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# Neural adaptation to peripheral blur in myopes and emmetropes

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## ABSTRACT

In the presence of optical blur at the fovea, blur adaptation can improve visual acuity (VA) and perceived image quality over time. However, little is known regarding blur adaptation in the peripheral retina. Here, we examined neural adaptation to myopic defocus at the fovea and parafovea (10° temporal retina) in both emmetropes and myopes. During a 60-min adaptation period, subjects (3 emmetropes and 3 myopes) watched movies with +2 diopters of defocus blur through a 6-mm artificial pupil in two separate, counter-balanced sessions for each retinal location. VA was measured at 10-min intervals under full aberration-corrected viewing using an adaptive optics (AO) vision simulator. By correcting subjects' native optical aberrations with AO, we bypassed the influence of the individual subjects' optical aberrations on visual performance. Overall, exhibited a small but significant improvement after the 60-min of adaptation at both the fovea (mean ± SE VA improvement: $-0.06 \pm 0.04$ logMAR) and parafovea (mean ± SE VA improvement: $-0.07 \pm 0.04$ logMAR). Myopic subjects exhibited significantly greater improvement in parafoveal VA (mean ± SE VA improvement: $0.10 \pm 0.02$ logMAR), than that of emmetropic subjects (mean ± SE VA improvement: $0.04 \pm 0.03$ logMAR). In contrast, there was no significant difference in foveal VA between the two refractive-error groups. In conclusion, our results reveal differences in peripheral blur adaptation between refractive-error groups, with myopes displaying a greater degree of adaptation.

## 1. Introduction

Visual adaptation is a process by which the visual system alters its functional properties in order to compensate for variations in the visual environment such as changes in contrast, color, brightness and motion. Such neural mechanisms are beneficial for improving visual performance in the presence of visual perturbations, such as optical blur. The neural system's ability to adapt to blur, has been demonstrated following both short-term (Mon-Williams, Tresilian, Strang, Kochhar, & Wann, 1998) and long-term (Artal et al., 2004; Sabesan & Yoon, 2010; Sawides et al., 2010) exposure to optical aberrations.

One proposed mechanism underlying blur adaptation is the re-weighting of individual spatial frequency (SF) channels in the neural visual system. Although low-SF components of the retinal image remain relatively unchanged with optical defocus, high-SF inputs are significantly degraded, showing both reduced contrast and altered spatial phase (Georgeson & Sullivan, 1975). As a result, optical defocus is associated with impaired visual acuity (VA) and reduced contrast sensitivity at high SFs (Mon-Williams et al., 1998). It has been hypothesized that, to overcome the effects of optical blur, neural adaptation mechanisms could recalibrate the properties of SF neurons and increase the visual system's sensitivity to high SFs following blur exposure (Mon-Williams et al., 1998; Webster, Georgeson, & Webster, 2002).

Although the neural system cannot completely compensate for optical aberrations, its impact is significant. The degree of blur adaptation is influenced by many factors, such as the duration of exposure, blur magnitude and the subject's native refractive error (Cufflin, Hazel, & Mallen, 2007a; Khan, Dawson, Mankowska, Cufflin, & Mallen, 2013; Rosenfield, Hong, & George, 2004). Blur adaptation has been shown to occur quickly, yielding VA improvements within the first 4-min of exposure to defocus blur (Khan et al., 2013). Previous studies observed significant improvements in VA, ranging from 0.04 to 0.27 logMAR, after adaptation to various levels of myopic defocus (1–3 D) and exposure durations (0.5–3 h) (Cufflin, Mankowska, & Mallen, 2007b; Cufflin et al., 2007a; Mankowska, Aziz, Cufflin, Whitaker, & Mallen, 2012; Mon-Williams et al., 1998; Pesudovs & Brennan, 1993; Rosenfield

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et al., 2004; Wang, Ciuffreda, & Vasudevan, 2006). Moreover, subject's native refractive error can play a role: myopic subjects display a relatively greater amount of blur adaptation, thus reducing their sensitivity to the presence of blur as compared to emmetropes (Cufflin et al., 2007b; George & Rosenfield, 2004).

While most previous studies of blur adaptation have focused on foveal vision (Cufflin et al., 2007a, 2007b; Khan et al., 2013; Mon-Williams et al., 1998; Rosenfield & Abraham-Cohen, 1999; Webster et al., 2002), the impact of blur adaptation on peripheral vision remains poorly understood. Critically, some evidence suggests that visual processing in the periphery may play an important role in the emmetropization process (Smith, Kee, Ramamirtham, Qiao-Grider, & Hung, 2005), and recent animal studies have shown that parafoveal refractive error could potentially cause myopia progression (Stone & Flitcroft, 2004; Wallman & Winawer, 2004). The peripheral retina, in isolation, regulates eye growth and when exposed to blur, can even lead to refractive error in the fovea (Smith et al., 2005, 2010). These findings generated considerable clinical interest in mitigating myopia progression by developing an optical method to manipulate the peripheral optical quality of the eye. Therefore, a better understanding of the functional responses of the peripheral retina to defocus blur is crucial.

In previous blur adaptation studies (George & Rosenfield, 2004; Mankowska et al., 2012; Rosenfield et al., 2004), subjects' habitual refractive error was corrected with conventional ophthalmic corrections (i.e., spectacle or contact lenses). However, the peripheral retina typically experiences a greater amount of optical aberrations than the fovea (Atchison & Scott, 2002; Atchison, Scott, & Charman, 2007; Mathur, Atchison, & Charman, 2009; Mathur, Atchison, & Scott, 2008). Consequently, significant amounts of residual optical errors were left uncorrected, particularly asymmetric higher-order aberrations for relatively large pupil sizes and eccentric retinal locations. In addition, changes in the optical properties of the eye (e.g., pupil size, accommodation, etc) occurring during blur adaptation could have affected the results. To overcome these issues, laser interferometery and adaptive optics (AO) have previously been used to isolate neural processing properties from optical factors in both foveal (Campbell & Green, 1965; Liang, Williams, & Miller, 1997; Yoon & Williams, 2002) and peripheral vision (Frisen & Glansholm, 1975; Lundstrom et al., 2007; Zheleznyak, Barbot, Ghosh, & Yoon, 2016). Similarly, in the present study, we used an adaptive optics vision simulator (AOVS) to examine the roles of optics and the neural system in peripheral blur adaptation.

The present study aimed to further our understanding of the effects of neural adaptation to defocus blur on peripheral visual processing. Specifically, we investigated changes in foveal and parafoveal visual performance after blur adaptation in both myopes and emmetropes, with and without cycloplegia (i.e., with and without accommodation). The AOVS fully corrected optical aberrations during visual performance measurements, eliminating the contributions of foveal and parafoveal ocular aberrations to the results and enabling us to solely investigate changes in neural function.

## 2. Methods

### 2.1. Subjects

Six healthy subjects participated in this study; 3 subjects were emmetropes (age range: 21–30 years; mean refractive error 0.33 ± 0.42 D) and 3 were myopes (age range: 22–23 years; mean refractive error -4.50 ± 0.41 D). None of the subjects had a history of ocular pathology or surgery and all subjects had best corrected VA of 0.0 logMAR or better. This study was approved by the University of Rochester Research Review Board and informed consent was obtained from all subjects before their participation. All procedures involving human subjects were in accordance with the tenants of Helsinki. Contact lens wearers were asked to refrain from lens wear on the day of experiment to avoid dry eyes.

### 2.2. Adaptive optics visual simulator (AOVS)

Optical aberrations and visual performance were assessed using an AOVS at retinal eccentricities of 0 (fovea) and 10 degrees in the temporal retina (i.e. nasal visual field), illustrated in a simplified schematic in Fig. 1A and described elsewhere (Zheleznyak et al., 2016). The AOVS consisted of a custom-built Shack-Hartmann wavefront sensor and a large stroke deformable mirror (ALPAO-97; St Martin, France) to measure and correct subjects' wavefront aberrations, a Badal optometer to determine the subjective best focus of the eye, an artificial pupil to control pupil size and a visual stimulus display for visual performance measurements. The AOVS was used in closed-loop to manipulate the subjects' wavefront aberrations in real-time (8 Hz). The wavefront sensing laser beacon was produced by a super-luminescent diode with center wavelength of 840 nm and a bandwidth of 40 nm. A narrow band interference filter transmitting 633 ± 5 nm (i.e. total bandwidth of 10 nm) was used in the AOVS to provide a monochromatic stimulus to avoid the eye's chromatic aberration. During measurements of VA at peripheral retina, subjects were fixating on an external Maltese cross target projected on the ceiling (2 m away from the eye), through a pellicle beam splitter (Fig. 1A). A dental-impression bite bar mounted to a 3-axis translation stage was used to stabilize head movements. Subject pupil alignment was maintained continuously using live images from a camera focused at the pupil plane. This AOVS apparatus enabled us to bypass any optical factors by correcting all monochromatic and polychromatic aberrations during VA measurements at all retinal eccentricities.

### 2.3. Visual acuity measurement

High-contrast VA was measured at each retinal location (0 and 10 degrees temporal retina) over 5.8 mm circular pupil using the AOVS. During the VA measurements, a black-tumbling letter "E" (oriented 0°, 90°, 180° or 270°) was displayed for 500 ms. The task was a four-alternate forced-choice (4-AFC) method in which subjects were asked to report the orientation of the E target on each testing condition. Auditory feedback was provided for both correct and incorrect responses. The visual stimulus (luminance = 65.4 cd/m$^2$) was presented using a digital light projector (Sharp PG-M20X; Sharp Corporation, Japan) placed at a conjugate plane to the retina. Each VA measurement was obtained using a QUEST (Watson & Pelli, 1983) staircase, based on 40 trials. VA threshold was defined as the letter size for which 62.5% of responses were correct. Four VA measurements were averaged for each testing condition and were recorded in units of logMAR. All VA measurements were performed in the right eye, with the fellow eye occluded with an eye patch.

### 2.4. Blur adaptation stimulus

Subjects watched movies on a LCD screen at a 2 m distance for a period of 60-min (Fig. 1B). Although we did not fully control for the spatio-temporal frequency contents and contrast levels of the movies, we ensured that all participants watched movies that contained dynamic scenes with high brightness and contrast. All subjects wore a trial spectacle frame with trial lenses to correct their refractive errors and induce myopic defocus on top of it (see *Experimental Protocol*). A fixed aperture (6 mm in diameter) was used to standardize the effective pupil diameter for all subjects. The visual stimulus during blur adaptation (LCD screen) subtended 9.4° and

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