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Blur adaptation: Contrast sensitivity changes and stimulus extent

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ABSTRACT

A prolonged exposure to foveal defocus is well known to affect the visual functions in the fovea. However, the effects of peripheral blur adaptation on foveal vision, or vice versa, are still unclear. In this study, we therefore examined the changes in contrast sensitivity function from baseline, following blur adaptation to small as well as laterally extended stimuli in four subjects. The small field stimulus (7.5° visual field) was a 30 min video of forest scenery projected on a screen and the large field stimulus consisted of 7-tiles of the 7.5° stimulus stacked horizontally. Both stimuli were used for adaptation with optical blur (+2.00 D trial lens) as well as for clear control conditions. After small field blur adaptation foveal contrast sensitivity improved in the mid spatial frequency region. However, these changes neither spread to the periphery nor occurred for the large field blur adaptation. To conclude, visual performance after adaptation is dependent on the lateral extent of the adaptation stimulus.

1. Introduction

It is well known that our visual system continuously changes its response characteristics based on the recent visual experience. For example, we can adapt to a visual environment with high or low contrast and thereby decrease or increase the contrast sensitivity (CS) respectively (Blakemore & Campbell, 1969; Kwon et al., 2009; Webster & Miyahara, 1997). Adapting to blur induced by defocus can also produce changes in visual acuity and contrast sensitivity (Mon-Williams et al., 1998; Ohlendorf & Schaeffel, 2009; Pesudovs & Brennan, 1993; Rajeev & Metha, 2010; Rosenfield, Hong, & George, 2004). It is important to understand the mechanism of this defocus-induced blur adaptation, e.g., in myopia development research and when evaluating spectacles and intraocular lenses that changes the peripheral blur. Most of the previous research on defocus-induced blur adaptation has been restricted to foveal and parafoveal blur stimulus. Extending the blur stimulus also to the periphery during blur adaptation will mimic the natural viewing conditions and give better insights about the underlying mechanism.

1.1. Contrast sensitivity changes following defocus adaptation

Defocus reduces contrast across spatial frequencies, with a small reduction for low spatial frequencies and increased reduction for middle and higher spatial frequencies. Defocus induced blur adaptation is therefore similar to low contrast adaptation. Defocus-induced blur adaptation has been reported to increase supra-threshold contrast sensitivity at 3.22 cycles/degree (cpd) (Ohlendorf & Schaeffel, 2009). Increases in contrast sensitivity were also reported at 8 and 12 cpd when the visual evaluation was performed with defocus (Rajeev & Metha, 2010). However, there is one report that instead found a decrease in contrast sensitivity for a large range of spatial frequencies (from 5 cpd to 25 cpd) following adaptation with a +2.00 D defocus (Mon-Williams et al., 1998).

1.2. Letter acuity changes following defocus adaptation

Adaptational changes in contrast sensitivity will also influence letter acuity although there are other factors like learning, which need to be considered. Most studies on blur adaptation following defocus exposure evaluated letter acuity changes. The reported improvement in high contrast letter acuity following blur adaptation is quite varying, ranging from two letters while adapting to subjects' own myopic refractive error (Pesudovs & Brennan, 1993) to around three lines while adapting to +2.50 D blur (George & Rosenfield, 2004). Rosenfield, Hong, & George, 2004 and George & Rosenfield, 2004 also noted an improvement in low contrast grating resolution in myopic subjects.

1.3. Adaptation stimulus extent in previous studies

In most of the defocus adaptation studies previously mentioned, the adaptation task was movie watching on a computer

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or a television monitor while wearing defocus lenses. This type of adaptation task is commonly employed to ensure attention and fixation at a particular distance. However, it restricts the adaptation stimulus to the fovea and parafovea. So far, there is only one report, in which the visual acuity was evaluated in the fovea and out to 10° nasal visual field (Mankowska et al., 2012). Similar vision improvements were found in fovea and parafovea. It should be noted that the adaptation task was movie watching on a television screen from the distance of 4 m and hence the adaptation stimulus could not have covered the full ±10° field. The authors therefore suggested that the adaptational effects could spread to peripheral locations. If this spread of foveal defocus adaptational effects to peripheral locations does occur, it will be of great importance for myopia development research. Animal studies have shown that peripheral blur can control the growth of the eye and thereby the development of myopia (Charman, 2005; Schaeffel, Glasser, & Howland, 1988; Smith et al., 2005). In addition, it has recently been reported that the correction of central myopia with progressive addition lenses that also induced myopic defocus in the periphery reduces the myopia progression (Berntsen et al., 2013).

To investigate visual field dependence of the blur adaptation effects more thoroughly, we need to meet two pre-requisites: (i) the adaptation stimulus should be extended to the periphery and (ii) a larger range of spatial frequencies and retinal locations in both fovea and periphery should be analyzed. In the current study, we addressed these aspects by comparing contrast sensitivity changes following adaptation with a small and a large field stimulus through measurements of the clear (i.e. not defocused) contrast sensitivity function (CSF) before and after adaptation in the fovea and in the periphery. Measuring CSF is both time consuming and tiring. Fatigue can introduce bias in the results of adaptation studies. To alleviate these problems, we used a quick method to measure CSF, qCSF. This method of assessing the complete shape of the CSF with a Bayesian adaptive estimation strategy was developed and verified by Lesmes et al. (2010) for foveal CSF estimation and was further modified and verified by Rosén et al. for peripheral CSF (Rosén et al., 2014). The qCSF method can estimate the shape of the CSF quickly and thereby allow for multiple measurements before and after adaptation. In addition, separate sessions with contrast sensitivity measurements at separate spatial frequencies and low contrast grating acuity measurements were performed to confirm significant changes noted with the qCSF method.

2. Methods

2.1. Subjects

Four subjects participated in the study: three of the authors who were experienced in the psychophysical procedures and one naïve subject. The authors were not naïve to the purpose of the study, but response bias was controlled by the forced-choice paradigm in the visual evaluation. All subjects had visual acuity or corrected visual acuity of 0.00 logMAR or better. One subject (S2) was myopic (−2.50 D) and was corrected with soft contact lenses. The study protocol followed the tenets of the Declaration of Helsinki and was approved by the regional ethics committee in Stockholm. Informed consent was obtained from all subjects prior to the measurements.

2.2. Experiment procedures

2.2.1. Adaptation conditions and protocol

Two different stimuli (small and large field) were used during adaptation under two optical conditions: (i) with +2.00 D blur induced with trial lens and (ii) clear, i.e. without blur. In total, four adaptation conditions were tested in four separate sessions: Small Field Blur Adaptation (SFBA), Small Field Clear Adaptation (SFCA), Large Field Blur Adaptation (LFBA) and Large Field Clear Adaptation (LFCA). Only the right eye was adapted, while the left was occluded during adaptation. The CSF measurements were made in the right eye fovea (REFovea), the right eye 10° nasal visual field (RE10N), and in the left eye fovea (LEFovea). The measurements in the REFovea was repeated twice and the average of these two measurements was considered for the analysis. The test locations were randomized for both initial and post adaptation measurements. The order of the adaptation conditions was also randomized. To summarize, each session had four initial CSF measurements followed by adaptation and then four CSF measurements after adaptation. A single adaptation session with 30 min of video watching and all visual evaluations lasted about one hour. The sessions were separated at least by two days.

2.2.2. Adaptation

The adaptation stimulus was a high definition video of forest scenery (30 min video clip from an episode of the Planet Earth series by BBC). A high-definition projector with a 1920*1080 pixels resolution was used to project the videos. For small field stimulus, the video was projected with a frame size of 274*154 pixels and for large field stimulus, seven tiles of the small video stacked horizontally were used (Fig. 1). Subjects were seated at a distance of 2 m from the projector screen and the horizontal size of the small and large stimuli were about 7.5° and 42° (26 and 180 cm) respectively. The tiled version was used as the large field stimulus instead of a scaled version in order to have the same frequency content in both adaptation stimuli. For the blur adaptation conditions (SFBA and LFBA), subjects viewed the video through a +2.50 D lens (+0.50 D for 2 m viewing distance and +2.00 D for blur) in front of the right eye. For clear adaptation conditions (SFCA and LFCA), no defocus lenses were used (only a +0.50 D lens for distance compensation) while watching the video. For the viewing distance and the magnification used, the pixel size of the projector was about 1.6 min of arc.

2.2.3. Psychophysical stimulus and apparatus

The stimuli for visual evaluation were presented on a calibrated 19-inch CRT display controlled by a Linux based system with 10-bit gray scale resolution. The mean luminance of the display was 52 cd/m^2. The psychophysical algorithm and monitor calibration were implemented with MATLAB and Psychophysics toolbox routines (Brainard, 1997; Pelli, 1997). An obliquely oriented (45° or 135°) Gabor stimulus with a Gaussian envelope of 0.8° standard deviation was used in a two-alternative forced choice resolution task for all vision testing. The subject's task was to identify the orientation of the grating. The stimulus presentation time was set to 500 milliseconds accompanied by an auditory cue. No feedback was given. An external fixation target (Maltese cross) was used for the RE10N measurements. The monitor and the external fixation target were 4 m away from the subject. Subjects wore a +0.25 D lens during the visual evaluations to compensate for the testing distance. The measurements were conducted in a dark room with natural pupils. The pupil size was monitored with an infrared camera to make sure that it was stable throughout the visual evaluation and not changing between initial and post adaptation measurements. The average pupil size was 6.0 and did not vary by more than 0.5 mm during the initial and post adaptation measurements. A chin-forehead-rest was used to minimize head movements and the pupil camera was also used to monitor the fixation stability.

Fig. 1. Examples of a small (7.5°) and large (42°) field adaptation stimulus video frame.

2.2.4. qCSF measurements

In the qCSF algorithm, the CSF curve is parameterized with four different parameters to describe the shape of the curve (truncated log-parabola) (Lesmes et al., 2010; Rosén et al., 2014). A four dimensional probability density function (PDF) is used to assign probabilities for various combinations of the parameters. After each trial, based on the results from that trial, the PDF is updated with Bayes rule and the next stimulus (spatial frequency and contrast) is chosen based on the updated PDF. The parameters used to describe the foveal qCSF as a function of spatial frequency (freq) are: the peak contrast sensitivity (CS_{max}), the spatial frequency of the peak (SF_{peak}), the bandwidth of the curve in octaves (BW), and the level of low-frequency sensitivity truncation (d_{fov}). The CSF is described as,

$$\text{logCSF} = \log_{10}\text{CS}_{\max} - (\log_{10}2)\left[\frac{(\log_{10}\text{freq} - \log_{10}\text{SF}_{\text{peak}})}{\text{BW}(\log_{10}2)/2}\right]^2.$$

$$\text{FovealCSF} = \begin{cases} \text{logCSF}, & \text{if freq} > \text{SF}_{\text{peak}} \\ \log_{10}\text{CS}_{\max} - d_{\text{fov}}, & \text{if freq} \leqslant \text{SF}_{\text{peak}} \text{ and } \text{logCSF} < \log_{10}\text{CS}_{\max} - d_{\text{fov}} \end{cases}$$

The difference between the foveal and the peripheral qCSF is in the truncation. The peripheral qCSF is described with the characteristic high frequency truncation (d_{peri}) instead of sensitivity truncation (d_{fov}) at low frequency of the foveal CSF. With d_{peri} as the high frequency truncation, the peripheral CSF is described as

$$\text{PeripheralCSF} = \begin{cases} \text{logCSF}, & \text{if freq} < d_{\text{peri}} \\ 0, & \text{if freq} \geqslant d_{\text{peri}} \end{cases}$$

The CSF was estimated in 100 trials. The stimulus space for the qCSF measurements contained Gabor gratings with varying contrasts and spatial frequencies. The possible stimuli were set to have 64 contrast levels between 0.4% and 100% and 50 spatial frequency levels between 1 cpd and 50 cpd. Both parameters and stimuli were distributed evenly in logarithmic space.

From each qCSF measurement, the expectation value of the contrast sensitivity at individual spatial frequencies was estimated from the four-dimensional PDF that was obtained at the end of 100 trials in each qCSF measurement, as described by Rosén et al. (2014). This procedure calculates the most probable *CS* value for each spatial frequency. The individual CS values for 10 spatial frequencies, equidistance in log-space between 1 cpd and 20 cpd were analyzed. Fig. 2 shows an example of a foveal CSF curve obtained with qCSF and the estimated CS values at spatial frequencies sampled for the analysis. To evaluate the changes in CS following adaptation, the difference in the $\log_{10}$CS between post adaptation and initial measurements were analyzed across the spatial frequencies with a two-tailed, paired *t*-test. Only changes of more than 0.1 log units were considered. $p < 0.05$ was set as significance level for the statistical analysis.

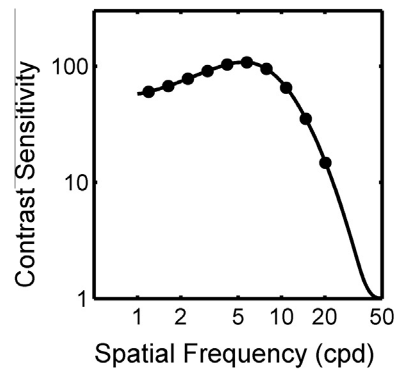

Fig. 2. A typical foveal CSF curve obtained with the qCSF algorithm with 100 trials. The solid circles indicate the estimated contrast sensitivity values at the sampled spatial frequencies considered for analysis.

2.2.5. Additional contrast sensitivity and grating acuity measurements

Four additional sessions of blur adaptation was done in two subjects (S1 and S2), in which contrast sensitivity at certain spatial frequencies and low contrast grating acuity were evaluated in the fovea of the adapting eye. The psychophysical algorithms for both these measurements were based on the Bayesian adaptive method (Kontsevich & Tyler, 1999) and 50 trials were used to estimate the threshold. The physical settings were the same as for the qCSF evaluation. For the CS, Gabor gratings of fixed spatial frequency but of varying contrast was shown and the sensitivity was estimated separately for 5 spatial frequencies roughly equidistant in log-space, between 1 cpd and 10 cpd (1, 2, 3, 5 and 10 cpd). Similar to the qCSF measurements, the individual contrast sensitivity measurements were also made under clear conditions, i.e. without any defocus lenses. For the low contrast grating acuity measurements, Gabor gratings of fixed contrast (10%) but with varying spatial frequency were used and blur lenses were worn during both adaptation and grating acuity measurements.

3. Results

3.1. Contrast sensitivity changes: qCSF measurements

The contrast sensitivity changes following the four different adaptation conditions, estimated with the qCSF, are shown in Fig. 3. The mean and the standard deviations of $\log_{10}$CS changes are plotted against the spatial frequencies. Positive values indicate an increase in CS following adaptation and the significant changes are highlighted as solid squares. Following blur adaptation, foveal contrast sensitivity in the adapting eye increased significantly in the mid spatial frequency region between 3 cpd and 4 cpd, for the small adaptation stimulus (SFAB, Fig. 3: 1A). Surprisingly, this enhancement in contrast sensitivity was not seen when the adaptation stimulus was large (LFAB, Fig. 3: 2A). In fact, there was a decrease seen around 5 cpd and higher. However, this decrease

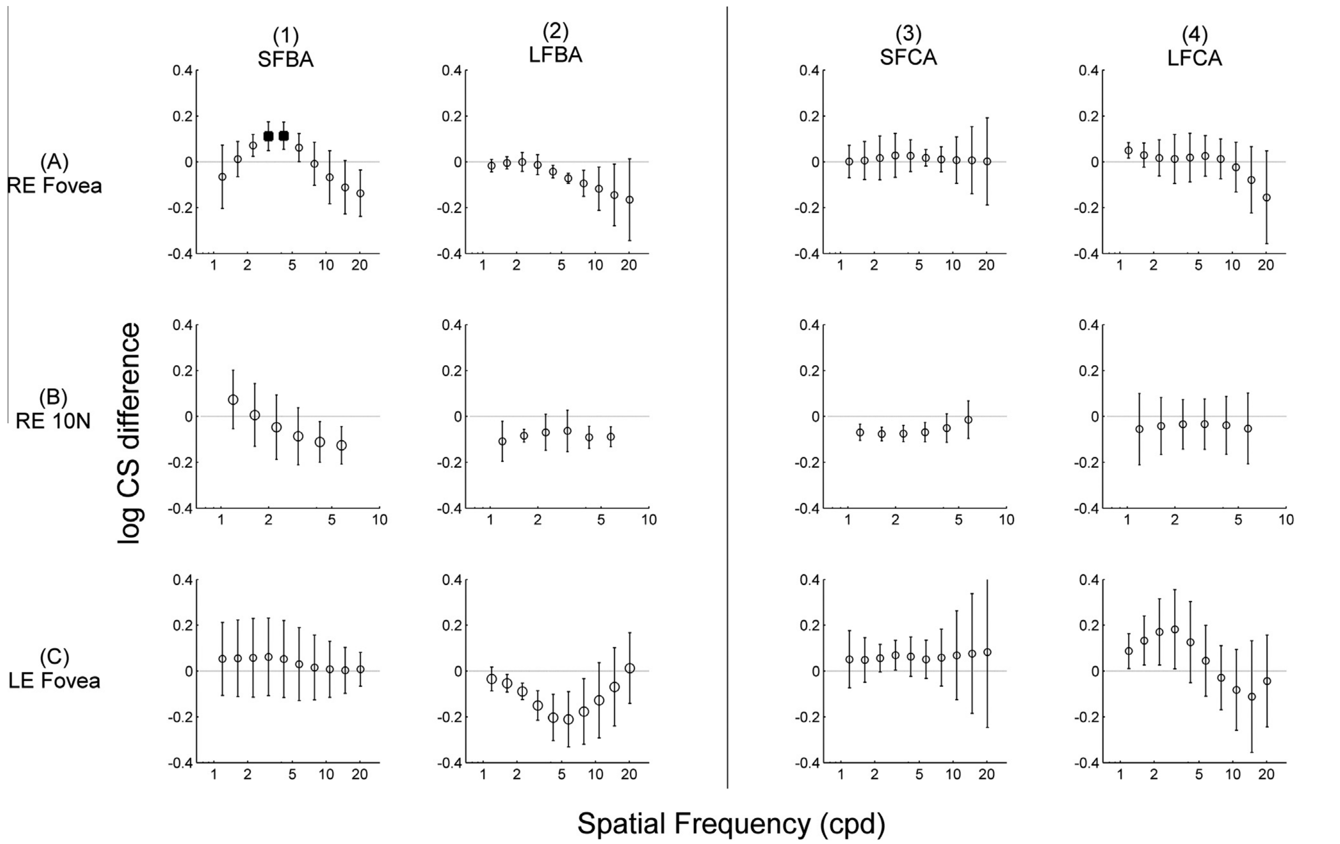

Fig. 3. Log CS differences (Post-Pre) following the four adaptation conditions measured with the qCSF method in three visual field locations (A) fovea of adapting eye, (B) 10° nasal in adapting eye, (C) fovea of fellow eye). For each adaptation condition, the average log CS differences and ±1 SD are shown. Solid squares indicate significant difference. Positive values indicate an increase in CS following adaptation. SFBA – Small Field Blur Adaptation, SFCA – Small Field Clear Adaptation, LFBA – Large Field Blur Adaptation, LFCA – Large Field Clear Adaptation.

at high spatial frequencies was not significant. Individual subjects data for adapting eye fovea for the blur adaptation conditions (SFBA and LFBA) is shown in Fig. 4. In this figure it can be seen that subject S4 showed a large overall decrease in the performance after adaptation for condition LFBA. The same overall decrease was also seen in the fellow eye of this subject during the same session. We therefore believe this to be due to fatigue and have removed subject S4 from condition LFBA in the analysis of Fig. 3.

Apart from the adaptational contrast sensitivity enhancement seen in the right eye fovea following SFBA no other significant changes in contrast sensitivity was found. The enhancement was not seen in the 10° nasal field (Fig. 3: 1B), not even for the LFBA condition although it had a blur stimulus in that location during adaptation (Fig. 3: 2B). Furthermore, no significant changes were observed in neither the fellow eye (Fig. 3: 1C and 2C) nor for the clear adaptation conditions (Fig. 3: 3 and 4). The large error bars in some graphs of Fig. 3 is due to individual variations and occurs especially in the high frequency (lower contrast sensitivity) regions, indicating that these changes are not consistent among the subjects.

3.2. Independent CS measurements and low contrast grating acuity measurements in adapting eye fovea

The results from the additional adaptation sessions on contrast sensitivity at separate spatial frequencies are shown in Fig. 5 for subject S1 and S2. The magnitude of change as measured with the independent method is different from qCSF method; however, the tendency of decrease in CS following LFBA (open circles in Fig. 5) and increase in CS around 3 cpd following SFBA (Solid circles in Fig. 5) was seen with both methods.

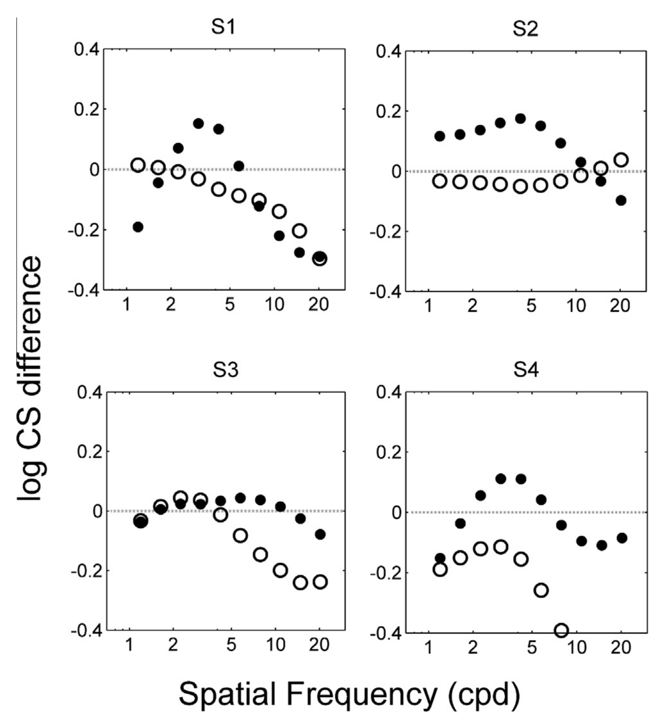

Fig. 4. Individual subjects data showing log CS difference in adapting eye fovea (REFovea) with small (closed circle) and large (open circle) field blur adaptation as measured with the qCSF method.

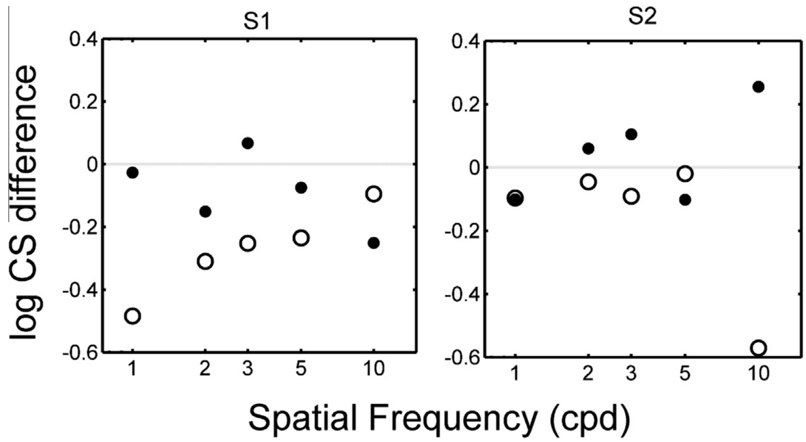

Fig. 5. Log CS changes (Post-Pre) measured at separate spatial frequencies in the fovea of the adapting eye in subjects S1 and S2. Solid circles indicate changes following small field blur adaptation (SFBA) and open circles indicate changes following large field blur adaptation (LFBA). Positive values indicate an increase in CS following adaptation.

Fig. 6 shows the changes in the 10% grating acuity measured with defocus in the fovea of the adapting eye following small and large field blur adaptation in the same two subjects. The individual standard deviations for the low contrast grating acuity measurements were within 0.08 logMAR. The grating acuity also showed an increase after SFBA in both subjects. For LFBA, the grating acuity was found to be unchanged or decreased.

4. Discussion

The current findings show that vision changes after blur adaptation are affected by the visual field extent of the blur stimulus. We found adaptational effects in foveal CSF for a small field adaptation stimulus, but these effects disappeared when a large field stimulus was used. Learning effects can be ruled out because the control conditions (clear adaptation) showed no changes in contrast sensitivity. No changes were seen in the peripheral *CS* following adaptation.

4.1. Contrast sensitivity evaluation following adaptation

Previously the qCSF method has been evaluated for precision, accuracy and test–retest reliability (Hou et al., 2010; Lesmes et al., 2010; Rosén et al., 2014). These studies report that the qCSF method is a reliable method to assess CSF. In the present study, the data from the two initial CSF measurements in the adapting eye fovea of each subject was analyzed for the test- retest difference. The mean and standard deviation of test–retest differences were 0.008 and 0.12 log units, which is in line with the earlier references. However, these values are for the estimation of CS when the CSF profile is normal. Hence, to verify the credibility of qCSF in estimating foveal CS values for CSF profiles with local changes, we performed simulations. In the simulations, various hypothetical CSF profiles with local increase or decrease in CS in different spatial frequency regions were used to calculate the responses of a simulated subject. In the spatial frequency region of interest, the CS values from the simulated response did not vary more than 0.06 log units from the hypothetical values.

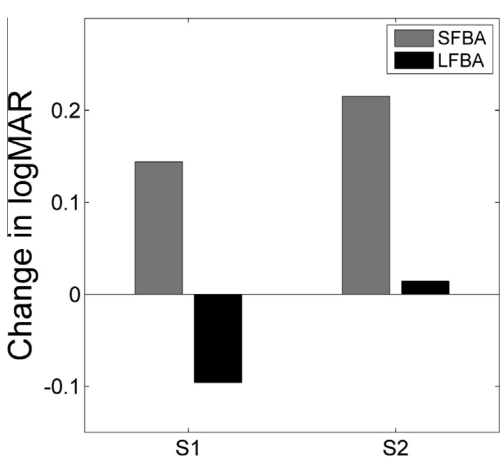

Fig. 6. Changes in 10% contrast grating resolution (in logMAR) in adapting eye fovea measured with defocus. Positive value indicate an improvement after adaptation. SFBA – Small Field Blur Adaptation, LFBA – Large Field Blur Adaptation.

Another concern in using qCSF for the evaluation of adaptational effects is the time taken for the post adaptational measurements. Displaying both adaptation and vision evaluation stimuli on the same monitor would have allowed presentation of top-up adaptation stimulus in-between the visual evaluation; however, this was not possible due to the monitor resolution requirements. Ohlendorf & Schaeffel, 2009 reported that after an adaptation time of 10 min, the sensitivity increase was maintained for 2 min and reached the baseline again after about 5 min. This recovery time is known to increase with adaptation time (Georgeson & Georgeson, 1987; Magnussen & Greenlee, 1985). In the present study, the post adaptation measurements took about 1/3 of the adaptation time. The adaptational effects should therefore have been present during the post adaptation visual evaluations, although decaying towards the end. The test location order (fovea, periphery, fellow eye) were randomized, thus any biases due to order of location and recovery time were minimized. It should also be noted that for the supplementary grating acuity and independent CS measurements in the fovea of the adapting eye for SFBA and LFBA, where the measurement time was much shorter, similar adaptational changes were revealed. The magnitude of these changes is different from those measured with the qCSF method, but as the independent measurements were not repeated more than once, it is difficult to interpret the difference based on the present data. Furthermore, as the independent CS measurement involved evaluation of CS for each spatial frequency separately, it is in general more vulnerable to measurement errors at individual spatial frequencies. Whereas the qCSF method evaluates all spatial frequencies interleaved, which prevents large fluctuations in measurement errors between frequencies. Moreover, starting the measurement at each spatial frequency with high contrast gratings in the independent CS measurements might itself affect the post adaptation measurements since top-up adaptation images were not used between measurements.

4.2. Contrast sensitivity enhancement following defocus induced blur adaptation

In the present study, we found increased sensitivity in the mid-spatial frequency region (about 3–4 cpd) following SFBA. Although it can easily be understood why the visual system benefits from reducing its sensitivity to strong signals (Blakemore & Campbell, 1969), it may seem irrational as to why it can improve and is not already working on maximum sensitivity. One possible explanation can be that the improvements seen in the mid-spatial frequencies in the present study could be a result of improvements from the baseline sensitivity, which in itself may be determined by long-term adaptation. The baseline sensitivity has been suggested to be determined by long-term adaptation to the visual environment (Bao & Engel, 2012; Kwon et al., 2009) and the existing optical errors (Artal et al., 2003; Sawides et al., 2011). Furthermore, adaptation to natural images can produce a decrease in sensitivity for low and mid-spatial frequencies due to the characteristics of the amplitude spectra of the natural images (Bex, Solomon, & Dakin, 2009; Webster & Miyahara, 1997). Hence, the findings following SFBA could be a result of de-adapting from the long-term adaptation to natural scenes. The present findings also show that the baseline sensitivity was maintained with the clear adaptation conditions. This finding is expected because the stimulus for clear adaptation was an unfiltered video with content that is dynamic in both spatial and temporal aspects, thus closely mimicking the normal viewing profile.

The spatial frequency region that had enhanced CS following SFBA (3–4 cpd) corresponds to details that are still present in the stimulus but with reduced contrast (i.e. not completely attenuated or resolved spuriously by the introduction of +2.00 D defocus). No changes were observed in higher spatial frequencies following SFBA. For a 5 mm pupil, the modulation transfer function (MTF) for 2 D of defocus will have the first zero around 2 cpd in the absence of other aberrations. With normal amount of aberrations and 2 D defocus, the first zero of MTF will be around 4 cpd. Rajeev & Metha, 2010 reported an increase in CS for higher spatial frequencies (8 and 12 cpd) but not for the lower spatial frequencies, when the CS measurements were made with +2.00 D defocus. Subramanian and Mutti (2005) evaluated blur adaptational changes in CS by assessing both clear and defocused CS and reported improvements in 2 cpd and 15 cpd respectively. From the present findings and the previous studies mentioned here, it should be noted that the reported adaptational improvements in the defocused and clear contrast sensitivity are in different spatial frequency regions. The shape of a defocused CSF is not regular as there will be multiple notches corresponding to the local minima in the MTF (Strang, Atchison, & Woods, 1999). This could be the reason for the different spatial frequency regions reported when the CSF measurements are made with and without defocus. The changes in contrast sensitivity from baseline for the mid-spatial frequencies are difficult to measure for the defocused condition due to the local notches in the MTF, while higher frequencies can still be visible through spurious resolution.

Many previous studies have reported improvements in defocused letter acuity and low contrast grating acuity following blur adaptation (George & Rosenfield, 2004; Mon-Williams et al., 1998; Pesudovs & Brennan, 1993; Poulere et al., 2013; Rajeev & Metha, 2010; Rosenfield, Hong, & George, 2004). These improvements could be a result of contrast sensitivity enhancements. However, it should be mentioned here that there is one study (Mon-Williams et al., 1998) that reported an overall decrease in contrast sensitivity in a larger range of spatial frequencies (5–25 cpd); this is not in agreement with the present findings or the other previous defocus adaptation studies.

4.3. Peripheral and fellow eye changes

We did not find any transfer in adaptation effects, neither to the fellow eye nor to the peripheral 10° visual field for SFBA. Similarly, we did not find any change in the contrast sensitivity in the peripheral field (10° nasal) for any of the adapting conditions. This is in contrast to Mon-Williams et al., 1998 who reported small interocular transfer of the adaptational effects and suggested that the blur adaptation occurs in the binocular sites of the visual cortex. However, the reported improvements in the fellow eye were minimal, only about 0.08 logMAR for high contrast letter acuity. Interocular transfer of blur adaptation has also been reported for the judgments of perceived focus (Kompaniez et al., 2013). However, the origin and underlying mechanisms may not be the same as the judgment of perceived focus occurs in the visual cortex whereas contrast adaptation may occur at various earlier stages in the visual processing. There are also reports suggesting that the contrast adaptation occurs at the level of the retina (Heinrich & Bach, 2002; Ohlendorf & Schaeffel, 2009). If the contrast adaption occurs mainly in the retina, there may not be a transfer to the fellow eye or spread to periphery, which is in agreement with our results.

4.4. Large field blur stimulus gave no improvement after adaptation

To our knowledge, this study is the first to compare blur adaptation to small and large field stimuli (7.5° and 42° in the horizontal direction). Interestingly, in contrast to the results of SFBA, the presence of blur stimuli also in the periphery during LFBA did not improve the foveal CS. Most previous studies on defocus induced blur adaptation used a small field stimulus for adaptation (<10°, as the television/computer monitor was viewed from a distance of more than 3 m). Even in a study that reported visual acuity changes in the periphery following blur adaptation, the adaptation stimulus was not extending to the periphery (Mankowska et al., 2012). However, Ohlendorf & Schaeffel, 2009 used a larger stimulus during adaptation; with a viewing distance of 1 m, the computer monitor must have subtended about 20°. They reported an increase in clear supra-threshold contrast sensitivity at 3.3 cpd, but no changes at threshold. This is in agreement with the present findings with no changes in contrast threshold when the adaptation stimulus was extended to the periphery, although it was extended only in the horizontal meridian in the present study.

No improvement in CS following LFBA was an unanticipated finding. One possible explanation for this is that peripheral blur is not as bothersome as foveal blur. In normal viewing conditions, objects in the peripheral visual space are not perceived to be very blurry though we constantly experience poor image quality in the periphery due to the existing peripheral optical errors. In fact, previous studies have shown that blurred edges are perceived to be sharper in peripheral vision (Galvin, O'Shea, Squire, & Govan, 1997; Galvin, O'Shea, Squire, & Hailstone, 1999). In this context, it should be noted that the +2.00 D in the present study was introduced over the existing peripheral refractive errors and, as the spherical equivalent in 20° eccentricity was myopic in all four subjects, gave a further increase in peripheral refraction. However, this additional +2.00 D defocus may have given a relatively smaller contrast reduction in the periphery than in the fovea. Hence, the overall blur experienced by the visual system might have been lesser for the large field stimulus than for the small stimulus, thus resulting in no improvements in CS following LFBA. The subjects also reported that viewing the large field video with blur was less troublesome than the small field video with blur. However, we cannot rule out other possibilities like attentional and fixational characteristics for a large field blur stimulus which can in turn influence the effects of adaptation (Pestilli, Viera, & Carrasco, 2007).

The influence of peripheral stimuli on the foveal adaptational effect is of special interest for myopia research. Corrections of central myopia with progressive lenses that induce myopic defocus in the periphery have been shown to reduce the myopia progression (Berntsen et al., 2013). Further experiments on the adaptational effects of a clear foveal stimulus surrounded by a peripheral blur stimulus will be of specific interest when designing corrective lenses for myopia.

To conclude, the effects of defocus-induced blur adaptation vary with the extent of the adaptation stimulus. Contrast sensitivity improves in selected spatial frequencies when the adaptation stimulus is small and covers only fovea and parafovea. However, these improvements disappear when the adaptational stimulus is extended to cover also the peripheral retina.

Acknowledgments

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