred over wavefront-based metrics, such as root mean square (RMS) (Applegate, Sarver, & Khemsara, 2002; Applegate, Ballentine, Gross, Sarver, Edwin, & Sarver, 2003; Marsack, Thibos, & Applegate, 2004), in relation to visual performance. For the purposes of this experiment, SR was defined as the volume under the modulation transfer function (MTF) (Experiment 1, as in Sawides, de Gracia et al., 2011b) or PSF Maximum (Experiment 2).

In the first experiment, PSFs estimated from 128 levels of defocus (varying from 0.036 to 0.29 D with a 0.002 D step) were generated. This range of defocus was chosen to match a blur level (in terms of SR)

Figure 2. Subset of images used in the first experiment (from a total of 128 images). Images are blurred by defocus (the corresponding Strehl Ratios are marked in white).

similar to that of natural HOA of a group of 128 patients, following an earlier study (Sawides, de Gracia et al., 2011b). The corresponding SR ranged from 0.049 to 0.844 (5-mm pupils).

Figure 2 shows a subset of eight images from the 128 defocused images used in the experiment.

In the second experiment, images were convolved by the PSFs generated from 100 wave aberrations from real eyes. Tilts, astigmatism, and defocus were set to zero. The original coefficients were scaled by a factor such that the resultant SR was similar across the 100 PSFs (within less than 2% deviation) and matched the SR of the test subject. Multiplying the Zernike coefficients by a factor modifies the amount of blur while preserving the relative shape of the PSF. The experiment therefore maintained a similar level of blur in all images presented to a given subject but different orientations of the blur. Four different series of images were generated, corresponding to the four subjects who participated in the second experiment, and for each of the images used in Figure 1 (i.e., 4,000 total images). Figure 3 illustrates a subset of images generated for the experiment by convolution with the corresponding subset of PSFs (upper-left image corner) for one of the subjects (S1).

The 100 wave aberration patterns, selected from a real subject database, presented a large diversity of orientation and aberration distribution. Correlation coefficients were used to quantify the similarity across patterns (keeping the blur level constant). Correlation coefficients between the subject's PSF and their rotated PSFs were 0.476 (S1), 0.387 (S2), 0.412 (S3), and 0.277 (S4) for each subject. Correlation coefficients ranged from 0.308 to 0.490 (between the subject's PSF and the other three subjects' PSFs), from 0.255 to 0.596 (between the subjects' PSFs and the 10 reference PSFs), and from 0.055 to 0.720 (between the subjects' PSFs and the test PSFs). The large range in the correlation coefficients indicated a wide distribution of orientations across aberration patterns.

Experimental protocols

The protocols to measure and correct the subject's aberrations were similar to those described in detail in previous publications (Marcos, Sawides et al., 2008; Gambra et al., 2009; Sawides, Gambra et al., 2010; Sawides, de Gracia et al., 2011a). Experiments were performed monocularly under natural viewing conditions (natural pupil and without cycloplegia). A 5-mm

Figure 3. Subset of images (convolved with the corresponding PSFs shown in the upper-left corners) used in the second experiment (from a total of 100 images) for one subject (S1, SR = 0.0625). PSFs were generated from HOA from real eyes, scaled to produce the same SR in all images, equal to the subject's natural SR. Simulations were for 5-mm pupil diameters.

artificial pupil ensured a constant pupil size during testing. The subject's pupil was continuously monitored to ensure proper centration and alignment with respect to the optical axis of the system.

A motorized Badal system was used by the subject to adjust his/her best subjective focus while looking at the Maltese cross on a minidisplay. The subject's natural aberrations were then measured and corrected in AO-closed-loop. The correction was typically achieved in 15 iterations and was deemed satisfactory when the residual wavefront error was less than 0.15 μm RMS (excluding tilts and defocus). In this corrected state, the subjects were asked to again adjust focus with the Badal system. The psychophysical measurements were performed under static correction of aberrations, and the residual wavefront error was continuously monitored (before and after each measurement) to ensure appropriate AO correction. A new closed-loop correction was applied if necessary. On average, the RMS (excluding tilts and defocus) decreased from 0.361 ± 0.124 μm to 0.081 ± 0.050 μm with an average RMS error correction of 78 ± 9% (for 5-mm pupil diameter). Subject S2 performed the measurements wearing her soft contact lenses.

In a first session, the aberrations of the participating subjects were measured to estimate their natural SR (which was needed to generate the set of images for the second experiment). This preliminary session and the test session for Experiment 2 were less than 1 month apart. Two psychophysical experiments were performed under full AO correction of the subject's aberrations: (1) Perceptual best focus from purely defocused images to investigate to what extent judgments of image focus might depend on the overall amount of their native blur (with no orientation) and (2) best focus from images with a similar blur level but different blur orientation to explore whether the focus judgments were also sensitive to the orientation of blur produced by HOA.

Experiment 1: Perceived best focus from images blurred with pure defocus

For six subjects, judgments of perceived blur were measured to determine the physical blur level that appeared best focused under neutral adaptation (to a gray field, which had a luminance level of 41 cd/m^2, similar to the average of the test images). The psychophysical paradigm consisted of a 2AFC procedure (sharp/blurred). The sequence of the psychophysical experiment consisted of 1 min exposure to the gray field after which a test image was presented (1 s) to the subject, who had to respond if the image was sharp or blurred. The subject readapted for 3 seconds between each test image. Stimulus levels were varied with a Quest algorithm to find the best-perceived focus point. The perceived focus point usually converged, in the 2AFC procedure, to the final value in less than 35 trials or 16 reversals (if not, the measurement was discarded and repeated). Each subject repeated the experiment three times. Figure 4 shows a sequence of images presented in Experiment 1.

Experiment 2: Perceived best focus from images blurred with different HOA at the same blur level

Judgments of best focus from pairs of images with identical overall blur level (SR) and different blur orientation were obtained on four subjects. The psychophysical paradigm consisted of a 2AFC procedure where two images blurred with two different HOA patterns were presented sequentially (1.5 s each). The subject had to respond whether the first or second image appeared better focused. A 20-second adapting gray field was presented at the beginning of the experiment and for 3 seconds between trials.

In each test, a series of 100 pairs of images (10 random repetitions of the 10 images of Figure 1) were presented to the subject. In all cases, one image in each pair was always blurred with a given reference PSF, while the other image was blurred by a PSF randomly selected among the 100 different PSFs (previously computed to match the subject's SR). Comparisons were performed between the images blurred by a reference pattern and a set of 100 other aberrations. The order of presentation of the images within a pair was random.

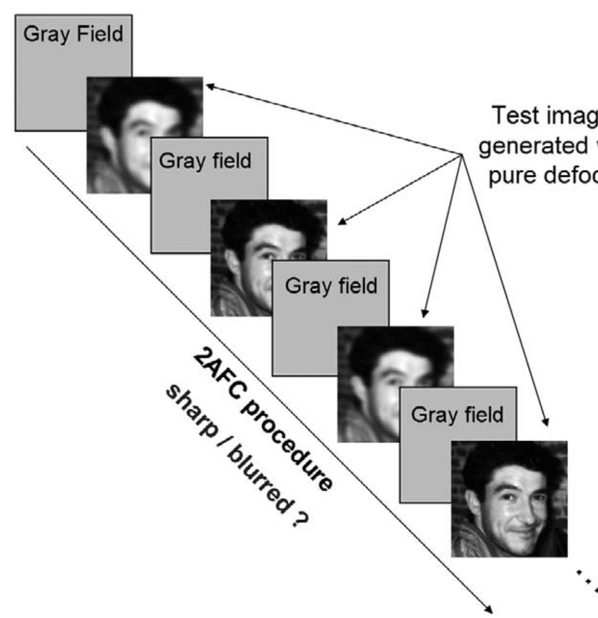

Figure 4. Sequence of images in the 2AFC procedure of Experiment 1 (perceived best focus from purely defocused images).

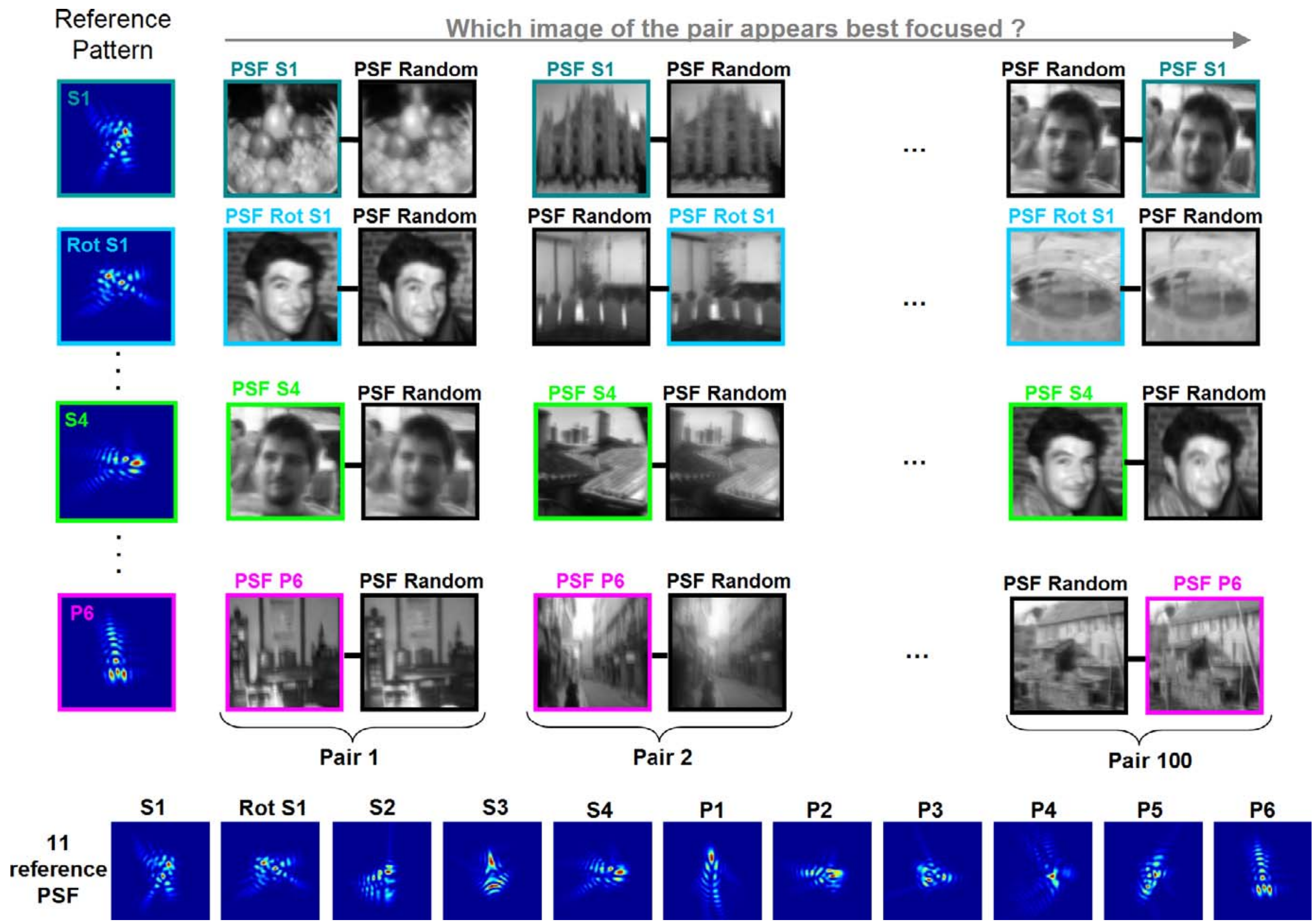

Figure 5. Sequence of images in the 2AFC procedure of Experiment 2 (in which images were blurred by different HOA but with the same SR as the subject's natural PSF, shown here for subject S1). In each pair, one of the images was always blurred with a constant reference PSF, while the other was blurred with a randomly selected PSF. The 11 reference PSFs corresponded to the PSF of the subject, a rotated version of their PSF, the PSFs for the three remaining subjects, and six other PSFs from the database. One-hundred image pairs were shown for each reference (corresponding to the 10 images in Figure 1, each shown 10 times in random order).

Each subject performed 11 tests for 11 different reference PSFs. The reference PSFs were: the PSF of the test subject (S#, condition 1); the 90°-rotated PSF of the subject (rotated S#, condition 2); and nine other PSFs, which included those corresponding to the other three participants of the study, as well as six additional patterns selected among the 100 PSFs (P#). Conditions 1 and 2 were tested three times in each subject, while the other nine conditions were tested once in each subject. Figure 5 shows an example of the image sequence in Experiment 2.

Data analysis

Experiment 1: Perceived best focus from images blurred by pure defocus

The blur level corresponding to the point of subjective best focus (perceptual blur) was obtained from the average of the last eight reverse responses in the Quest sequence. The level was expressed in terms of SR (normalized volume under MTF) and compared to the SR of the natural retinal image blur for each subject (natural blur). Data were fitted by linear regression, and the correlation coefficient and significance were estimated.

Experiment 2: Perceived best focus from images blurred with different HOA at the same blur level

For each image series, the percentage of times the image blurred with the reference PSF was perceived as better focused was recorded. The preferences were compared across conditions to assess whether the subject showed a bias for or against a particular HOA. The arcsine square root transformation was applied to all sets of percentage data to guarantee a normal distribution in the data set before the application of ANOVA and t-tests.

A one-way ANOVA (post-hoc: Tukey's b-test; $p < 0.05$) was applied to the arcsine square root transfor-

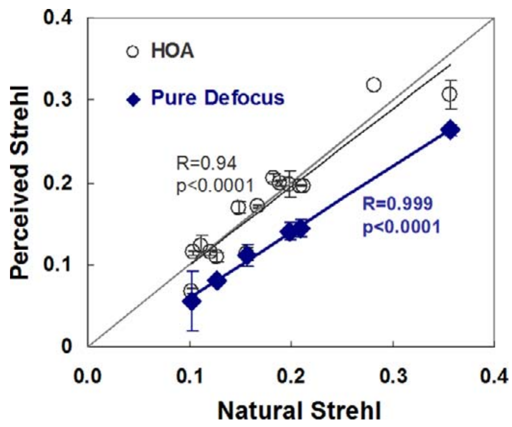

Figure 6. Strehl Ratio of the image perceived as best focused versus the natural Strehl Ratio of the subjects. Data in gray are the results reported in previous study (Sawides, de Gracia et al., 2011b) when blurring the sequence of images with different HOA patterns, tested for 15 subjects ($y = 0.952x + 0.0004$; $R = 0.94$; $p < 0.0001$). The blue symbols are for the six subjects of the current study (a subset of the subjects from the previous study) when testing images blurred with only defocus ($y = 0.806x – 0.022$; $R = 0.999$; $p < 0.0001$).

mation to test for differences in the percentage across the 10 different references (all references except the rotated version)—with the reference pattern as the factor and the percentage preference for each image type as the dependent variable with separate responses—for every group of 10 image pairs (equal image, different blurring pattern).

One-sample *t*-test was applied to test whether the percentage of preferred images blurred with the subject's PSF as reference was significantly different from 50% and significantly higher than with other reference patterns. *T*-test as well as a mixed model analysis were also used to compare the percentage of images preferred when blurred with the subject's PSF or its rotated version. In the mixed model analysis, the fixed effect was the reference pattern (own/rotated); the random effect was the subject; and the repeated effect was the number of repeated measures (three in each condition [own/rotated]) associated with each reference pattern. The dependent variable was the arcsine square root transformation of the percentages. Statistical analysis was performed with SPSS software.

Results

Perceived best focus from purely defocused images

Figure 6 shows the correspondence between the level of physical defocus perceived as best focused and the subject's natural blur in terms of SR (blue points), along with a linear regression fit to the data. The correlation between the subject's natural blur and the defocus level identified as neutral is highly significant and nearly perfect ($R = 0.999$; $p < 0.0001$). Thus the differences in the focus percepts across subjects could be accounted for almost entirely by the differences in their overall levels of native blur, regardless of the individual HOA. On the other hand, the negative offset of the regression line indicates that, for the same amount of blur (Strehl Ratio defined by the normalized volume under MTF), pure defocus appears more blurred than the blur produced by their natural aberrations. Notably, this differs from the effects when images are blurred by the subject's actual HOA (shown by the gray points in the figure, from a previous study; Sawides, de Gracia et al., 2011b), for which SR accurately predicts the absolute levels of the subjective neutral points. We tested possible effects of the specific choice of image quality metric on the results of Figure 6. A strong correlation between the subject's natural blur and the perceived neutral blur was found regardless of the image quality metric (SR or Augmented VSOTF Visual SR; Iskander, 2006) in all cases (images blurred by HOA or pure defocus), with regression coefficients *R* ranging from 0.87 to 0.999 ($p < 0.05$). The offset ranged from zero (HOA, all metrics) to negative (pure defocus, SR) and positive (pure defocus, Visual SR), because different metrics differently capture the effect of high spatial frequency content in purely defocused images.

Perceived best orientation from images with the same blur level

Figure 7 shows the percentage of images that were judged as better focused when filtered with a given HOA reference pattern. Each panel shows the settings for each subject, measured using his/her natural pattern (first bar) as a reference, or a pattern corresponding to a different subject: the other three subjects of the study (bars 2–4) or six additional patterns (bars 5–10, denoted P1–6). (The remaining reference corresponding to a rotated version of the subject's own PSF is considered in the following text and shown in Figure 8).

Figure 7 reveals that none of the patterns (the subject's own, in particular) is consistently chosen as best focused or alternatively consistently rejected by all subjects. We assessed these preferences in a number of ways. First, if subjects were strongly adapted to the specific pattern of blur formed by their own HOA, then they should prefer images blurred with their HOA. However, the percentage of images judged as best focused was not systematically higher when filtered with the subject's own HOA pattern. For example, based on a conventional one-sample *t*-test applied to the arcsine

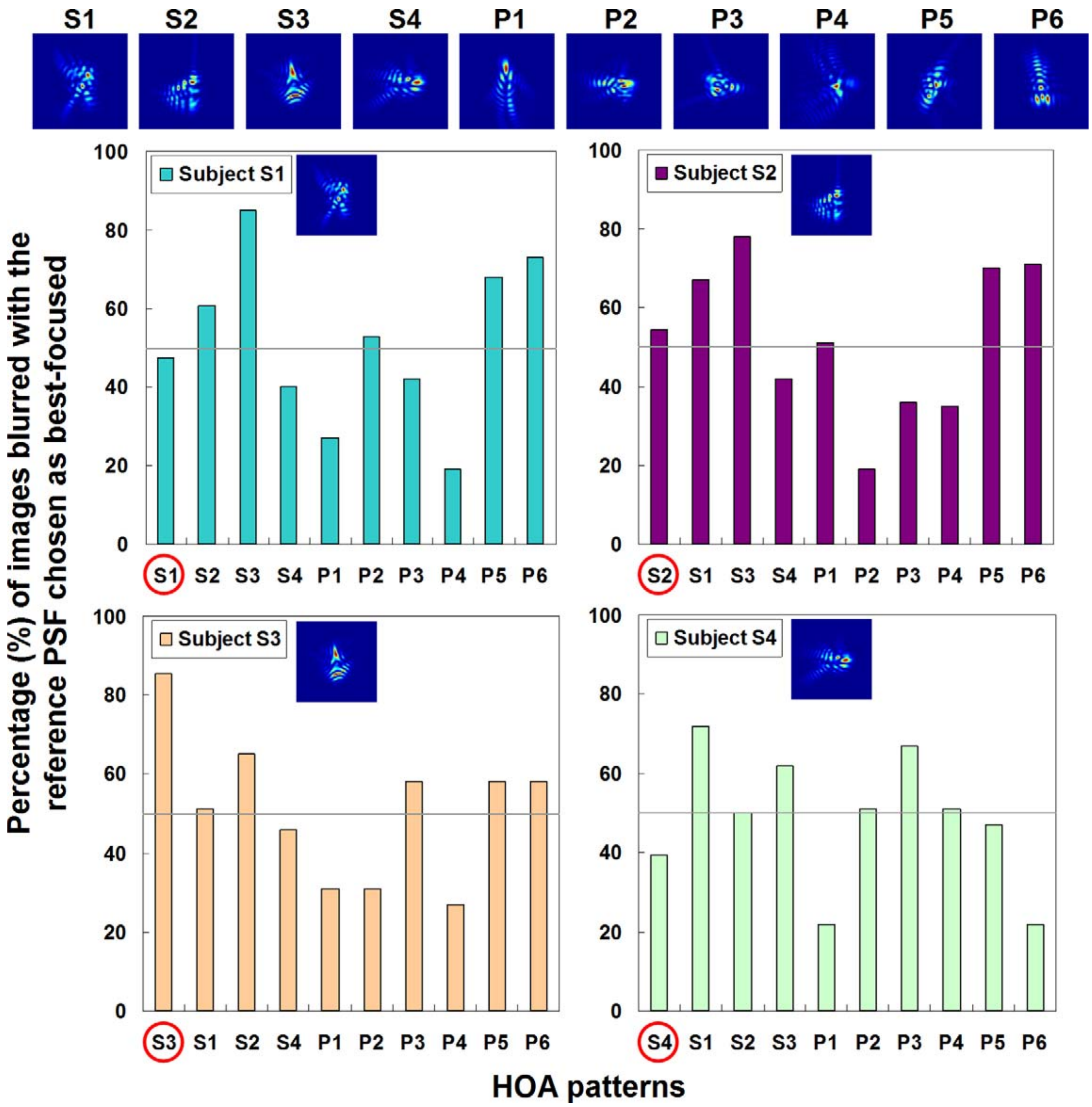

Figure 7. Percentage of images blurred with each reference pattern, which were judged as best focused. Data are for 10 different reference patterns (illustrated by the corresponding PSFs). Four reference patterns correspond to the HOA of the tested subjects (S1–S4) and the rest to additional HOA patterns selected among 100 PSFs (P1–P6). Each panel shows responses for each subject. The first bar in each panel represents the response for each subject's own PSF.

square root transformation for the 300 pairs that included each subject's own HOA to test whether the percentages were different from 50%, S2 did not show a significant preference ($p = 0.205$), while S3 strongly preferred their own blur ($p = 0.001$), and S1 and S4 instead showed a significant bias against their own blur (S1, $p = 0.015$, and S4, $p = 0.046$). Second, if subjects were sensitive to their specific PSF, then the preferences for the remaining nine reference PSFs should be lower on average, yet this was again found only for S3 (*t*-test, $p < 0.001$). Finally, if the specific HOA pattern mattered at all for the blur judgments, then the preferences should show an effect of the reference HOA. To test this, we used a one-way ANOVA applied to the arcsine square root transformation to test for differences in the percentages across the different reference levels. The one-way ANOVA was performed for each individual subject for the 10 reference patterns (all patterns except the rotated version). Separate responses for every group of 10 image pairs (equal image, different blurring pattern) were analyzed. The percentages of images judged as best focused for each pattern were compared. The analysis revealed that there was a statistically significant difference between the percentages of images perceived as best focused within the different PSF references, as determined by the one-way ANOVA for each subject: for S1, ($F[9, 90] = 13.516$, $p < 0.001$); for S2, ($F[9, 90] = 12.462$, $p < 0.001$); for S3, ($F[9, 90] = 10.887$, $p < 0.001$); and for S4, ($F[9, 90] = 11.614$, $p < 0.001$). Together, these analyses suggest that subjects

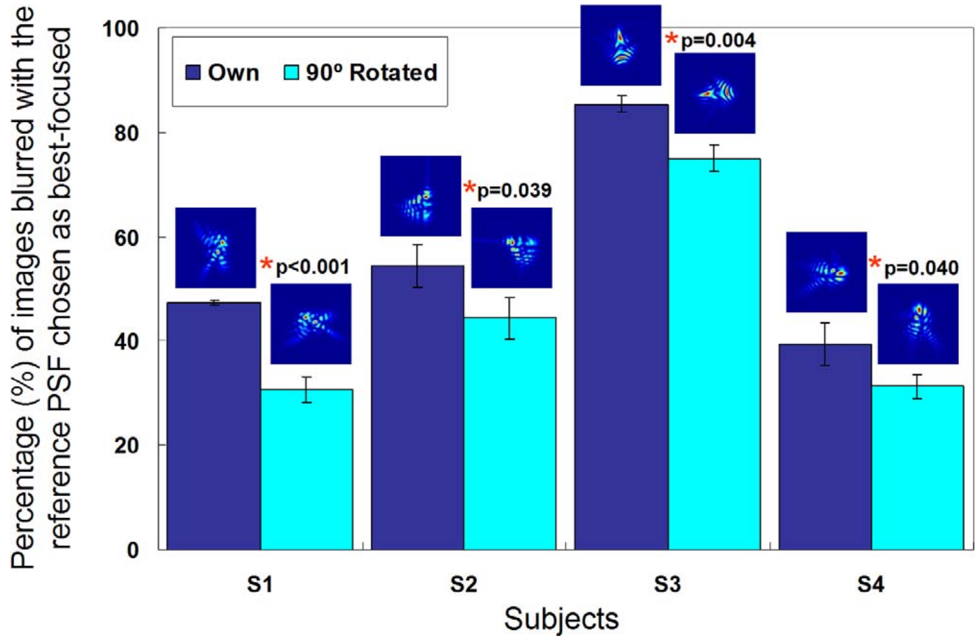

Figure 8. Percentage of images considered as best focused when the PSF reference corresponded to the subject's natural HOA pattern or to a 90° rotated version of subject's HOA pattern.

were sensitive to the specific pattern of HOA in their blur judgments, but were not biased toward preferring their own HOA for these judgments.

As a further test, we compared preferences when the reference blur corresponded to their own HOA or the same PSF rotated 90° (Figure 8). Comparisons were performed between the natural aberration condition (taken as a reference) and a set of 100 other aberrations, and between the rotated aberration condition (taken as a reference) and a set of 100 other aberrations. In this case, there was a clearer tendency for subjects to favor their own HOA. Specifically, with the rotated version, the percentage of images blurred by the reference PSF was systematically lower than that with the subject's natural pattern (averaging 45% versus 57% across subjects). This difference was significant for each subject (t-test on the arcsine square root transformation; p-values displayed in Figure 8 for each subject). The mixed model analysis showed that the reference patterns had a significant effect on judgment of the perceived best-focused images ($F = 206.609$, $p < 0.001$), and the percentages with their own PSF were significantly higher than the percentages with the rotated version of the subject's PSF ($t = 14.374$, $p < 0.001$, 95% Confidence Interval for the difference is 0.0985 to 0.1427). These results thus point to a weak but consistent bias for the orientation of the subject's own HOA, an effect also hinted at by the pattern of results in Figure 7. Specifically, subjects with a vertically or horizontally oriented PSF tended to perceive as best focused those images blurred by PSFs with similar orientations. For example, for S2 (dominated by vertical coma) the percentages of images judged as better focused were higher when blurred by P1 or P6 (dominated by vertical coma) than when blurred by P2 and by P4 (dominated by horizontal coma). In contrast, for S4 (dominated by horizontal coma) the percentages of images judged as better focused when blurred by P2 and P4 were higher than those when blurred by P1 and P6. Moreover, Tukey's b-post-hoc test revealed that, for S4, both P2 and P4 belonged to the highest subset (for alpha = 0.05) whereas both P1 and P6 belonged to the lowest subset. In contrast for S2, P2 was the only component of the lowest subset and P6 belonged to the highest subset.

Controlling for short-term adaptation to the reference pattern

Finally, we explored the possibility that the judgments might be contaminated by adaptation to each reference PSF during the experiment, as this was shown repeatedly in each test pair. This adaptation might lead subjects to renormalize for the current reference HOA and thus mask a bias for their natural HOA. Short-term adaptation to the reference pattern blur would be expected to increase the percentage of selected reference pattern images over the course of the measurements. However, this effect was not found. We analyzed the responses grouped in series of 10 image pairs. There was no increase in the percentage of selected images over time for any of the conditions.

Discussion

In recent studies, we have examined the ability of subjects to dynamically adapt to new amounts and patterns of low and higher order aberrations (Sawides, Marcos et al., 2010; De Gracia et al., 2011; Sawides, de Gracia et al., 2011a). Also, we have examined how perception of focus is compensated for the retinal image blur produced by the eye's optics. These studies have shown that the point of subjective focus corresponds closely to the level of physical blur introduced by the high order aberrations of the individual's eye (as illustrated by the gray symbols in Figure 6). Thus the judgments of focus appear to nearly completely discount the habitual uncorrected retinal blur from the observer's HOA so that perceived focus is tied to the properties of the stimulus rather than to the retinal image. Moreover, we also found that these focus judgments probably reflect an actual adaptation to the level of natural blur and are not simply a learned criterion for judging the blur. Specifically, the level of blur perceived as focused not only matched the observer's native blur, but was the level that did not produce a blur aftereffect. In contrast, when observers were exposed to images with higher or lower blur levels, their focus judgments were shifted to higher or lower levels because of short-term adaptation (Sawides, de Gracia et al., 2011b). Thus this suggests that the perceptual null for focus corresponded to an actual null in the neural mechanisms encoding focus, because it was the stimulus level—specific to each observer—that did not alter the relative responses within the spatial mechanisms mediating blurred or sharp percepts. This is similar to the finding in color vision that the stimulus that appears white is compensated through adaptation for the specific spectral sensitivity of the observer (Webster & Leonard, 2008).

In the present study, we extended these results to directly assess how sensitive adaptation is to the specific pattern of blur resulting from the subject's HOA. To isolate the effects of the magnitude versus the orientation of blur, we tested blur judgments from purely defocused images with no orientation bias and blur judgments of images with a constant level of blur (matched to the subject's blur level) but different patterns.

The first experiment restricted blurring to pure defocus and thus the only cue for focus judgments was the magnitude of the blur. Nevertheless, intersubject differences in the point of subjective focus could be very closely predicted from differences in the SR of their native blur. Again, this is similar to the effects we found previously when asking subjects to judge the perceived blur from images blurred by different natural HOAs, which could also be closely predicted from the overall blur or SR (Sawides, de Gracia et al., 2011b). Together, these results suggest that overall blur level is a highly salient cue and likely the primary cue in the internal coding for blur, at least for HOAs. However, despite similar correlations between the subject's natural blur and the percepts of blur produced by pure defocus (current study) or actual HOAs (previous study), there were two differences in the results. First, unlike the previous experiment where there was a close absolute correspondence between the two measures (as shown by the gray regression line in Figure 4), the subject's natural SR overestimated the SR for subjective focus (i.e., images defocused by an amount equal to the subject's natural SR appeared too blurred as shown by the blue regression line in Figure 4). This negative offset for the purely defocused images suggests intrinsic differences to the blur nature of pure defocus versus HOA, likely as a result of the image quality metric used to describe the level of blur. In fact, analyzing the data in terms of visual SR revealed a similar correlation of natural versus perceived blur, but a shift in the offset. Several studies suggest that subjects differently perceive blur from pure defocus or HOA, implying that the specific orientation of the blur in each subject's HOA does play a role in the judgment of best-perceived focus. The actual basis for this difference is not clear. Guo and Atchison (2010) also reported that subjective tolerance to blur produced by an oriented aberration (astigmatism) was greater than the tolerance to defocus, although the amounts varied with the experimental conditions. The relative effects of simple myopic defocus or myopic astigmatism on visual acuity appear however to be controversial in the literature (Sloan, 1951; Miller, Kris, & Griffiths, 1997; Remón, Tornel, & Furlan, 2006). Also, while the relative effect of defocus and high order aberrations on vision have been reported in several studies (Applegate, Sarver et al., 2002; Applegate, Ballentine et al., 2003; Atchison, Guo, Charman, & Fisher, 2009; Atchison & Guo, 2010), in most cases comparisons are performed for similar Zernike coefficient weights or RMS (across orders or terms), which, unlike the current study, do not represent equal amounts of blur in terms of SR, so that direct comparisons are difficult.

A second difference between our current (using blur from pure defocus) and former (using blur produced by high order aberrations) measurements of the impact of overall blur level on focus judgments is in the strength of the correlation. Specifically, variability in the predicted settings was higher when blur was introduced from actual HOAs rather than from defocus. This difference may again indicate that subjects were sensitive to the actual HOA on the focus judgments. To directly evaluate this sensitivity, Experiment 2 was designed so that the overall amount of blur was kept constant, and only the shape of the PSF varied. This revealed a significant contribution of orientational aspects of the blur to the subject's judgments. In agreement with Artal et al. (2004), images blurred by a 90° rotated version of the subject's PSF were perceived consistently as less focused than images degraded by their natural PSF (a consistent effect across all subjects). In the current study, the comparisons were not directly made between the HOA and its rotated pattern, but rather each was evaluated as a reference compared to 100 other aberrations. This again revealed a preference for the natural aberrations (57% on average) in comparison with the rotated version (45% on average). This bias was nevertheless surprisingly weak. In fact, only one of the four subjects judged their own blur as significantly better focused, suggesting that, in general, individuals may exhibit little preference for their own degradation pattern. Some subjects actually showed a higher bias for other aberration patterns than their own. The basis for these differences and how they depend on the subject's specific HOA is unclear and is a question we are currently investigating. However, the present findings strongly suggest that the perception of focus is primarily calibrated for the overall level of blur introduced by HOAs and may be only weakly impacted by the local features associated with the asymmetric blur arising from a particular HOA, as other patterns are frequently identified as better focused than the native pattern.

Conclusions

(a) Perceived best focus (from purely defocused images) is highly correlated with the overall amount of blur produced by the high order aberrations of the eye.

(b) The negative offset in that correlation suggests differences in the appearance or perception of blur produced by pure defocus from the blur produced by the natural aberrations of the eye, as measured by a global metric of blur like Strehl Ratio.

(c) The fact that blur is discriminated across reference patterns as well as the higher preference for natural than rotated aberrations suggests some sensitivity to the orientation. However, the findings do not support a strong bias to prefer the individual's own HOA pattern.

(d) The codification of internal blur thus seems to be highly driven by the overall amount of blur and only to a weak extent by blur orientation, as other patterns are frequently identified as better focused than the native pattern.

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