Supplemental Information

A cyclopean neural mechanism compensating for optical differences between the eyes

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Supplemental Experimental Procedures

Judgments of image focus and how these change with adaptation were assessed using images computationally degraded with differing amounts of optical blur measured from real eyes. Figure 1 A-C shows the general experimental procedure. All measurements were performed monocularly in both eyes of normal subjects with undilated pupils.

Ethics Statement

The protocols met the tenets of Helsinki and were approved by the Consejo Superior de Investigaciones Cientificas Ethics Committee. All the participants provided written informed consent.

Apparatus

Each subject viewed images through a system that could correct their own aberrations while introducing arbitrary magnitudes and patterns of blur. Defocus was compensated with a system of lenses (Badal optometer) that allows changing focus without changing the magnification of the retinal image. The level of defocus was chosen to maximize optical quality [S1, S2, S3, S4]. Astigmatism and high-order aberrations were measured and corrected using a custom-developed adaptive optics (AO) setup. In an AO system ocular aberrations are quantified with a Hartmann Shack sensor (HASO 32 OEM, Imagine Eyes, France), which uses a microlens array to measure the distortions of the wavefront emerging from the eye from a light source projected on the retina. All measurements were performed using an artificial pupil (5-mm pupil diameter). The measured aberrations were used to compute the Point Spread Function (PSF), i.e. the image of a point source on the retina distorted by the aberrations of the eye. The magnitude of blur was then quantified in terms of the Strehl Ratio. This index corresponds to the peak intensity of the PSF of the aberrated eye relative an ideal eye whose image quality is limited only by diffraction. Thus an eye with no aberrations has a Strehl Ratio of 1, while lower values correspond to progressively more overall blur. The shape of the Point Spread Function was fit to an ellipse, and the angle of the main axis of that ellipse was taken as the orientation of the Point Spread Function [S5].

The computations were performed for a 5-mm pupil diameter. Astigmatism and high order aberrations were corrected by means of an electromagnetic deformable mirror (52 actuators, MIRAO, Imagine Eyes, France), operating in a static closed-loop during the psychophysical measurements. The average Strehl Ratio prior to adaptive optics correction was 0.149±0.096 and following adaptive optics correction was 0.55±0.12, which was periodically monitored during the psychophysical measurements. Visual stimuli for psychophysical tasks were programmed in Matlab with dedicated software for psychophysical experiments, Psychtoolbox [S6], and presented on a CRT monitor controlled through a high resolution graphics card (ViSaGe, Cambridge Research System, UK). The stimuli were viewed through the Badal optometer correcting defocus, and the adaptive optics mirror correcting astigmatism and high order aberrations. A detailed description of the setup and its accuracy is reported in earlier studies involving adaptive optics correction and visual performance [S7, S8].

Subjects

Aberrations and focus judgments were collected for twelve young subjects (age range: 22 to 42 yrs) with spherical error ranging from +1.00D (Diopters) to -5.50D and astigmatism <1D. Five of the twelve subjects had prior experience in performing psychophysical experiments. Subjects S#1 and S#5 (myopia >4D) performed the experiments with contact lenses. Sighting dominance was established in subjects using the Miles test [S9]. Subjects S#1-S#12 participated in Experiment 1. Subjects S#1-S#5 participated in Experiment 2.

Experiment 1. Measurement of Perceived-Best-Focus

The experiments allowed blur levels (as indexed by Strehl Ratio) to be varied over a wide range that appeared either “too blurry” or “too sharp” to the observer. That is, images that had too little blur were easily judged as overly sharpened, while images with too much blur appeared out of focus. A psychophysical task was used to estimate the boundary between these percepts, at which the image appeared to have the “Perceived Best Focus.”

Stimuli: Test stimuli were generated by applying the optical blur measured in 128 different eyes to an image of a face. These computations were done assuming a 5-mm pupil diameter. The amount of blur across the simulated eyes varied from a Strehl Ratio of 0.75 (very sharp) to 0.008 (very blurred). The images subtended 1.98 degree at the retina.

Procedure: The subject first adapted to a gray screen for 30s and a test image with a random magnitude of blur was then presented for 500ms. The psychophysical task employed was a single interval binary choice task [10]. Specifically, the subject had to respond whether the presented image was “too blurred” or “too sharp” according to their subjective criterion for a correctly focused image. Depending on the response, the blur in the next image was chosen by a QUEST algorithm [S11, S12]. Thus a series of test images interspersed with a gray screen was presented until the test converged at the boundary between the two judgments. This convergence was usually attained in 40 or less trials. The level of blur corresponding to Perceived-Best-Focus was calculated as the average of the last 10 stimulus values that oscillated around the boundary with a standard deviation less than 0.02. The measurements were done in one eye first (three repetitions), followed by the other eye, with the eye order chosen at random. Overall the session lasted for approximately 1 hour per subject.

Experiment 2. Measurement of Blur After-Effects

For the 5 subjects that had the strongest differences in blur between their eyes, we assessed how adaptation to blur in either eye affected their focus judgments.

Stimuli: For each subject an array of images was created that varied the magnitude of their own aberrations. For three subjects (S#1, S#2, S#5) their two eyes differed only in the magnitude but not the shape of the PSF, and thus the arrays were generated from the PSF of their better eye. For two other subjects the PSFs had slightly different orientations, and thus the array was based on the average of the blur in their two eyes. To create the arrays, the magnitude of the aberrations were scaled by a factor from 0 to 3 times the original values in steps of 0.01, yielding 301 different PSF's, with similar shape but different spread. A face image was then convolved with each of these scaled PSF's to generate the image array, which ranged from no blur (Strehl Ratio of 1) to 3 times the blur of their better eye (S#1, S#2, S#5) or their average blur (S#3, S#4). Adapting conditions were: Gray; Sharp 1: Strehl Ratio of better eye+Average Strehl Ratio between eyes; Sharp 2: Strehl Ratio of better eye; Average Strehl Ratio between eyes; Blur 1: Strehl Ratio of worse eye; Blur 2: Average Strehl Ratio between eyes - Strehl ratio of worse eye.

Subjects again judged the blur level that appeared neither too blurred nor too sharp, but this time after again adapting to the gray field or to images that had different degrees of blur chosen to bracket the magnitude of blur in their two eyes. This included the blur level corresponding to each eye, the intermediate blur level based on averaging the two eyes, and extreme levels that were either sharper than the better eye or blurrier than the worse eye. The five levels varied linearly in Strehl Ratio in steps that were half the difference between the two eyes.

Procedure: The same psychophysical task was used as in the preceding experiment, except that either a gray field or adapting image was interspersed with each test image. Subjects initially adapted to an adapting image with given blur level for 60 s (the image was spatially jittered over time (5Hz) to avoid local light adaptation). Each subsequent response was preceded by a 3s period of re-adaptation, until the QUEST algorithm again converged. The order of the adapting conditions and the eye tested (left or right) were randomized. The gray adaptation condition was repeated three times to establish the baseline, and measurements following a given adapting condition were performed once, so that a complete session lasted approximately 2 hours.

Data Analysis

Non-parametric mean comparisons and correlations were performed for the Perceived-Best-Focus measurements (Experiment 1) and non-parametric analysis of variance was done to study the changes with adaptation (Experiment 2).

Supplemental Results

Ocular aberration profile

The wavefront aberration maps, Point Spread Function and the corresponding Strehl Ratios for each subject are given in Figure S1A. The optical quality (SR) of all eyes is represented as gray star symbols in Figure S1B. The average optical quality (Strehl Ratio) in the right eye was 0.143±0.099 and in the left eye was 0.156±0.096, for 5 mm pupil diameter. For reference, a Strehl ratio of 0.15 represents 0.11 D of pure blur, for 5 mm pupil. Interocular differences in Strehl Ratios averaged 0.080±0.080. This corresponds to an average difference of 26% between the two eyes of the subjects. Moreover, 7 of the 12 subjects (S#1-S#7) had a 30% or more difference in Strehl Ratio between their eyes. In most (10 of 12) subjects, the eye with better optical quality was also the eye with motor dominance.

Perceived-Best-Focus

Despite the differences in optical quality between the eyes, the judgments of image focus were very similar when viewing the images through either eye (blue and green bars in Figure S1B). On average, the amount of physical blur that subjects perceived as “in focus” (neither too blurred nor too sharp) was 0.197±0.095 in the better eye and 0.191±0.094 in the worse eye, a difference that was not significant ($p=0.547$).

Perceived-Best-Focus Vs Optical quality

Figure S1B compares the blur level that observers chose as best focused to the level of retinal image blur in each of their eyes. As suggested above, the percepts of image focus were very similar through each despite interocular differences in retinal image blur. This is illustrated by the similarity in height of the blue and green bars in Figure S1B and the flatness of the lines joining the data for both eyes of each subject (meaning similar perceived best focus with either eye) in Figure S1C. Moreover, the focus judgments co-varied with the observer’s own optical quality, except in subjects S#8 and S#11, who demonstrated higher thresholds for blur. Figure S1C shows the correspondence between optical quality (x-axis) and the perceptual quality (y-axis), which is closest to the eye with better optical quality (higher SR value, or right-most symbols, $r=0.783$, $p<0.0001$). In Figure S1C the larger open symbols correspond to the sighting dominant eye. Interestingly, in most subjects this dominance also corresponded to the eye with better optical quality. The subjective neutral focus points align more closely with the blur level afforded by the better eye. To quantify this, we calculated the difference between the focus settings and the blur level within each eye or the average of the two eyes (Figure S1D). In subjects with different blur magnitudes between their eyes (S#1-S#7), the judgment of Perceived-Best-Focus was much closer to the blur level dictated by the better eye quality (-0.03±0.05) than the worse eye (0.10±0.07), a difference, which was significant (p=0.019). Note again that these results are based on correcting the native aberrations of each eye and then introducing equivalent retinal blur within each eye. The implication is that the retinal blur we normally experience through the better eye is judged as properly focused, while the image blur we typically encounter through the worse eye is judged as too-blurred. That is, a common calibration is applied to the blur from either eye, even when the two eyes differ in the level of retinal image blur they typically introduce.

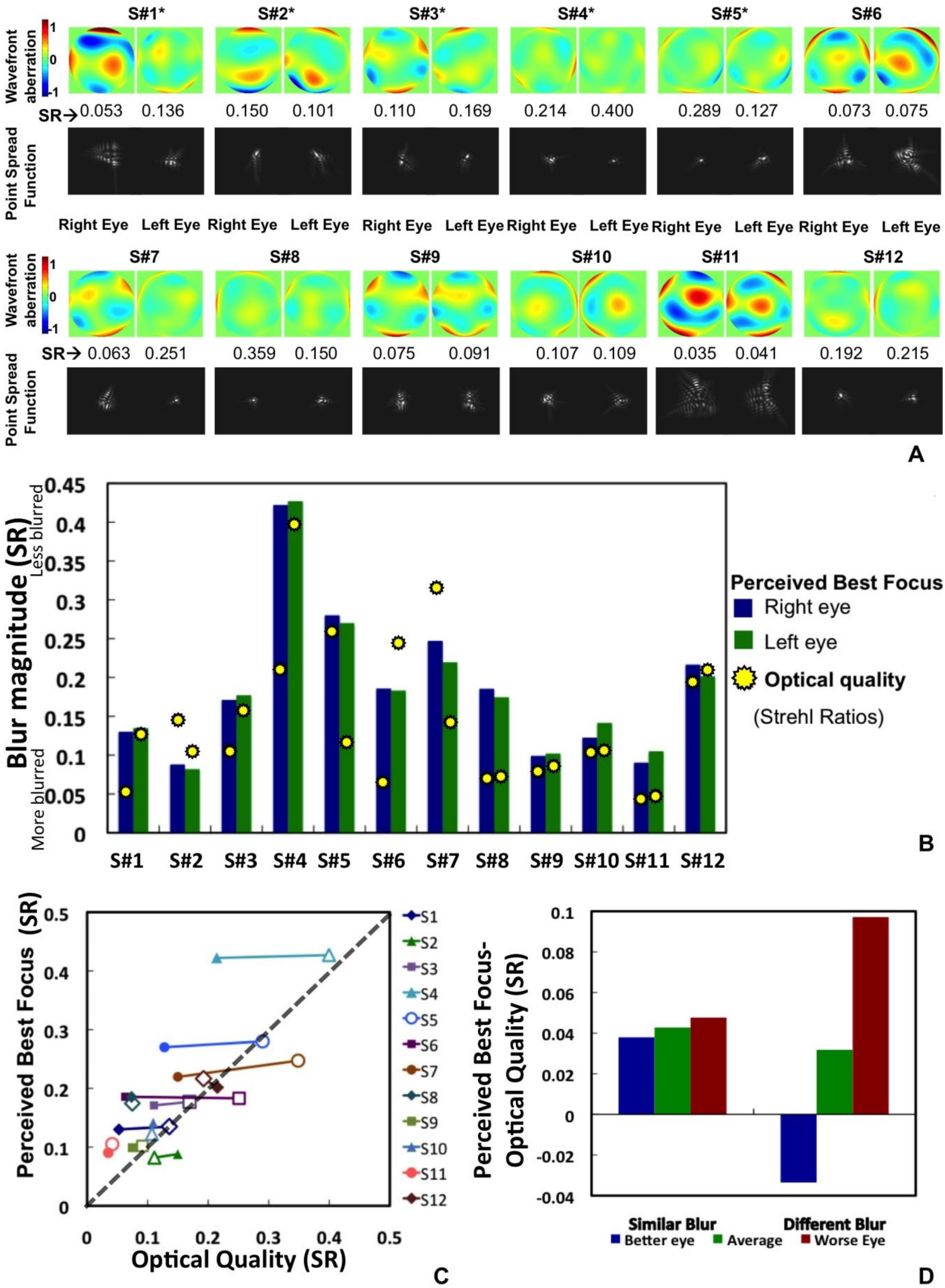

Figure S1. A. Ocular wave aberrations, Point Spread functions and Optical image quality (Strehl Ratio) of both eyes for all subjects of the study. Data are for High Order Aberrations, and 5-mm pupil diameters. Subjects marked with asterisk (*) differ in optical quality between eyes by >30%. Subjects S#1-S#12 participated in Experiment 1; S#1-S#5 participated in Experiment 2; B. Perceived-Best-Focus (bars, from Experiment 1) and Optical Quality (stars, Strehl Ratios from Figure S1) in both eyes of all subjects; C. Perceived Best Focus versus Optical Quality. Same color and symbol shape represent both eyes of the same subject (linked by a segment). Large, Open symbols denote the sighting dominant eye for each subject; D. Difference between the Perceived-Best-Focus and optical quality of the better eye, the average and the worse eye, averaged across subjects with similar blur (left bars) and different blur (right bars) between eyes.

Experiment 2: Shifts of Perceived-Best-Focus following adaptation

The effects of adaptation on judgments of focus are shown in Figure S2A. Despite large differences between subjects in Perceived-Best-Focus (which varied from 0.094 to 0.412 Strehl Ratio), for each subject the pattern of aftereffects was very similar between their eyes (Strehl Ratio difference 002±0.002, on average). Moreover, the judgments on the gray background remained very similar to the settings the subjects made in the preceding experiment. Note again that these experiments differed in whether subjects were shown scaled versions of their own aberrations (Experiment 2) or actual aberrations measured from other eyes (Experiment 1). This indicates that subjects are primarily sensitive to the overall magnitude of blur as measured by Strehl Ratio, rather than to the specific pattern of blur [S13].

However, these settings were strongly affected by prior adaptation to images with different blur levels. Figure S2B shows the aftereffects following adaptation for all subjects. The sharpest adapting images (i.e. less blurred than the better eye) caused the blur level that was rated best focused under gray adaptation to appear too blurred. Subjects thus chose a less blurred image to compensate for this bias. Alternatively, adaptation to the most blurred image (i.e. more blurred than the eye with poorest image quality) induced the opposite aftereffect. These after-effects are consistent with previous measurements of blur aftereffects [S14]. However, here we probed which blur level did not produce an aftereffect, and how this depended on the stimulated eye. For either eye, the blur level at which the after-effect was nulled corresponded closely to the better eye, while exposure to the worse eye's blur or the average blur of the two eyes caused the previous subjective focus level to appear too sharp.

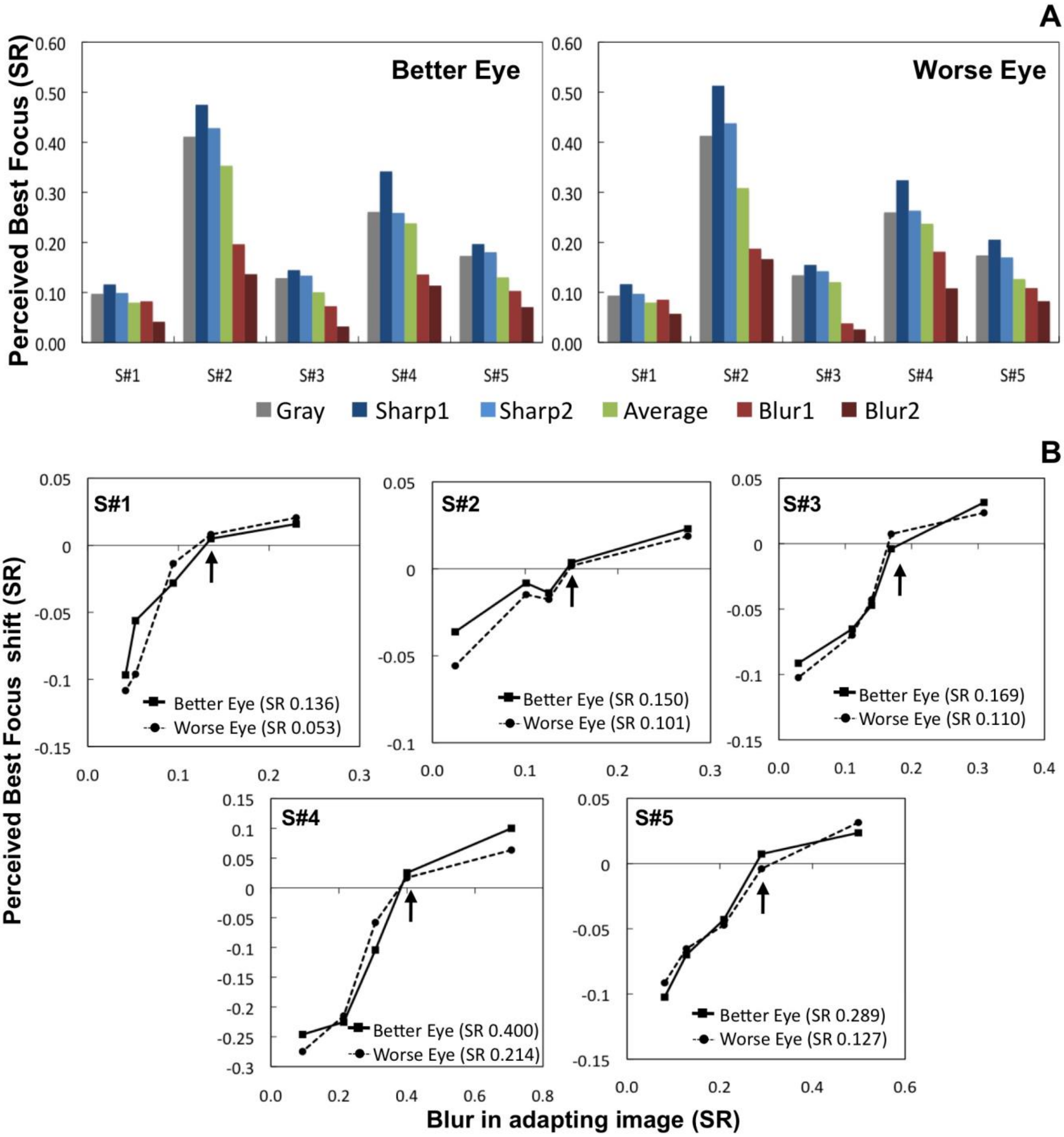

Figure S2. A. Best-Perceived Focus following adaptation to a gray field and to different amounts of blur. Adapting conditions were: Gray; Sharp 1; Sharp 2; Blur 1; Blur 2. Left panel shows results for eyes with better SR; right panel for eyes with worse SR; B. Shift of Perceived-Best-Focus following adaptation to different amounts of blur (as in A). Each panel depicts data for each subject S#1-S#5. Solid lines and squares are data for better eyes; dashed lines and circles are data for worse eyes. No after-effects occur for an adapting image blurred with the aberrations of the better eye (indicated with an arrow), when either eye is tested.

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