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Role of parafovea in blur perception

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The blur experienced by our visual system is not uniform across the visual field. Additionally, lens designs with variable power profile such as contact lenses used in presbyopia correction and to control myopia progression create variable blur from the fovea to the periphery. The perceptual changes associated with varying blur profile across the visual field are unclear. We therefore measured the perceived neutral focus with images of different angular subtense (from 4° to 20°) and found that the amount of blur, for which focus is perceived as neutral, increases when the stimulus was extended to cover the parafovea. We also studied the changes in central perceived neutral focus after adaptation to images with similar magnitude of optical blur across the image or varying blur from center to the periphery. Altering the blur in the periphery had little or no effect on the shift of perceived neutral focus following adaptation to normal/blurred central images. These perceptual outcomes should be considered while designing bifocal optical solutions for myopia or presbyopia.

1. Introduction

Our vision is at its best in the central visual field and declines rapidly with increasing eccentricity due to declining neural and optical quality (Banks, Sekuler, & Anderson, 1991; Curcio & Allen, 1990; Lundström, Gustafsson, & Unsbo, 2009; Mathur, Atchison, & Scott, 2008; Navarro, Moreno, & Dorronsoro, 1998). Although the neural limitations pose a major restriction on high-contrast resolution in peripheral vision, other characteristics like detection and low contrast resolution are affected by optical errors (Anderson & Ennis, 1999; Rosén, Lundström, & Unsbo, 2011; Shah, Dakin, & Anderson, 2012; Wang, Thibos, & Bradley, 1997; Wilkinson, Anderson, & Thibos, 2016). In the presence of normal foveal vision, the reduced image quality in the peripheral visual field often goes unnoticed. However, the peripheral visual quality may still have an influence on our foveal vision. With many studies suggesting that peripheral optical quality can affect the emmetropization process, leading to excessive eye growth and myopia progression, the peripheral optical quality is gaining more attention in the last decades (Smith, Kee, Ramamirtham, Qiao-Grider, & Huang, 2005). Altering the peripheral optical quality of the eye is a major strategy applied in many myopia control interventions (Huang et al., 2016). On the other hand, peripheral optical quality is altered by most optical corrections. For example, conventional spectacles (Tabernero, Vazquez, Seidemann, Uttenweiler, & Schaeffel, 2009) and intraocular lenses (Smith & Lu, 1991) often increase the blur on the peripheral retina and isoplanatic lens designs that improve peripheral optical quality have been proposed (Barbero, Marcos, Montejo, & Dorronsoro, 2011). In addition, the multifocal corrections used in presbyopia management also alter the blur in the peripheral visual field.

How the visual system copes with altered peripheral optical quality in the above mentioned conditions is unclear. Peripheral visual quality may influence our perception of the foveal image and there are evidences suggesting that foveal perception may either change or remain unaltered in the presence of peripheral blur. Webster and colleagues (Webster, Webster, & Taylor, 2001) reported that the perception of a foveal image is influenced by the quality of the surrounding peripheral images; central images flanked by blurred images appeared sharper to the subjects compared to the same images flanked by sharp images. This finding suggests that foveal blur perception is a relative judgment. Another study on adaptation to blur with different stimulus extents also showed that the presence of peripheral information influenced central perception (Venkataraman, Winter, Unsbo, & Lundström, 2015). On the other hand, it is well known that foveal vision is processed by a larger area in the visual cortex, which suggests that peripheral visual quality affects visual perception less than the

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foveal input. Hence, if the foveal image is sharp, the peripheral blur may not disturb the perceptual quality. Recent studies supporting this foveal dominance hypothesis found that perception is influenced primarily by the sharp component of the visual scene (Radhakrishnan, Dorronsoro, Sawides, Webster, & Marcos, 2015) and that the effect of foveal blur adaptation spreads to parafoveal vision (Mankowska, Aziz, Cufflin, Whitaker, & Mallen, 2012).

A useful measure of blur perception is the perceived neutral focus (PNF), also called as perceived focus or perceived best focus in the literature (Radhakrishnan, Dorronsoro, Sawides, & Marcos, 2014; Radhakrishnan et al., 2015; Webster, Georgeson, & Webster, 2002). The PNF is defined as the amount of physical blur with which the visual stimulus is perceived as neither sharp nor blurred. The PNF is influenced by previous visual experience or by a short exposure to blurred or sharp images (Webster et al., 2002). What is known about the PNF and its variations after visual adaptation (Radhakrishnan et al., 2014, 2015; Webster et al., 2002) is mostly limited to central vision, as the stimuli have generally been restricted to the fovea. However, in most daily viewing situations the stimuli are extended over the visual field and it is therefore important to understand the role of peripheral vision in determining PNF.

The present work aims at widening our understanding of the role of peripheral vision in blur perception. We studied blur perception by evaluating PNF using test images of different angular subtenses. We also evaluated the adaptational changes in foveal PNF by using numerically simulated images that had different blur profiles in the center compared to the periphery.

2. Methods

In this study, subjects viewed images with different center-peripheral blur profiles in an open view setup. We measured PNF for test images with five different angular subtenses (Experiment 1) and after adaptation to 6 different adapting images (Experiment 2).

2.1. Subjects

Measurements were performed in the left eye of eight subjects (28–34 years of age) with spherical refractive error range of −4.00 D to +1.00 D and none of the subjects had astigmatism >0.75 D. All subjects performed the measurements with natural pupils (pupil diameter range 5.1–6.0 mm) and their habitual spectacle or contact lens correction. All subjects except S7 had previous experience in performing psychophysical measurements. The study met the tenets of declaration of Helsinki and all subjects provided an informed consent approved by the regional ethics committee and Institutional Review Board.

In Experiment 1, the PNF for images with five different angular subtenses were measured with three repetitions. In Experiment 2, the PNF was evaluated for six adaptation conditions. The measurement order was randomized across the total 21 trials (measurement conditions and repetitions for both Experiment 1 and 2). Overall, the session lasted for about 2 h. During the measurements, the change in pupil size and refraction was monitored using the Power-refractor II (PlusOptix, Germany). Across subjects and conditions, the average change in the refraction was (0.50 ± 0.50 D) and the average pupil size was (5.3 ± 0.6 mm)

2.2. Setup

A high resolution (1920 * 1080) projector (front-illumination) was used to project the test and adapting images on a projection screen. The mean luminance at the screen was 40 cd/m^2 and all measurements were performed in a dark room. The subjects were seated 380 cm in front of the projector screen and the projector was placed in front of the subject. The position of the subjects was controlled using a head and chin rest. Other than the power refractor placed at 130 cm from the subject just outside 10° temporal visual field, the subject's peripheral field was free of visual distractions. The subjective responses were obtained using a numeric keyboard. The general experimental setup is shown in Fig. 1.

An image (1080 * 1080 pixels) of Jigsaw puzzle pieces that subtended 20° at the retina was used as stimulus. The image was cropped for different sizes for generating test and adapting images for both the experiments. These images had comparable RMS contrast and 1/f frequency spectrum (Fig. 2). Stimulus projection and response acquisition were synchronized using Psychtoolbox in MATLAB-Mathworks Inc. (Brainard, 1997; Pelli, 1997).

2.3. Experiment 1: changes in perceived neutral Focus with different angular subtenses of test images

In order to assess the role of including peripheral input on PNF, we studied the changes in PNF with increase in test stimuli size. PNF was assessed after adaptation to a uniform gray patch (Natural PNF) for test stimuli of five different angular subtenses: 4°, 8°, 12°, 16° and 20°.

2.3.1. Test stimuli

Test stimuli were generated by convolving the 20° image (1080 * 1080 pixels) with point spread functions (PSF) representing defocus (generated using Fourier techniques) ranging from 0 to 2.5 D in 0.01 steps. The PSF consisted of pure defocus such as

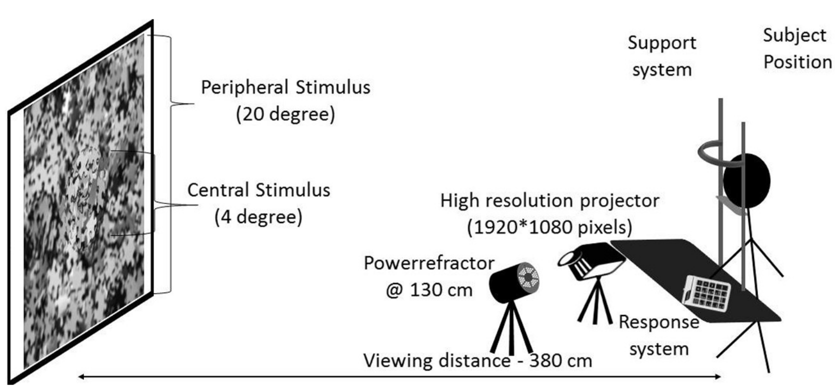

Fig. 1. Experimental Setup: The manipulated images were projected by a high resolution projector on to a matte-screen. The subject is seated at 380 cm from the screen. The overall screen subtended 20° at the subject's retina.

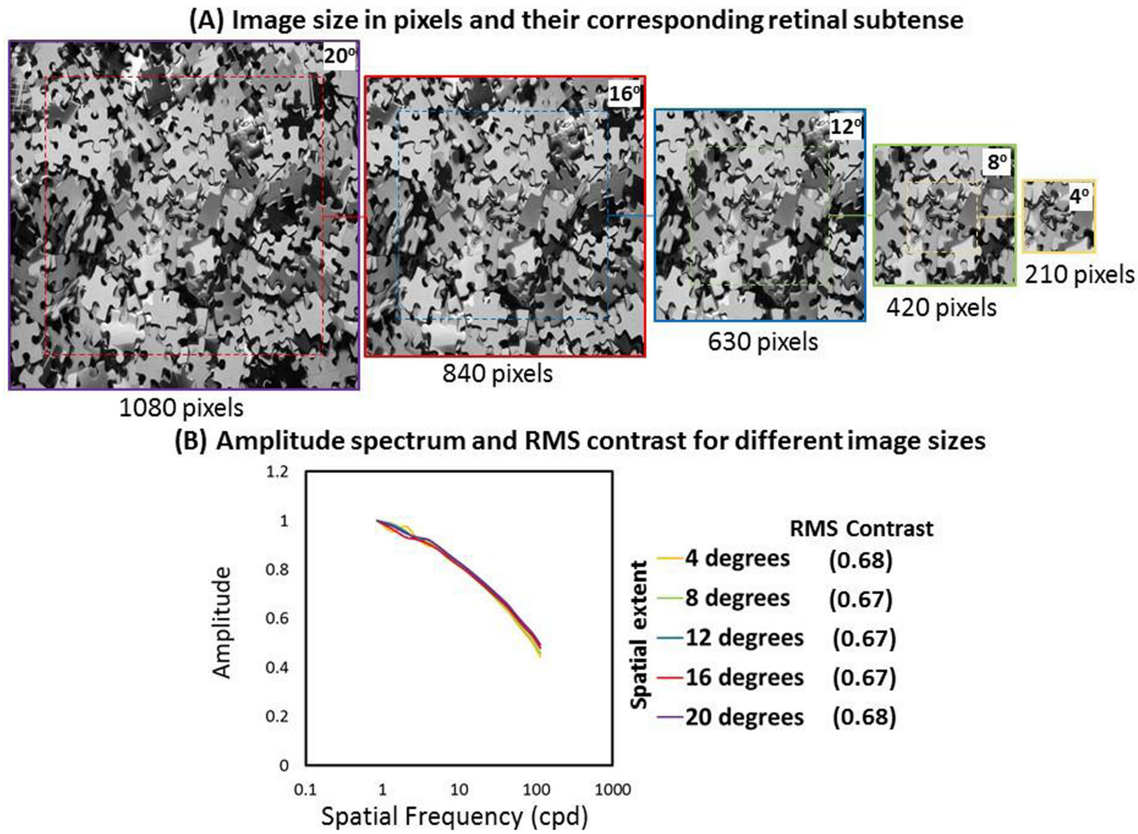

Fig. 2. (A) Examples of cropped test images with retinal subtense (inset) in degrees (B) Change in amplitude spectrum across different test images (All images had 1/f tendency). The corresponding RMS contrast is given as insets in the legend.

that simulated by optical lenses as shown in previous studies (Sawides, Gracia, Dorronsoro, Webster, & Marcos, 2011). All computations were performed for a pupil diameter of 5 mm, which was also close to the average pupil diameter of the subjects during the measurement (5.3 mm ± 0.5 mm). For test stimuli of smaller angular subtense, the test image was cropped to corresponding sizes as described before. The images were presented against a 20° gray field so that the smaller images were surrounded by the gray field to ensure uniform retinal illumination across the different conditions. Fig. 3 shows examples of the test images.

2.3.2. Procedure

Natural PNF was measured after adapting subjects for 30 s to a uniform gray patch of 20° with a small fixation cross. Test images of different blur level were then presented to the subject for 500 ms each. The subjects were instructed to respond whether the presented image was blurred or sharp according to their own internal code for sharpness/blur (single stimulus blur detection). Based on the subject's response the blur level in the subsequent test image was computed using the QUEST algorithm where the threshold criterion was set to 75% (Watson & Pelli, 1983). The subjects re-adapted to the gray field with a small fixation cross for 3 s in between each test image presentation. The predictive staircase procedure was designed to be terminated after 40 trials or 16 reversals, and the PNF was estimated as the average of the last 10 blur/sharp reversals.

2.4. Experiment 2: changes in perceived neutral Focus after adaptation to different center-periphery blur profiles

To assess the role of altered peripheral image quality on central PNF changes, the PNF was measured after adaptation to six adapting images with different center-peripheral blur profiles, using test images of 4° subtense.

2.4.1. Test stimuli

For all adapting conditions, the PNF was assessed using test images subtending 4° at the retina with blur ranging from 0 to 2.5 D (in 0.01 steps). These images had a tapering circular edge profile with a transition zone of 1° and were presented on a 20° gray background.

2.4.2. Adaptation stimuli

Six adapting images of three categories were used: Only central (4°) images in 20° gray background, full-field (20°) and combined (central 4° and peripheral 20°). The images were either blurred (2 D) or had normal (0 D) versions of the jigsaw puzzle image. The combined images had a smooth transition zone of around 1° and were meant to represent differences in central/peripheral imagery through a bifocal concentric design. Examples of the test and adapting stimuli are shown in Fig. 4.

2.4.3. Procedure

The PNF was measured as described in Experiment 1, except that instead of adapting the subjects to a gray field, the subjects were initially adapted to one of the six adapting images (randomly chosen) for 60 s. After adaptation, the subject was presented with a blurred test image for 500 ms, and based on the subject's response the blur level in the next test image was calculated using the QUEST algorithm (as in Experiment 1). While the subject responded, the screen with gray background and fixation target was shown and after the response the adapting image was displayed for 3 s followed by the test image. The measurement was then repeated for another adapting image.

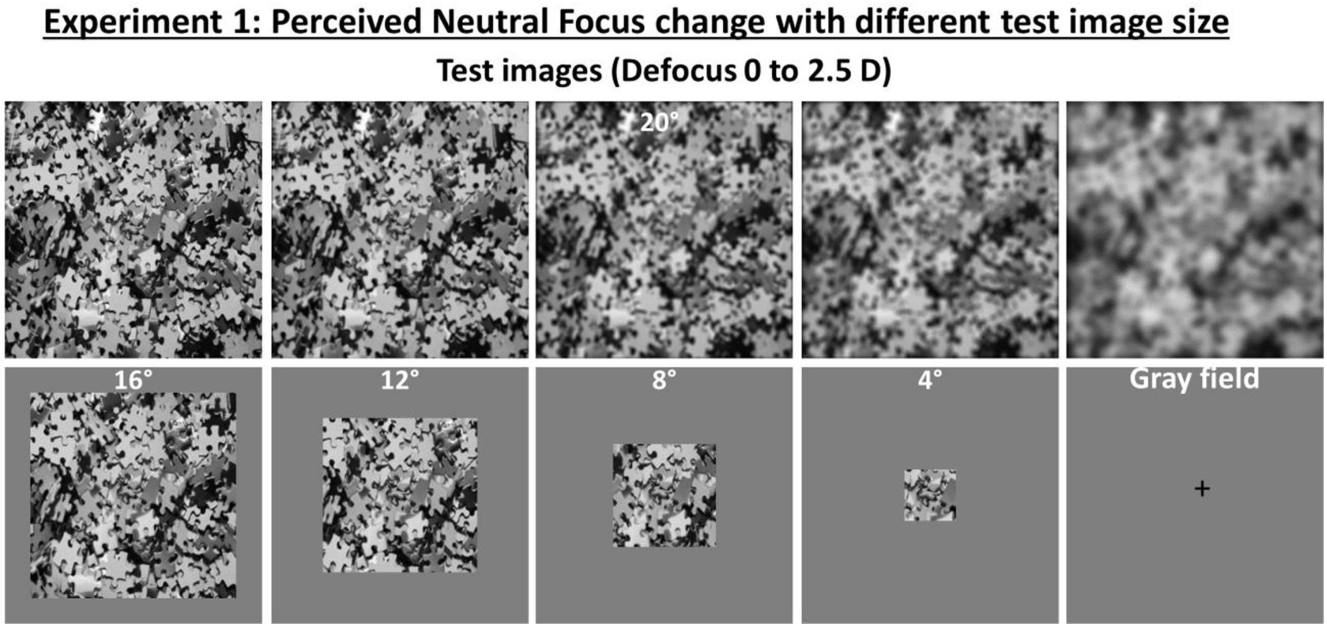

Fig. 3. Images used in Experiment 1: Perceived Neutral Focus for different test image subtense. Top row shows examples of five test images with blur range of 0 D to 2.5 D for 20 degree subtense. Bottom row shows examples of 0 D test images of 16°, 12°, 8° and 4° subtense against a gray background and the 20° gray patch adapting image.

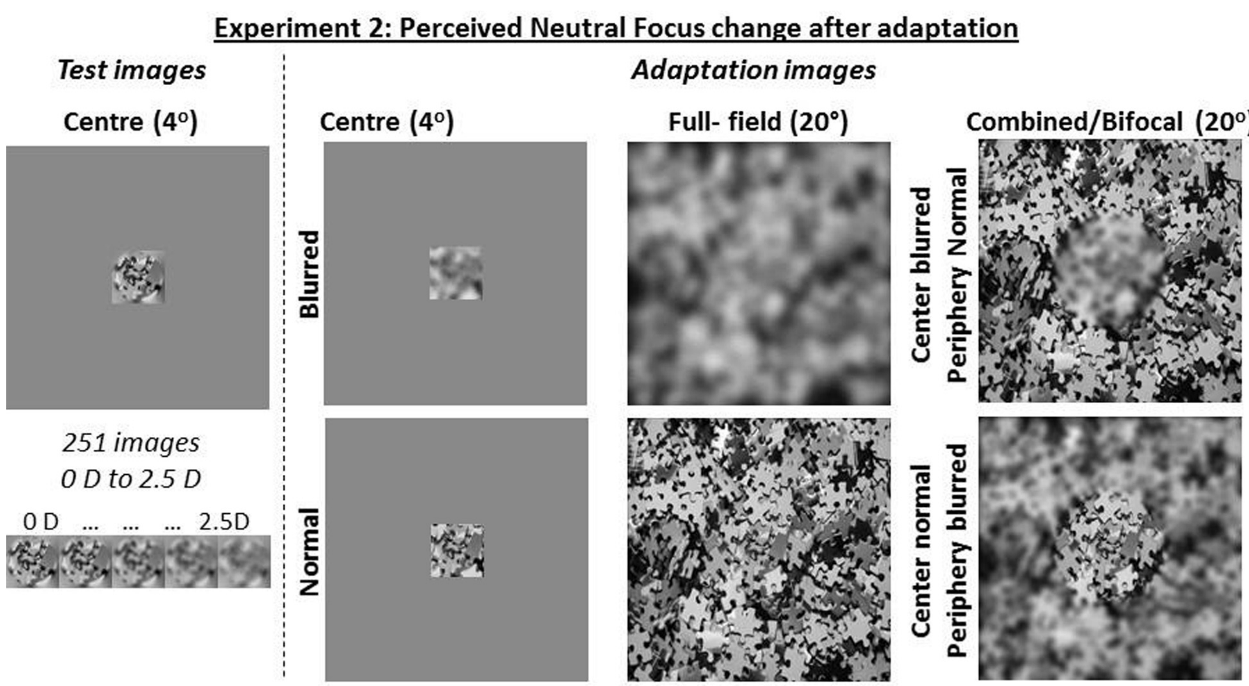

Fig. 4. Images used in Experiment 2: Changes in Perceived Neutral Focus after adaptation to images of different blur profiles. Examples of test images and the six different adaptation images (central, full field and combined images with 2D and 0 D blur) used in Experiment 2 are shown. The test images were shown on a 20° gray background.

3. Results

3.1. Effect of test image angular subtense on perceived neutral Focus

Fig. 5 shows that the amount of physical blur that is perceived as neutral (PNF on y-axis) increases with the *spatial extent of the* test images with a correlation coefficient of 0.88 ($p < 0.05$). There were inter-subject differences in the magnitude of change in PNF ($p = 0.043$) but all the subjects showed similar trends of increasing PNF with test image size. On average, the PNF increased by 0.18 D ± 0.09 D for the large test image (20°) compared to the small test image (4°). The slope of the PNF curve increased steeply from 4° up to 12° (0.017 D/degree) and stabilized from 12° to 20° (slope = 0.006 D/degree).

3.2. Perceived neutral Focus shift after adaptation

Fig. 6 shows the change in PNF after adaptation to the different adapting conditions in all subjects. Red bars indicate central adaptation, blue bars indicate full-field adaptation and in green com-

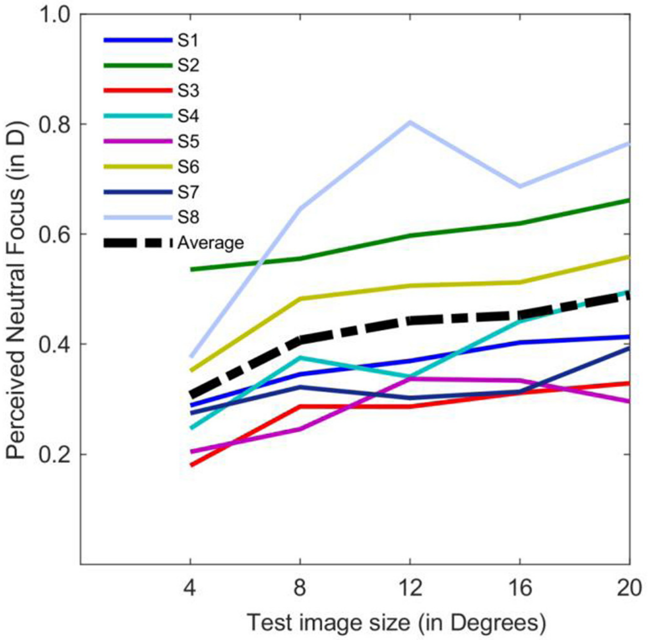

Fig. 5. Perceived Neutral Focus (PNF) as a function of angular subtense of the test image. Each line corresponds to data from each of the eight subjects. The black thicker dashed line represents the average across subjects.

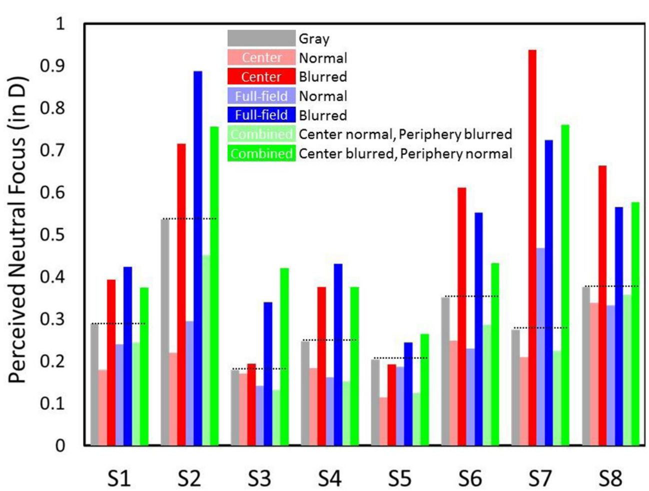

Fig. 6. Perceived Neutral Focus after adaptation to central (Red), full-field (Blue) and combined (green) adapting images. Dotted black lines indicate the Gray baseline values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bined adaptation is shown. The lighter and darker shades indicate adaptation to normal and blurred images respectively. Adapting to a normal image in the center resulted in a decrease in PNF and adapting to a blurred central image resulted in an increase in PNF (indicated as bars below and above the baseline). Similar changes in PNF were noted for full-field adaptation. However, it is interesting to note that in combined adaptation, even if the periphery was blurred, the presence of normal central image still resulted in an effect similar to normal central adaptation and, similarly, even if the periphery was normal, a blurred center still resulted in an increase in PNF.

The averages as well as individual subject's after-effects (PNF adapting image - PNF gray) are shown in Fig. 7. For all three conditions, the after-effects for the normal and blur adaptation were significantly different ($p < 0.05$) as shown by the upper dotted lines in Fig. 5.The shifts in PNF were 0.30 D ± 0.23, 0.26 D ± 0.15 D and 0.25D ± 0.13 D larger for blur as compared to normal adaptation for center, full field and combination conditions respectively. One-way ANOVA showed that this average shift was not significantly different ($p = 0.47$, $df = 2$) between the three conditions (center, full field and combination, shown as red, blue and green bars respectively in Fig. 7).

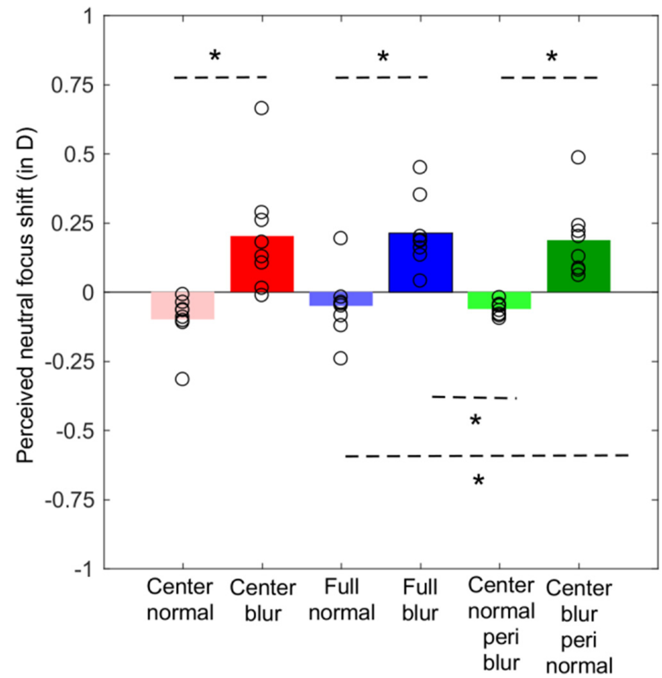

Fig. 7. After-effects of adaptation in Perceived Neutral Focus. The bars and circles indicate average and individual values respectively for all 8 subjects. The comparison between normal and blur adaptation difference are shown on the top and the effect of altering the center or periphery is shown in the bottom with dotted lines (* denotes $p < 0.05$). Note that only differences that are significant are marked.

Comparing the differences in the post adaptation PNF for different adaptation image categories, it is clear that the PNF is strongly influenced by the central input. In the presence of both central and peripheral input, a difference in PNF is noted only when the central input itself is altered as shown with the lower dotted lines in Fig. 7. The conditions compared are Center normal with periphery blurred–Full blurred (mean difference in PNF 0.27 D ± 0.13 D, $p < 0.05$) and Center blurred with periphery normal–Full normal (mean difference in PNF 0.23 D ± 0.11 D, $p < 0.05$).

When the central input is normal, adding a normal periphery (Full normal – Center normal) or a blurred periphery (Center normal with periphery blurred – Center normal) or deblurring an existing blurred periphery (Full normal – Center normal with periphery blurred) did not change the PNF significantly. Similarly, including a blurred (Full blurred – Center blurred) or normal periphery (Center blurred with periphery normal – Center blurred) or blurring an existing normal periphery (Full blurred – Center blurred with periphery normal) in the presence of blurred central input did not result in significant changes in PNF.

4. Discussion

We measured the change in PNF with different angular subtenses of test images and found that the amount of blur perceived as neutral increased with increasing angular subtense. However, the after-effects of adaptation to different central/peripheral blur profiles are still dominated by the central input.

4.1. Angular subtense and blur perception

The present results show that the amount of blur perceived as neutral, i.e. PNF, changes when the stimulus is extended from fovea to parafoveal regions. From Experiment 1, it is shown that while the PNF was low for the small test images, an increased amount of blur was considered as neutral in large test images. The amount of blur perceived as "normal" in foveal vision is closely tied to previous blur exposure (Mon-Williams, Tresilian, Strang, Kochhar, & Wann, 1998; Radhakrishnan et al., 2015; Sawides et al., 2011). The increase in PNF with image extent could thereby be due to prior adaptation to the reduced blur detection and discrimination thresholds in the parafovea (Wang & Ciuffreda, 2005). It has also been shown earlier that blurred edges in the periphery are perceived as relatively sharp (Galvin, O'Shea, Squire, & Govan, 1997; Galvin, O'Shea, Squire, & Hailstone, 1999). Furthermore, adapting to a large target with blur is shown to produce less after-effects in terms of clear contrast sensitivity (without blur) changes than a smaller adaptation target (Venkataraman et al., 2015). To summarize, both the present results from Experiment 1 and the previous studies mentioned here suggest that extending the image beyond the fovea will make the blur less noticeable.

4.2. Mechanisms of adaptation

In Experiment 2, adapting to normal central images produced only small changes in the PNF compared to the gray adaptation (lower bars in Fig. 7) whereas adapting to central blur produces a large increase in PNF (upper bars in Fig. 7). This finding was expected since the visual system of the subjects was already exposed to sharp central images before the experiments. It is also similar to previous studies where the after-effect for adaptation to images without any blur is smaller compared to the adaptation to blurred images (Radhakrishnan et al., 2015; Sawides et al., 2011). Note that the after-effects would have been different if the images had been sharpened by increasing the contrast of the high spatial frequencies of the images (Webster et al., 2002).

In Experiment 2 similar after-effects in PNF were seen for 4° and 20° adaptation stimuli. It should be noted that the results of Experiment 2 are not contradicting the significant difference in the PNF for the small and large test images found in Experiment 1. It simply means that although the PNF for the small and large test images were significantly different, the magnitude of this difference was too small (on average 0.18 D from Experiment 1) to have any significant impact in the after-effects when adapting to an image with 2 D blur.

Our findings on adaptational after-effects support the foveal dominance theory. Though we did not use test stimuli at different retinal locations, the after-effects after adaptation to combined central-peripheral images showed effects corresponding to foveal adaptation. This is different from what was reported earlier in a study where the central test image was flanked by either blurred or sharp surrounding image (Webster et al., 2001). The main difference between that study and Experiment 2 in the present study is that we did not use flankers around the test images and hence there was no central-peripheral relative comparison during the PNF evaluation. Because Experiment 1 showed that the PNF depends on the angular subtense of the test image, there is a possibility that the change in PNF after adaptation would have been different in Experiment 2 if we had used larger test images.

4.3. Optical defocus vs Numerical simulations

Our results were obtained by using numerically manipulated images that simulated central and peripheral blur. There are a number of advantages and some disadvantages of using simulated images. Simulated images render changes in physical properties of the image that are constant across subjects and the inter-subjective differences in response are mainly influenced by neural properties. In addition, these allow for simultaneous assessment of various optical designs, which could be tried on subjects prior to manufacturing. Although the visual system processes the simultaneous blur similar to that of pure defocus (Radhakrishnan et al., 2014), it has been shown that the foveal visual system tolerates optical blur better than simulated blur (Ohlendorf, Tabernero, & Schaeffel, 2011a, 2011b). While this might indicate that the effect of adaptation to optical blur would be somewhat lesser than obtained in the current study, we believe that the trends will be similar. With simulated images, the blur in the peripheral retinal image might be amplified due to the presence of normal peripheral optical errors, which differ between individuals. However, in our study we do not expect large blur variations across subjects because the variation in refractive error with eccentricity is minimal within the central 20° visual field; e.g. Lundström et al. found that the relative peripheral refractive error out to ±10° eccentricity stayed well below 1 D both in emmetropic and myopic eyes irrespective of the state of accommodation and field meridian (Lundström, Mira-Agudelo, & Artal, 2009). Furthermore, the blur sensitivity is reduced in the near periphery compared to fovea (Maiello, Walker, Bex, & Vera-Diaz, 2017; Wang & Ciuffreda, 2005). In any case, it would be interesting to further study the adaptational effects using lenses customized for each subject such that they have similar blur profiles.

4.4. Implications on refractive corrections

One theory on emmetropization indicates that the presence of peripheral defocus triggers myopia. This theory is supported by several structural and functional results, that demonstrate changes in axial length and refractive error when defocus is induced or corrected in the parafovea (Huang et al., 2016). Our results support the role of peripheral vision in the foveal perception as the PNF is influenced by the angular subtense of the test stimulus (Experiment 1). Increasing the angular subtense of the images further to include vision in the near and far periphery also and assessing the blur perception will be interesting and give additional information to the role of peripheral vision.

Multifocal lenses used in presbyopia correction introduce a simultaneous blur on the retina. A secondary effect of these multifocal lenses is that they also alter the peripheral blur. It is therefore important to consider the dynamic visual functions like motion detection and low contrast vision, which are more relevant to the periphery than the fovea. A careful assessment of these functions in subjects wearing multifocal lenses will help in obtaining a holistic picture. Though the present study is limited to blur perception, a significant role of the peripheral stimulus is demonstrated. Further evaluations with larger images and various outcome measures are recommended.

5. Conclusion

The amount of blur perceived as neutral, the PNF, increases when the blur stimulus is extended to cover peripheral regions compared to pure foveal stimulus. However, the value of the PNF varies among subjects. Furthermore, our results indicate that the after-effects of adaptation to blur are determined mainly by the foveal input; In the presence of sharp foveal vision, including a sharp or blurred periphery during adaptation has little effect on the change in PNF. Further investigations are recommended with more extended stimuli.

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