Blur Adaptation to Central Retinal Disease

Fuensanta A. Vera-Diaz,[1–3] Russell L. Woods,[2,3] and Eli Peli[1–3]

[1]New England College of Optometry, Boston, Massachusetts, United States
[2]Schepens Eye Research Institute of Massachusetts Eye and Ear, Boston, Massachusetts, United States
[3]Department of Ophthalmology, Harvard Medical School, Boston, Massachusetts, United States

PURPOSE. The long-term, low-resolution vision experienced by individuals affected by retinal disease that causes central vision loss (CVL) may change their perception of blur through adaptation. This study used a short-term adaptation paradigm to evaluate adaptation to blur and sharpness in patients with CVL.

METHODS. A variation of Webster's procedure was used to measure the point of subjective neutrality (PSN). The image that appeared normal after adaptation to each of seven blur and sharpness levels (PSN) was measured in 12 patients with CVL (20/60 to 20/320) and 5 subjects with normal sight (NS). Patients with CVL used a preferred retinal locus to view the images. Small control studies investigated the effects of long-term and medium-term (1 hour) defocus and diffusive blur.

RESULTS. Adaptation was reliably measured in patients with CVL and in the peripheral vision of NS subjects. The shape of adaptation curves was similar in patients with CVL and both central and peripheral vision of NS subjects. No statistical correlations were found between adaptation and age, visual acuity, retinal eccentricity, or contrast sensitivity. Long-term blur experience by a non-CVL myopic participant caused a shift in the adaptation function. Conversely, medium-term adaptation did not cause a shift in the adaptation function.

CONCLUSIONS. Blur and sharp short-term adaptation occurred in peripheral vision of normal and diseased retinas. In most patients with CVL, neither adaptation nor blur perception was affected by long-term attention to peripheral low-resolution vision. The impact of blur/sharp adaptation on the benefit of image enhancement techniques for patients with CVL is discussed.

Keywords: visual adaptation, central vision, low vision, blur, sharp

Blurred vision may be a consequence of optical[1–3] or neural factors,[4] as well as simulated blur applied by processing of distal (displayed) images.[5–7] Optical blur may result from defocus on the retina (e.g., uncorrected refractive errors). This type of blur is characterized by a low-pass decrease in contrast as well as phase reversals that appear as abruptly reversed polarity. Optical blur may also result from translucent or irregular optical media (e.g., cataract, corneal edema, keratoconus, or looking through translucent filters). This diffusive blur is not accompanied by the phase reversals found in defocus blur. All the effects of optical blur can be simulated in displayed images by using image processing. Neural blur may result from a number of factors. For example, retinal image motion resulting from eye movements or actual image motion causes neural blur. Motion blur is characterized by a low-pass decrease in contrast, but only in the direction of motion, and has no phase reversal effects. Neural blur may also result from undersampling, the sampling of the image at a lower rate than the content bandwidth of the image, which causes aliasing artifacts (mainly phase-scrambling effects) that are usually reported as blur, even though the image contrast is not necessarily reduced. Such undersampling occurs naturally in the retina, more so in the peripheral retina, and can also be applied using image processing. Image processing is a very effective tool for studying the effects of natural blur, as it allows simulations of different types of blur in the displayed image, but also sharpening of these images, therefore providing an experimental control to determine the level of blurriness and sharpness that makes an image be perceived to be in focus. It is important to note that the word "blur" is typically used to describe all of the phenomena addressed above, even though each of these have different effects on image quality and the observer's perception is likely different.

Patients who suffer from damage to their central retina that includes the fovea (central vision loss [CVL]), caused by diseases such as macular degeneration, use a peripheral area of their retina (preferred retinal locus [PRL]) for fixation.[8,9] As a consequence of being forced to attend with their peripheral retina, these patients constantly experience reduced spatial resolution (neural blur).[4] Individuals with normal vision who use their fovea for central high-resolution fixation, are not aware of the reduced spatial resolution in their peripheral vision, and they do not perceive blur in the periphery, despite the neural blur. In fact, smoothed edges presented in peripheral vision appear sharper than when they are viewed foveally.[10] Often, patients with CVL report that their vision is blurred. It is possible that their use of the term "blur" represents insufficient vocabulary, or a difficulty distinguishing between blur and low resolution. It is also possible that the long-term experience of attending to the neural blur at the PRL leads to a change in the perception of blur.

Our judgments of image blur are modulated by blur adaptation, which is the change in the perceived level of blur

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following even a short period of exposure to image blur (induced optically or by image processing). Hence, adaptation to blur and sharpness refers to the changes in perception that take place after viewing images that are either blurry or sharp. Patients with low levels of myopia frequently report that when they remove their glasses the amount of blur they perceive without their glasses lessens over time or that they even no longer perceive blur.[11] Adaptation to image blur and sharpness can be elicited and directly measured by looking at natural images or videos that have been computationally blurred or sharpened.[5,12,13] This procedure measures perceived neutrality (i.e., image that appears normal) after a period of adaptation to blurry or sharpened images. After adapting to sharpened images, subsequently viewed normal images appear to be blurred so that a mildly sharpened image will be perceived to be normal (less sharp). Similarly, after viewing blurred images for a while, subsequently viewed normal images appear sharpened. The perceptual effects of blur and the aftereffects of adaptation to optically induced blur have previously been measured, and small improvements in visual acuity and contrast sensitivity following adaptation to optical blur have been reported.[11,14-18] Adaptation to blur has been shown to modify other oculomotor responses such as the accommodative response.[2,19] Adaptation to blurred text, as measured with similar procedures, may also improve the ability to read blurred text.[20]

Minimum detectable blur increases with retinal eccentricity.[7,17] The aftereffects of adaptation to blur and sharpness may also vary with retinal eccentricity. There is indication that adaptation may also occur in the peripheral field of subjects with normal sight (NS).[21,22] Haber et al.[21] have measured adaptation to blur and sharpness by using the paradigm of Webster et al.[5] in three subjects foveally and at a peripheral eccentricity (8°). They have found adaptation curves that are similar in peripheral and central vision. Mankowska et al.[22] have measured the effect of medium-term (30 minutes) adaptation to blur in central and near-peripheral vision (2° to 10° eccentricity) in young healthy adults with normal vision and found a similar improvement in visual acuity at all eccentricities after the blur adaptation. However, it is not known whether the long-term, low resolution experienced by patients with CVL affects their perception of image blur. It is also not known whether patients with CVL adapt to their peripheral reduced resolution differently than individuals with normal vision. Their adaptation may be stronger, as they constantly use the peripheral retina for viewing and therefore they constantly experience the reduced-resolution, peripheral-retinal images, as suggested by Gheorghiu et al.[23]

A subjective judgment of change in perceived blur with adaptation may reflect a learned, cognitive change in criterion (what the observer is used to seeing), or it may be a result of a real adjustment in sensitivity. The fact that there is an improvement in visual performance following blur adaptation,[11,14,15,24] supports the latter. These studies show a change in sensitivity to blur at the fovea.

Assuming that the short-term adaptation paradigm of Webster et al.[5] could be used in patients with CVL, we investigated adaptation to blur and sharpness in a group of subjects with CVL and compared it to the adaptations in the peripheral vision of subjects with NS. If patients with CVL experience long-term adaptation to their intrinsic neural blur, the consequence of reduced resolution caused by the use of their peripheral vision, they would show compensation for their poor peripheral-vision resolution, reflected in a change in their perception of a normal image. Their blur adaptation curves would show a downward offset, a change in the gain (slope), and local maxima and minima (peaks) occurring at

higher adapting stimulus levels. We hypothesized that subjects with CVL would instead show short-term adaptation similar to that experienced by subjects with NS in their peripheral vision,[21,22] with a characteristic blur adaptation curve,[12] despite their long-term neural blur.

METHODS

Adaptation to various levels of computationally induced image blur and sharpness was measured by following the procedure described by Webster et al.[5] and Vera-Diaz et al.[12] A group of subjects with CVL ($n = 12$) was tested while looking at the images freely, presumably using their habitual PRL. A control group of subjects with NS ($n = 5$) was tested (1) while looking at the images freely, using their central vision, and (2) while fixating targets located above the image, placing the image at various eccentricities in their peripheral vision.

Subjects

Of 14 subjects with CVL who were recruited to participate in this study, 12 completed the adaptation experimental testing. Two subjects did not successfully complete the trials; one because she was biased toward pressing one key, hence the staircase never ended; the other subject declined to continue the test as he found the test technique too complicated. Staircases of the 12 remaining subjects were reliable. Thus, 12 subjects (six female) with binocular CVL caused by various retinal diseases (Table) participated in the study. Their age range was 24 to 84 (median 61) years. The NS subjects ($n = 5$, four female) were 21 to 35 (median 25) years old.

During the entire testing, and whenever necessary, study participants wore trial frames with their best correction for the viewing distance used, as determined by subjective refraction. Best-corrected visual acuities for the CVL subjects ranged from 0.48 to 1.20 logMAR (Snellen equivalent 20/60 to 20/317; median 0.70 logMAR). Best-corrected visual acuities for the NS subjects ranged from −0.12 to 0.00 logMAR (Snellen equivalent 20/15 to 20/20; median −0.06 logMAR). Letter contrast sensitivity (CS) was measured for 2.5° high (approximately 1 cyc/deg) letters by using an in-house computer system that was equivalent in angular letter size and stopping rules to the MARS printed-chart system.[25]

All subjects were tested monocularly, while using their best-acuity eye, or the subject's preferred eye if equal. Subjects with CVL were tested while using their habitual PRL, the area that they used when asked to look at an object, which varied in eccentricity between 1.9° and 19.9° (median 4.5°) from the fovea, as measured with the Nidek MP-1 (Nidek Technologies, Padua, Italy) (Table). Even though the PRL information was obtained when the subjects were performing a different task (fixating a high-contrast cross in the Nidek MP-1), subjects were observed while doing the experimental procedures and they appeared to be using a PRL consistent with the PRL measured with the MP-1. All NS subjects showed stable foveal fixation with the MP-1.

This research followed the tenets of the Declaration of Helsinki. The protocol, procedures, and consent forms were approved by Schepens' Institutional Review Board. All subjects consented to participate in the study after explanations of the nature and possible consequences of the study were given.

Image Processing

Image processing was performed as previously described in detail by Vera-Diaz et al.[12] The original image used in these

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TABLE. Demographics and Vision Information on the Participants With Central Vision Loss

Subject No.	Diagnosis	Age, y	VA, logMAR	CS*, Log Units	PRL Eccentricity, Degrees From Fovea	PRL Location, In Visual Space	Fixation Stability, Deg^2
1	Dry AMD	83	0.50	1.23	4.5	Left/below	2.3
2	Myopic degeneration	63	0.70	1.4	4.8	Above	1.2
3	ROP	59	1.20	1.04	8.0	Right/below	60
4	Myopic degeneration	63	0.50	N/A	4.3	Right/above	5.7
5	Doyne-Honeycomb retinal dystrophy	57	0.50	1.55	2.4	Left/below	14.3
6	ROP	24	1.00	1.45	N/A	Above	N/A
7	JMD	30	1.00	1.15	19.9	Left/below	2.5
8	JMD	76	0.90	N/A	4.5	Right/below	4.2
9	Wet AMD	84	0.90	N/A	9.7	Below	7.0
10	Myopic degeneration	50	0.90	0.75	N/A	Left/below	N/A
11	Wet AMD	75	0.70	1.45	1.9	Left/below	2.2
12	JMD (Stargardt's)	68	0.70	1.6	5.8	Below	1.8

VA was measured with best refractive correction. See text for more details on vision measurements. Note that for the two subjects who had ROP (subjects 3 and 6), we had difficulty determining whether the retina was folded or where the fovea was located. Fixation stability is the 95% confidence interval of a bivariate contour ellipse fit to the fixation points found in a fixation examination of approximately 30 seconds when using a Nidek MP-1. AMD, age-related macular degeneration; JMD, juvenile macular degeneration; N/A, not available; ROP, retinopathy of prematurity.

* Twenty-mm letters viewed from 450 mm (~1 cyc/deg).

experiments was a gray scale image of a male face provided by Michael Webster[5] and originally from the database of Matsumoto and Ekman (Fig. 1).[26]

The level of blur or sharpness—the relative slope (Δs)—described the change relative to the original image of the slope of the image spatial frequency spectrum. Slope refers to the slope of the linear fit to the radially averaged amplitude of the spatial frequency spectrum on a log-log plot.[27] Images were digitally blurred or sharpened by varying the slope of the spatial frequency spectrum by Δs relative to the slope of the original image. The original amplitude spectral slope $s = -1.39$ (for the image used in this study) was modified by scaling the log of the spatial frequency coefficients of the Fourier-transformed images proportionally to their log frequency and inverse transformed to the space domain. Following the procedure of Webster et al.,[5] the root mean square (RMS) luminance of each filtered image was also adjusted to match that of the original image. This was done to prevent the subjects from using the global image RMS contrast as a cue to the level of sharpness or blur of the stimuli (high-pass filtering increases RMS contrast and low-pass filtering decreases RMS contrast). We implemented some modifications to the procedure of Webster et al.[5] as described in detail previously.[12]

Two hundred images were created from the original image by varying the global amplitude spectra slope from $\Delta s = +1.00$ to $\Delta s = -1.00$, in $\Delta s = 0.01$ steps. These steps are sufficiently small, as the just noticeable difference for perception of blur and sharpness in these images was found in a small control study ($n = 3$ subjects with CVL) to be approximately $\Delta s = +0.18$ for sharp images and $\Delta s = -0.15$ for blurred images.

The images (256×256 pixels) were presented on a 17-inch-diagonal (36.1×27.3 cm; 800×600 pixels) CRT monitor (Sony FD Trinitron; Sony Corporation American, New York City, NY, USA) running at a frame rate of 100 Hz controlled by a Cambridge Research System (Rochester, Kent, UK) VSG 2/5 graphics card. The test and adapting images were presented in the center of a gray background (mean luminance of 20 cd/m^2). At the viewing distance of 40 cm, the images subtended $16° \times 16°$ (Fig. 2). Monitor calibration, including gamma correction, was handled by the VSG software driver and was performed before experimental setup and repeated at frequent intervals.

Psychophysical Procedures

Procedures were as described previously.[12] In summary, subjects adapted to a digitally blurred or sharpened image, "the adapting image," for 30 seconds initially, followed by 3 seconds for readaptation (top-up time) after each test trial. In forced-choice trials, subjects were asked to decide whether the test image was perceived to be "too blurred or too sharp compared to what you think is normal." Adapting and test images were separated by a 500-ms "blank" period in which the stimulus was replaced with gray level matching the surround. Subjects responded to the 500-ms "test image" with "too blurry" or "too sharp" by using two keys on a keyboard number pad. Responses were to be made as quickly as possible, and before the reappearance of the top-up image, resulting in a response window of 1 second (500-ms "test image" followed by 500-ms "blank" period).

Each study participant was tested in each fixation condition with a minimum of seven blocks, where each block used an adapting stimulus with a different level of blur or sharpness (or the original image: $\Delta s = 0.00$). For each adaptation level (block) the spectral slope of the image was modified relative to the original image by either $\Delta s = \pm 0.75$; $\Delta s = \pm 0.50$; $\Delta s = \pm 0.25$; or $\Delta s = 0$. Two subjects with CVL were tested with additional levels of blur and sharpness of the adapting image ($\Delta s = \pm 0.90$). Each block consisted of two interleaved staircases of presentations to find the level of blur (or sharpness) appearing "normal" (point of subjective neutrality; PSN) for a single adapting stimulus. One staircase started at a random positive Δs (sharpened) level and the other started at a random negative Δs (blurred) level. The mean of the last 10 reversals from each staircase was computed as the PSN and the values from the two staircases were averaged to derive the relative slope of the image that appeared normal. Typically, there were approximately 100 trials per adapting level.

All subjects with CVL were tested under one condition: freely looking at the image presented in the center of the screen. A subgroup of subjects with CVL ($n = 7$) was retested in a separate session to determine repeatability. For these subjects, an average of their data from both sessions was used to calculate the adaptation fitting function. NS subjects were tested under four fixation conditions, allocated in random order during four separate sessions: (1) freely looking at the
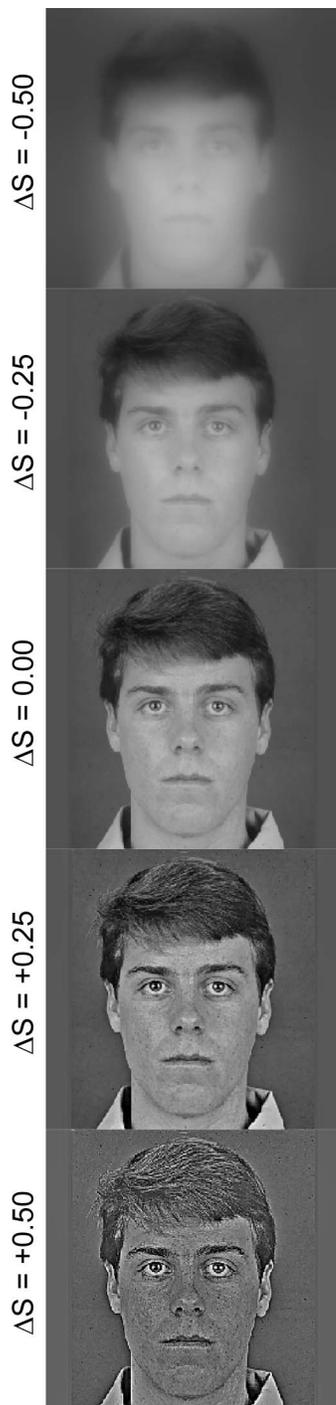
FIGURE 1. Original (Δs = 0.00) image and examples of processed images used in this study.
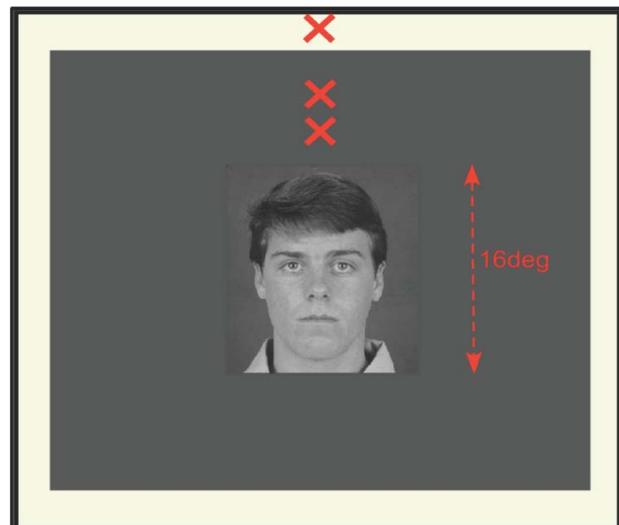

FIGURE 2. The adapting and test images were presented in the middle of the monitor. Subjects with CVL looked at the images freely, presumably with their habitual PRL. Subjects with normal sight were tested, in random order, either centrally (looking straight at the images) or in the periphery by fixating a red cross located at 2°, 5°, or 10° of eccentricity (from the edge of the image).

image presented in the center of the screen; or looking at a fixation cross located at (2) 2° from the edge of the image, (3) 5° from the edge of the image, and (4) 10° from the edge of the image (Fig. 2).

Data Analyses

Internal consistency of the staircases was evaluated by comparing the output values from the two interleaved staircases for each run. Spearman rank correlations between the two staircases were high and significant for the subjects with CVL ($\rho = 0.87$, $P << 0.01$) and the NS control group ($\rho = 0.94$, $P << 0.01$).

The PSN for each adaptation level was used to plot individual adaptation curves. Adaptation curves had the tumbled-S shape previously described.[12] To perform quantitative analyses, adaptation data were fitted with a modified Tukey biweight function (Equation 1) as described previously[12]:

$$ y = G \cdot (x - Off) \left(1 - \frac{(x - Off)^2}{C^2} \right)^2 + Off, \qquad (1) $$

where y represents the relative slope (Δs) of the image chosen as the PSN and x represents the relative slope of the adapting image. G is the slope of the function in the region near $x = 0$, Off is the vertical offset of the function, and C is related to the peaks of the function. The function was fitted by using a nonlinear least squares method in Matlab (MathWorks, Inc., Natick, MA, USA).

As described previously,[12] adaptation functions were characterized by the following values: (1) $X_{SharpPeak}$ and $X_{BlurPeak}$, the adapting stimulus (x) levels that produced maximum and minimum PSN (peaks in y) for the sharpened and blurred images, respectively, beyond which the magnitude of the PSN would not increase as the Δs of the adapting stimuli was increased (were made blurrier or sharper); (2) $Y_{SharpPeak}$ and $Y_{BlurPeak}$, the maximum and minimum PSN (y) for sharp and blurred images, respectively; (3) G, the slope of the function or gain of adaptation; and (4) $Y_{Intercept}$, the PSN to an original image, which related to the asymmetry of adaptation to blur and to sharpness.

Statistical analyses were performed with SPSS version 11.5 (SPSS, Chicago, IL, USA; www.ibm.com/SPSS_Statistics), JMP 10 (SAS Institute, Cary, NC, USA; http://www.jmp.com/), and Stata version 14 (Stata, College Station, TX, USA) software.

RESULTS

The five subjects with NS showed adaptation curves (Fig. 3) with the same tumbled-S shape as those previously described.[12] Most raw adaptation data were within the 95%
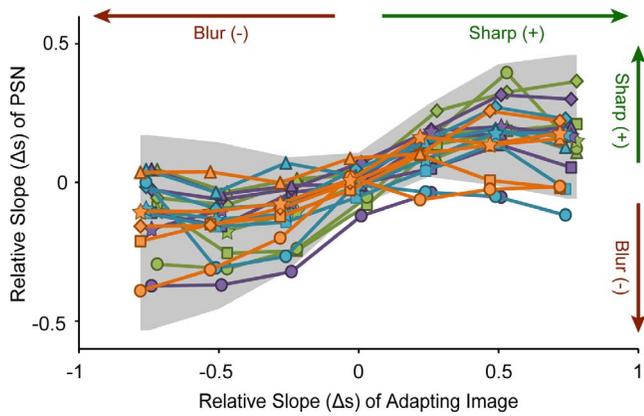
FIGURE 3. Raw adaptation data points at each level for the five subjects with normal sight in this study. Each subject's data are represented by a different symbol. Each condition is represented by a different color: *green* = 0°, *purple* = 2°, *blue* = 5°, and *orange* = 10° from the edge of the image. The *shaded gray area* represents the 95% confidence intervals for the 39 subjects with normal sight in the study by Vera-Diaz et al.[12] There were 10 data points outside the confidence interval, which is not different from what would be expected (Fisher exact, $P = 0.31$). Negative Δs represents blur, while positive Δs represents sharp.

confidence intervals (CIs) of the previously published data.[12] Ten (of 140) data points fell below the limits of the CI (i.e., more adaptation to blur), none above. The adaptation descriptors for these subjects' foveal vision were not significantly different from those previously reported (Mann-Whitney; $z \leq 1.71$; $P \geq 0.08$).[12]

The adaptation descriptors derived from the fits to the adaptation data for these control subjects are shown in Figure 4. Adaptation descriptors in the periphery of NS individuals

were not different from those obtained foveally, except for the location of the $X_{BlurPeak}$ being different at 2° (mixed effect model, $P = 0.03$) and 10° ($P = 0.004$) and for *Gain* at all three eccentricities (≤ 0.02) (Fig. 4). Since there were few differences between the conditions, data for each of the four eccentricity conditions were combined for subsequent comparisons to the CVL group.

All 12 subjects with CVL showed adaptation to blur and/or sharpness, and their adaptation curves (Fig. 5) appeared similar to those previously described in NS subjects.[5,12] Most of the subjects with CVL had tumbled-S adaptation curves that were similar to those found in the NS group.

Since adaptation curves were only fit when at least six adaptation levels were available, 2 of the 12 subjects with CVL (CVL8 and CVL9) were excluded in the next analysis. For the remaining 10 subjects, the PSN for the original image (curve offset or $Y_{Intercept}$) was not significantly different from that of the five NS subjects (Mann-Whitney U test; $z = 0.26$; $P = 0.79$).

Half of the CVL subjects (CVL3, CVL5, CVL6, CVL8, and CVL12) did not reach a peak in adaptation within the measured range ($\Delta s = \pm 0.75$), for either blurred or sharpened (Fig. 5). To allow analysis of the peak descriptors, for those subjects, we set $X_{BlurPeak} = -1$ and $X_{SharpPeak} = 1$, and $Y_{BlurPeak}$ and $Y_{SharpPeak}$ were set to the estimated value at those assumed X-peak values. In our previous study,[12] using the same methodology, 7 of the 39 subjects with normal sight had adaptation curves without peaks in the measured range, and a further five have only one peak within the range. These proportions between subjects with CVL and NS were not significantly different (Fisher exact test, $P = 0.12$).

Using these arbitrary values, the adaptation descriptors $X_{BlurPeak}$ ($z = 3.40$, $P = 0.001$) and $X_{SharpPeak}$ ($z = 2.34$, $P = 0.02$) for subjects with CVL were greater than the NV group values. For the raw adaptation values at $\Delta s = -0.75$ condition
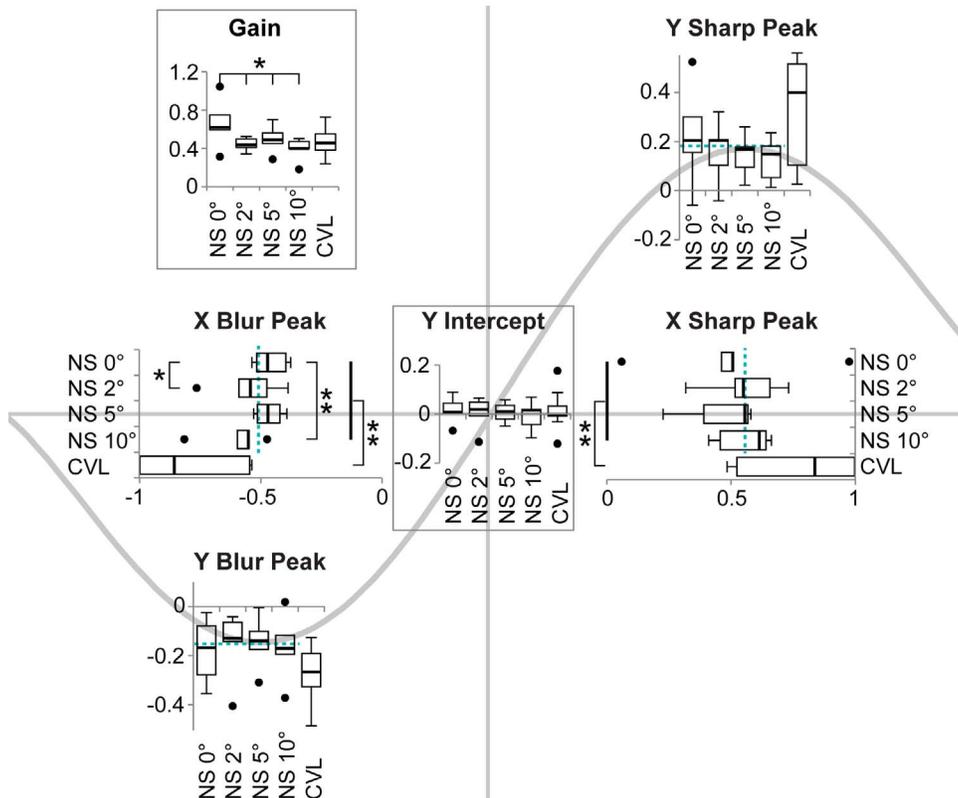
FIGURE 4. Adaptation descriptors for the control subjects with NS for all conditions (0°, 2°, 5°, and 10°), and for those with CVL. *Aqua dashed lines* represent the means for the NS control subjects across all eccentricities.
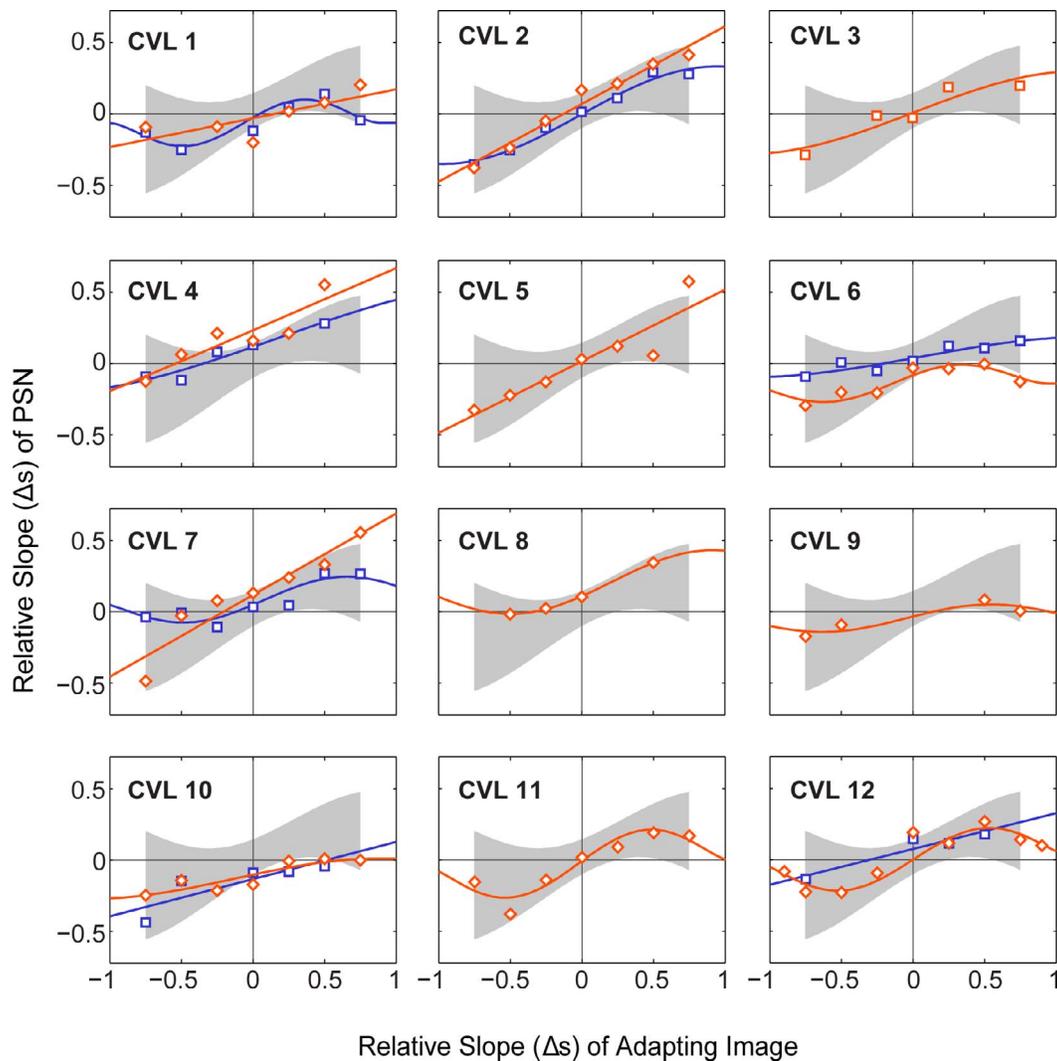
FIGURE 5. Blur adaptation raw data (*diamonds* and *squares*) and fits (*red* and *blue curves*) for the 12 subjects with CVL who completed the study. *Red data points* and *curves* indicate first test data and *blue data points* and *curves* indicate retest data. The adaptation curves were fit with a modified Tukey biweight function as described in the text. This figure illustrates individual variability and repeatability in the shape of the adaptation function. For some subjects with CVL, adaptation curves only showed the ascending zones of the function and did not reach peaks within range of blurred and sharp images tested in this study. The *gray zone* in each panel represents the 95% confidence interval from our previous study.[12]

(blur), the PSNs of subjects with CVL were greater (median −0.23; range, −0.11 to −0.37) than those of NS subjects when tested in the periphery (median −0.12; range, +0.04 to −0.35) (Kruskal-Wallis, $\chi^2 = 9.71$, $P = 0.002$); no significant differences were found at $\Delta s = +0.75$ (sharp; $P = 0.09$).

Individual variability of the measured adaptation was evaluated in a subgroup of subjects with CVL ($n = 7$) who repeated some or all the adaptation levels during a second session (Fig. 5). Using an approach described previously,[12] the distribution of the within-observer differences between the test and retest sessions (median 0.06; range, 0.03–0.13) was compared with the distribution of all possible between-subjects paired differences between test and retest sessions (median 0.09; range, 0.03–0.19). The two distributions were different (Kolmogorov–Smirnov, $z = 0.81$; $P \ll 0.001$), showing that there were individual differences between subjects with CVL in the shape of the adaptation function, as was previously found for NS individuals.[12] The distribution of the within-observer differences were not different from the within-subjects distribution previously found in NS individuals

($z = 0.50$; $P = 0.06$),[12] confirming that raw adaptation responses data for subjects with CVL were as repeatable.

To show the robustness of the fitting function, two subjects with CVL (CVL6, CVL12) who were available were tested with adapting additional stimuli that had been blurred and sharpened to $\Delta s = \pm 0.90$ (beyond the range from the main study). The adaptation functions with the additional levels confirmed the tumbled-S shape (Fig. 6) and were not substantively different from those found with the smaller range (± 0.75).

PRL eccentricity was positively correlated with best-corrected logMAR visual acuity (VA) (Spearman $\rho = 0.69$, $P = 0.03$). There were no significant correlations between the other individual characteristics described in the Table. There was a trend toward higher fixation stability with better VA, closer PRL eccentricity and CS, but these were not statistically significant. No significant correlations were found between any of these parameters and the raw adaptation values or the gain of the adaptation function in subjects with CVL. The blurred and sharp peak (*X* and *Y*) PSN levels for these subjects were
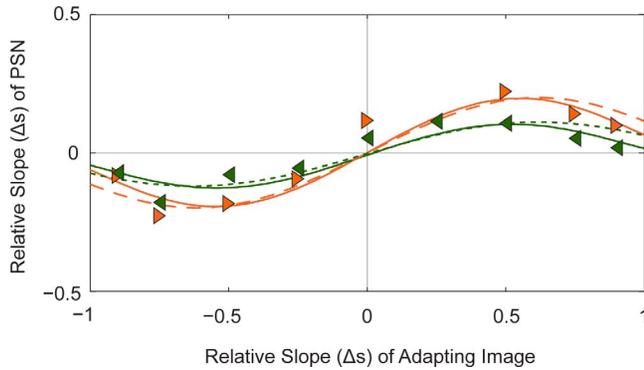
FIGURE 6. Adaptation data for the two subjects with CVL who were also tested with higher adaptation levels; $\Delta s = \pm 0.90$ (*continuous lines*) and for the adaptation levels used for all subjects; $\Delta s = \pm 0.75$ (*dashed lines*). Adaptation peaks did not differ when an extra sharper adaptation image ($\Delta s = +0.90$) was used.

inversely correlated (Spearman $\rho = -0.90$, $n = 7$, $P = 0.03$). Thus, subjects with CVL with lower, absolute values, of adaptation peak values for blur showed higher adaptation saturation values for sharpness and vice versa.

We performed two additional control experiments. In the first, we measured adaptation by using the same paradigm described earlier in one NS subject who has experienced long-term adaptation to defocus blur due to uncorrected refractive error (right eye: −5.50 sph; left eye: −1.25 −0.25 × 015). When this subject's myopia was corrected with lenses and tested with our adaptation paradigm monocularly on his right eye (Fig. 7), a shift of the adaptation curve toward blur was evident ($Y_{Intercept} = -0.14$; outside the $Y_{Intercept}$ spread [+0.12 to −0.12] as previously reported for 39 NS subjects.[12] This shift indicates that this subject experienced long-term adaptation to defocus blur that resulted in perceiving a blurred retinal image as normal.

In the second control experiment, one of the NS control subjects who participated in this study (NV5) underwent two additional experiments. In the first, the subject, who habitually wore glasses to correct her myopia, adapted to a translucent diffuser filter (Bangerter occlusion foil; The Fresnel Prism and Lens, Co., Bloomington, MN, USA) mounted in the spectacle plane for 1 hour. In the second, conducted on a different day, the same myopic subject adapted to +2.00 diopters of defocus blur (under correction of her myopia using trial lenses
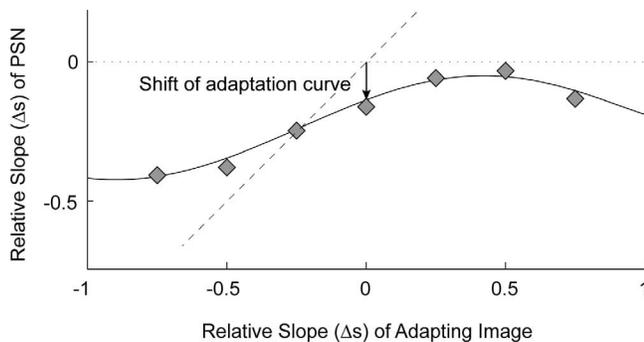
FIGURE 7. Adaptation data and fitted function of a subject with normal sight (right eye) who had long-term adaptation to defocus blur in this eye (uncorrected high myopia). The subject's refractive error was fully corrected during the experiment. Once the high myopia was corrected, a significant shift of the adaptation curve toward blur ($Y_{Intercept}$ downward offset), outside the 95% confidence interval reported in Figure 2, is evident (*arrow*).
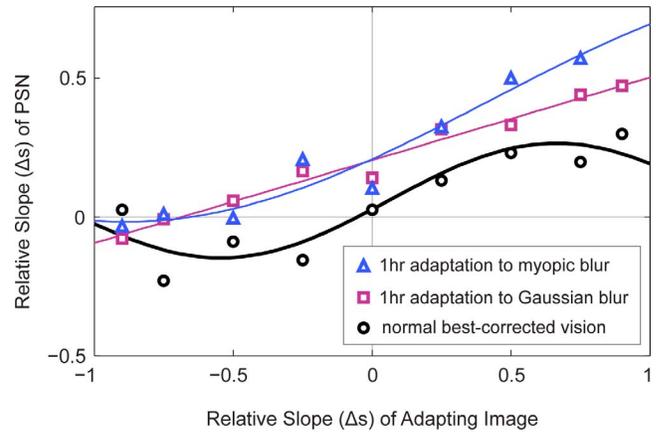
FIGURE 8. Adaptation function of subject with normal sight (NS5) under three different conditions. In all cases the subject was tested with the adapting lenses in place. This subject showed no indication of medium-term adaptation to the blur used in either of these conditions, as $Y_{Intercept}$ values were shifted toward sharpness, not toward blur, for both conditions. This suggests that, unlike the subject shown in Figure 7 who had long-term adaptation to blur, adaptation to 1 hour of blur was not sufficient to show an effect in the adaptation paradigm used in this study.

mounted in the spectacle plane) also for 1 hour. In each of these experiments, the blur adaptation testing was conducted while the subject was still wearing the optical blur-inducing, adapting lens. The results for these additional control experiments are shown in Figure 8. Both show that with the optical blurring lenses on, the subject did not perceive a shift towards blur, indicating that, unlike the subject shown in Figure 7 who had long-term adaptation to blur, adaptation to 1 hour of optical blur did not induce an overall perceptual change in perceived image blur.

DISCUSSION

To our knowledge, there have been no previous reports on how reduced resolution affects the perception of blur in patients with CVL or other visual impairments, with the exception of a case study on cataracts removed in adulthood[28] and on patients undergoing routine cataract surgery[29] that suggest long-term contrast adaptation in these patients. However, as we noted, cataracts do reduce contrast in a low-pass fashion, unlike the reduced resolution without the contrast reduction associated with the sparse sampling of peripheral retina. We have demonstrated that adaptation to blur and sharpness can be measured in patients with vision impairments, specifically with CVL. Adaptation to both blurred and sharpened images was repeatable and demonstrated individual variability for subjects with CVL, as shown previously in NS individuals.[12] Although many subjects with CVL reported difficulty performing the test and they believed they were doing poorly, most (12/14) of the subjects with CVL who participated in this study could perform the task. The two subjects who could not complete the test did not have worse vision than the others. Patients with vision impairments similar to those who participated in this study have difficulties performing common everyday tasks such as reading, driving, and watching television.[30–33] Nevertheless, our subjects with CVL could differentiate blur from sharpness in the tested images. This is an important consideration in both designing image-enhancement devices and correcting refractive errors for patients with CVL.

It is possible that in our experiment, subjects with CVL used image-processing artifacts as cues rather than the intended blur and sharpness, to differentiate the images. For example, even though the images were equalized for mean brightness, it is possible that local brightness cues were available to the participants. More importantly, the method that we and others[5] have used to process the images (changing the slope of the original image spatial frequency spectrum), followed by adjustment of the overall RMS, causes an unintended change at the very low frequency range of the spatial spectrum. Specifically, when creating blurred images, in addition to the intended reduction of contrast for high frequencies, an unintended increase in contrast in the low-frequency content is created as well. Similarly, a contrast decrease in low frequencies is a consequence of increasing high frequency contrast when sharpening the images. This spatial content change might have been used by our subjects to differentiate between blurred and sharpened images. Even if these artifacts allowed discrimination of the differences, it is not clear that it would lead to any change in the PSN. Yet, this could be considered a limitation of studies using blurred and sharpened image processing until an alternative solution is found.

We hypothesized that subjects with CVL, despite their long-term neural blur (reduced resolution), would adapt to image blur similarly to the adaptation found at the fovea of NS controls. Indeed, we found that short-term blur adaptation takes place despite the long-term neural (low-resolution) blur in subjects with CVL, as perception of best focus in subjects with CVL was similar to that of subjects with normal vision. There was no difference in the perceived normal image when adapted to the original image ($Y_{Intercept}$) or the gain (slope) of the blur adaptation curve between the CVL and NS groups. Attention to low-resolution images (from long-term use of peripheral vision, the PRL) does not change the apparent focus in subjects with CVL and thus does not require adaptation. Our results also indicated that the short-term blur adaptation is not a change in criterion, as the null stimulus for the adaptation (i.e., the spatial-spectral slope that does not produce a blur aftereffect) is also roughly the same stimulus that appears subjectively in focus foveally.[34]

The CVL group had adaptation curve peaks ($X_{BlurPeak}$, $X_{SharpPeak}$, beyond which the magnitude of the PSN would not increase as the adapting stimuli was made blurrier or sharper) at more extreme adapting-stimulus levels than subjects in the NS group in this study. However, there was no difference in the proportion of subjects with CVL who had peaks that were not in the measurement range when compared to a larger sample of subjects with normal sight.[12] The adaptation level to the most blurred image tested in this study showed greater PSNs for subjects with CVL than for those with normal vision when tested in the periphery. This difference was not found for sharpness. Overall, the short-term adaptation to blur of the subjects with CVL was very similar to the foveal and peripheral adaptation of individuals with NS. The experience of reduced resolution consequent to using peripheral retina is often described as blur by patients with CVL. However, in an unrelated study (not published) in which CVL was experimentally induced with simulated scotomas and a gaze-contingent display system in subjects with normal sight, all the participants described their vision as having reduced resolution, not as appearing blurred. Thus, even though patients with CVL use the term "blur" to describe their vision, this may simply reflect a lack of vocabulary to distinguish between blur and reduced resolution.

No significant correlations were found between any of the individual demographic or visual parameters and the raw adaptation values or the gain of the adaptation function in subjects with CVL. Our results did not show differences in adaptation between the patient and control groups despite a significant difference in age between the groups (median for subjects with CVL was 61 years versus 25 years for NS subjects). Furthermore, no correlation between age and adaptation was found in either group. That result may appear different from that reported by Elliott et al.,[35] as they found a small difference when comparing central vision adaptation in a group of young adults (mean age, 25 years) and a group of older adults (mean age, 74 years). The greater within-individual variability found in our study, a consequence of testing subjects who use their peripheral vision, likely accounts for this difference between the studies. No differences in adaptation were found between sexes. In addition, no correlations were found between adaptation and habitual PRL, in spite of significant variability in PRL stability and location among the subjects with CVL. This was the case even when subject CVL3, who had very poor fixation stability, was excluded from the analyses. Grouped data showed that $Y_{Intercept}$ adaptation values were not different from those of NS control subjects. Thus, the image that appears normal to patients with CVL after adapting to the "normal" original image would be a normal image, unlike the myopic, non-CVL subject with long-term blur adaptation (Fig. 7). In addition, when NS subjects adapted, using peripheral vision, they showed very similar values to the subjects with CVL using their PRL; adaptation was not stronger in the periphery.

When an NS subject was tested who was long-term adapted to dioptric blur because he did not use his glasses, a significant shift toward image blur being perceived as in focus was found in the adaptation curve measured with full refractive correction (Fig. 7). This shift indicates that this subject experienced long-term adaptation to the defocus blur that resulted in perceiving a blurred retinal image as normal. Adaptation to defocus blur is different from the adaptation to the low-resolution, neural "blur" experienced by patients with CVL. When another NS subject was adapted to different types of optical blur (Fig. 8), that subject showed no indication of long-term adaptation to the blur used in either of these conditions, as the $Y_{Intercept}$ was shifted toward sharpness for both conditions. This finding suggests that, unlike the subject who was habitually uncorrected and therefore exposed to long-term defocus blur (Fig. 7), the amount of time this other subject (Fig. 8) adapted to blur (1 hour) was not sufficient to provide the long-term adaptation required to show an effect with the short-term adaptation paradigm used in our study.

When NS subjects were freely looking at the processed images, they showed adaptation levels that were similar to those previously described.[5,12] Apart from differences in $X_{BlurPeak}$ and *Gain*, there were no differences between the free-viewing (central) and eccentric-viewing (peripheral) adaptation conditions in our subjects. Broadly, this finding is consistent with data reported by Haber et al.[21] on three subjects. As perception of blur and sensitivity to blur (and sharpness) vary with retinal eccentricity,[10,17] it might be expected that adaptation to blur and sharpness would also vary with eccentricity. However, the lack of an effect of eccentricity on adaptation found in our study may reflect a higher-level normalization to perception of blur and sharpness,[36] caused by a greater change in neural gain control in the periphery that causes greater suppression of sensitivity to blur in the periphery, not by a change in criterion.[34]

Both groups of study participants adapted also to sharp images as part of the procedure. Subjects with CVL did not show significantly more adaptation to sharpness than NS subjects and did not seem to adapt to enhanced images differently. The main difference found in the adaptation values between NS and CVL subjects was that subjects with CVL had blur and sharp peaks that were at larger values of the adapting

stimulus. We recommend that in future studies measuring adaptation using this paradigm in subjects with poor vision, the adaptation images should extend to levels beyond $\Delta s = \pm 0.75$.

Short- and long-term aftereffects of adaptation to enhanced (sharpened) images[12,37,38] may have significant implications in low vision rehabilitation options such as image enhancement. If patients adapt to the level of enhancement in a display (e.g., television, head mounted display), the benefits of the enhancement could be diminished, as they may no longer be perceived as enhanced. On the other hand, there are potentially beneficial effects of adaptation to sharpness. If patients adapt to the enhancement, the displayed images could appear more natural to them (not artificially distorted), so it would be more likely that they, as well as others with normal vision who may be using the display (e.g., television) at the same time, accept the enhancement. Individual variability found in the preferred level of enhancement of the displayed images, even when controlling for VA or impairment,[37,38] may be a consequence of individual differences in adaptation to various sharpness levels.[12] Adaptation to blur in patients with CVL may also influence their tolerance of blur with consequent implications for the prescription of visual aids.

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