

**BLUR PERCEPTION and EYE MOVEMENTS:
RELATIONSHIP TO REFRACTIVE ERROR**

A thesis presented to the graduate faculty of
the New England College of Optometry in partial fulfillment
of the requirements for the degree of Master of Science.

Lenna E. Walker

December 2017

© Lenna E. Walker
All rights reserved

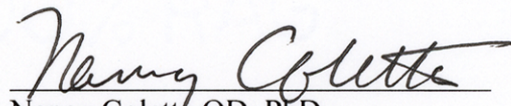
The author hereby grants the New England College of Optometry permission
to reproduce and to distribute publicly paper and electronic copies
of the thesis document in whole or in part.

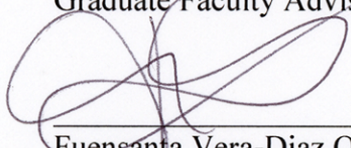
BLUR PERCEPTION and EYE MOVEMENTS:
RELATIONSHIP TO REFRACTIVE ERROR

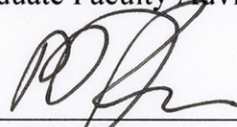
Lenna E. Walker

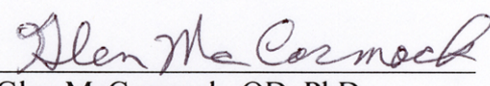
This manuscript has been read and accepted by the Thesis Examination committee in satisfaction of the thesis requirement for the Degree of Master of Science.

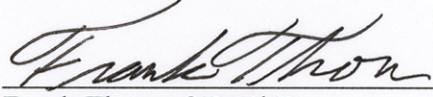
August 19, 2017
Date


Nancy Coletta OD, PhD
Graduate Faculty Advisor

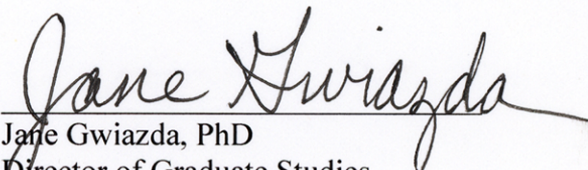

Fuensanta Vera-Diaz OD, PhD
Graduate Faculty Advisor


Peter Bex, PhD
Thesis Committee Member


Glen McCormack, OD, PhD
Thesis Committee Member


Frank Thorn, OD, PhD
Thesis Committee Member

August 19, 2017
Date


Jane Gwiazda, PhD
Director of Graduate Studies

ABSTRACT

Blur Perception and Eye Movements: Relationship to Refractive Error

Lenna E. Walker

New England College of Optometry, 2017

Purpose:

Human and animal studies suggest that an ability to accurately detect and respond to blur is essential for emmetropization, as is an adequate balance between central and peripheral retinal stimulation. We evaluated the effect of refractive error on blur sensitivity at different retinal eccentricities, under both monocular and binocular viewing conditions.

Additionally, studies have shown that people with myopia exhibit larger VA loss at low luminance than people with emmetropia, and often complain that letters are difficult to fixate during visual acuity (VA) measures in dim light. In this study, we also evaluated the effect of refractive error on eye movements when reading VA charts under mesopic and photopic illumination conditions.

Methods:

Subjects were 48 young (21-32 yrs) healthy adults with best-corrected VA 0.0 LogMAR (20/20) or better in each eye and no binocular or accommodative dysfunction. Refractive error (Range +3.31 to -10.94) was determined by binocular subjective refraction. Soft contact lenses were worn if optical correction was necessary.

Monocular and binocular blur discrimination thresholds were measured as a function of pedestal blur using an adaptive 4AFC task. Stimuli were presented in a 46° diameter window @ 40cm. Gaussian blur pedestals were confined to an annulus at 0°, 4°, 8° and 12° eccentricity, with a blur increment applied to one quadrant of the image. Blur discrimination thresholds were fit with a two-parameter (intrinsic blur and blur sensitivity) dipper function.

Eye movements were measured using a video-based eye tracker (EyeLink 1000; SR Research). Mesopic (0.276 cd/m²) and photopic (325 cd/m²) VA was measured with high contrast letters, 5 letters per line, displayed on an LCD panel viewed at 4 m. Eye position was recorded relative to that display and eye movements were analyzed for letter sizes

corresponding to the mesopic and photopic VA levels. Eye movement variability was expressed both as the standard deviation (SD) of vertical eye position and overall bivariate contour ellipse area (BCEA) during VA reading.

Results:

The amount of intrinsic blur increased for retinal eccentricities beyond 4° ($p < 0.01$) and was lower in binocular than monocular conditions ($p < 0.01$), but was similar across refractive groups ($p = 0.47$). Blur sensitivity decreased with retinal eccentricity ($p < 0.01$) and was highest in the binocular condition, but only in central vision ($p < 0.05$). Myopes showed worse blur sensitivity than emmetropes monocularly ($p < 0.05$) but not binocularly ($p = 0.66$).

Retinal acuity was significantly reduced in myopes in both the photopic ($p < 0.01$) and mesopic ($p < 0.01$) conditions, and myopes showed a relatively greater log unit loss of acuity in dim light than emmetropes ($p = 0.02$). Vertical SD increased significantly with increasing myopia for the three conditions examined: mesopic VA limit ($p = 0.034$), photopic VA limit ($p = 0.03$), and mesopic VA limit with photopic illumination ($p < 0.01$). BCEA also increased significantly with increasing myopia for all three conditions: mesopic VA limit ($p = 0.05$), photopic VA limit ($p = 0.04$), and mesopic VA limit with photopic illumination ($p = 0.04$).

Conclusions:

As expected, blur perception worsens in the visual periphery and binocular summation is most evident in central vision. Myopes were found to exhibit a monocular impairment in blur sensitivity that improves under binocular conditions. The latter finding may have implications in myopia development as discussed in this thesis.

Myopes showed a greater loss of visual acuity in dim lighting in comparison to emmetropes. Also, eye movement variability increases significantly with increasing myopia during a visual acuity task in both mesopic and photopic lighting conditions. This variability may be contributing to myopes' acuity losses in dim lighting and, therefore, may interfere with reading or visual tasks in challenging, low light conditions.

ACKNOWLEDGEMENTS

Above all, I would like to sincerely thank my faculty advisors, Dr. Nancy Coletta and Dr. Fuensanta Vera-Diaz, for their guidance throughout this process. They have both been incredibly supportive and encouraging, and I could not have asked for more knowledgeable and patient mentors. I consider you both to be leading figures in the fields of optometry and vision science, and will think of you as role models as I begin the next chapter of my life as an optometrist.

I would like to extend a special thanks to Dr. Guido Maiello and Dr. Peter Bex for their crucial contributions to this project. They provided the framework for the blur perception study, lent us equipment, and were always willing to give constructive feedback when asked.

I would like to thank Guido, additionally, for his help with statistical analysis and creating graphical representations.

Thank you to my thesis committee members, Dr. Peter Bex, Dr. Glen McCormack, and Dr. Frank Thorn, for their time and input. Thank you to John Nguyen for his help creating the Matlab program necessary for the eye movements study. Thank you to Dr. Andrew McLeod for supplying contact lenses for subjects when needed.

Thank you to the Graduate Studies Program at the New England College of Optometry, the NEI T35 Program, and to Beta Sigma Kappa for helping to fund this research.

Finally, thank you to Brian Hunke, and to my parents, Charlotte and Robert Walker, for unwavering love and support.

TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES & TABLES	vi
1. GENERAL INTRODUCTION	1
2. BLUR PERCEPTION STUDY	6
2.1 Background & Hypothesis.....	6
2.2 Methods.....	15
2.2.1 Subjects	15
2.2.2 Study Procedure.....	16
2.2.3 Study Design	21
2.2.4 Data Analysis.....	24
2.3 Results.....	25
2.3.1 Main Findings.....	25
2.3.2 Difference Between “Best” and Habitual Eyeglass Prescription	29
2.3.3 Preliminary Data from Subjects with Hyperopia	30
2.4 Discussion	33
3. EYE MOVEMENTS STUDY	40
3.1 Background & Hypothesis.....	40
3.2 Methods.....	47
3.2.1 Subjects	47
3.2.2 Study Procedure.....	48
3.2.3 Data Analysis.....	54
3.3 Results.....	58
3.3.1 Acuity vs. Refractive Error	60
3.3.2 Eye Movement Variability vs. Refractive Error.....	63
3.3.3 Eye Movement Variability and Mesopic Acuity.....	67
3.3.4 Reading Duration.....	67

3.4 Discussion	69
4. GENERAL CONCLUSIONS & SUMMARY	75
5. BIBLIOGRAPHY	77
APPENDIX I: Conference Presentations	88
APPENDIX II: Publications	93

LIST OF FIGURES & TABLES

A. FIGURES

Figure 1: <i>Blur Perception</i> experimental setup	18
Figure 2: Example of “dead leaves” stimuli	20
Figure 3: Effect of modifying blur dipper model parameters	23
Figure 4: Example dipper function estimated for one subject	24
Figure 5: Blur dipper functions averaged across all subjects	26
Figure 6: Myopes/Emmetropes: Intrinsic blur findings.....	27
Figure 7: Myopes/Emmetropes: Blur sensitivity findings	29
Figure 8: Hyperopes: Intrinsic blur findings.....	31
Figure 9: Hyperopes: Blur sensitivity findings.....	32
Figure 10: Visual acuity vs. Refractive error, in photopic and mesopic conditions	41
Figure 11: <i>Eye Movements</i> experimental setup	50
Figure 12: EyeLink 1000 Desktop Mount	51
Figure 13: Example of EyeLink “Camera Setup” screen	52
Figure 14: <i>Eye Movements</i> stimulus display, with and without ND filter	54
Figure 15: Example graphs: Vertical eye position vs. time, pre- and post-blink removal	55
Figure 16: Diagram: Retinal image size in axial myopia	58
Figure 17: Axial length vs. Refractive error	61
Figure 18: Retinal acuity vs. Refractive error.....	62
Figure 19: Mean loss of acuity in the mesopic condition	63
Figure 20: Mean vertical SD findings.....	65
Figure 21: Mean BCEA findings	66
Figure 22: Mesopic retinal acuity vs. Photopic BCEA.....	67
Figure 23: Mesopic reading duration vs. Mesopic acuity.....	68

B. TABLES

Table 1: <i>Blur Perception</i> subject demographics	26
Table 2: <i>Eye Movements</i> subject demographics	59

1. GENERAL INTRODUCTION

Refractive errors, when left uncorrected, can significantly impair visual function and, as such, they can hinder academic performance, limit education and employment opportunities, and cause an overall decrease in quality of life. In 2013, uncorrected distance refractive error was estimated to affect 108 million people globally and was named the most common cause of vision impairment (42%) and the second most common cause of blindness (3%) (Bourne et al., 2013). On a global scale, uncorrected refractive errors constitute a heavy economic burden, resulting in a global loss of productivity estimated at I\$269 billion (international dollars) (Smith et al., 2009) or US\$202 billion (Fricke et al., 2012).

Of the refractive errors, myopia presents a particular threat to vision throughout the world. Uncorrected myopia as low as -1.50 D can result in moderate vision impairment, while more than -4.00 D can result in a classification of blindness (World Health Organization, 2015). Even if available, spectacle correction cannot account for the abnormal growth of the eyeball or reduce the risk of such conditions as retinal detachment, glaucoma, or myopic macular degeneration (e.g., World Health Organization, 2015). The prevalence of myopia is increasing at alarming rates worldwide and is already considered an epidemic in several East Asian countries (e.g., Dolgin, 2015; Grosvenor, 2003; Rose, French and Morgan, 2016). Furthermore, the onset of myopia is occurring at even younger ages in childhood. Recent projections indicate that by 2050, 50% of the world's population will have myopia (defined as refractive error ≤ -0.50 D) and 10% will have high myopia (≤ -5.00 D), (Holden et al., 2016). This is in comparison to 22% with myopia and 2% with high myopia in the year 2000 (Holden et al., 2016). To put it a different way, myopia and high myopia is

estimated to affect nearly 5 billion people and 1 billion people, respectively, by 2050, should recent trends persist (Holden et al., 2016).

The increase in myopia prevalence has important implications for eye care professionals and vision scientists worldwide. Comprehensive eye care services will continue to be necessary, both to correct the refractive component of myopia (with spectacles and contact lenses) and to manage myopia-related ocular complications and vision loss. Furthermore, interventions aimed at prevention or slowing the progression of myopia are imperative.

The research presented in this thesis comprises two separate studies. Both studies aim to evaluate how visual function differs in individuals with refractive error versus individuals with emmetropia (absence of refractive error). We place special emphasis on myopia. Both studies have the same subject inclusion criteria and both experimental procedures were completed in one single visit. Otherwise, each study stems from different underlying questions and measures different outcomes.

The aim of the first part of this work, the *Blur Perception* study, was to evaluate differences in blur detection and discrimination across refractive groups in both the central and near peripheral retina, under both monocular and binocular viewing conditions.

The process by which the eye grows during postnatal development to match its optical components is called emmetropization. It has been established that primary refractive errors stem from a failure of the emmetropization mechanism and, subsequently, large amounts of research have been dedicated to this topic in recent decades. While evidence from research in refractive error development and progression has led to numerous theories, we still do not know conclusively why people with refractive error fail to normally emmetropize or why,

with age, they lose their emmetropia. The development of myopia is widely considered to be driven by optical and environmental factors, such as decreased time outdoors and increased near work activities (e.g., World Health Organization, 2015). Genetic predisposition is likely to play a role, as well, but that role may largely be to determine a person's susceptibility to environmental influences (e.g., Fan et al., 2014; Pan, Ramamurthy and Saw, 2012; Rose, French and Morgan, 2016). Indeed, decreased time outdoors and increased time spent doing near work are lifestyle changes associated with increased urbanization and more high-pressure educational systems, as is seen in East Asia, where the prevalence of myopia is surging rapidly. In general, it is accepted that visual feedback is essential to guiding the growth of the eye, and that the disruption of a "normal" visual experience can lead to refractive error development (e.g., Wallman and Winawer, 2004).

There is still no consensus as to what aspects of the environment are necessary to provide a "normal" visual experience and appropriate signals for emmetropization, but continuous retinal blur has repeatedly been shown to induce abnormal eye growth (and therefore refractive error) in animal models (e.g., Norton, Siegwart and Amedo, 2006; Smith III et al., 2007; Smith III and Hung, 1999; Wildsoet and Wallman, 1995; Zhu et al., 2013).

Considering the essential objective of emmetropization is to minimize retinal blur, it is believed that a proper response to blur is needed in order for this mechanism to succeed. An adequate response to blur is thought to include the ability to detect a wide range of visual spatial frequencies and contrast levels, to determine the sign and magnitude of defocus, and then to use those cues accurately to bring retinal images into sharp focus (e.g., Bartmann and Schaeffel, 1994; Chin et al., 2015; Diether and Schaeffel, 1997; Wallman and Winawer,

2004). Furthermore, the eccentricity of retinal blur and the effects of binocularity may be significant to the process (e.g., Ciuffreda, Wang and Vasudevan, 2007; Hoffman and Banks, 2010; Plainis et al., 2011).

Blur is a fundamental feature of the human visual system. Emmetropization aside, blur serves as a powerful signal to ocular accommodation, vergence and depth perception in everyday vision. Blur is also important in the context of image displays and the development of new technologies. Consequently, human blur sensitivity has been the subject of considerable amounts of research and theoretical modeling. Previous studies have measured blur sensitivity across refractive groups, but indirectly, in the form of either changes in accommodative response or changes in visual acuity (e.g., Cufflin, Mankowska and Mallen, 2007; Poulere et al., 2013; Radhakrishnan et al., 2004; Rosenfield and Abraham-Cohen, 1999; Wang and Ciuffreda, 2004). Previous studies have also largely focused on foveal sensitivity and have been completed monocularly. Overall, there is no consensus as to whether myopes (in comparison to emmetropes and hyperopes) have a decreased ability to perceive normally occurring blur under normal viewing (binocular) conditions.

Given previous inconclusive results, our intention was to further investigate human blur perception. Specifically, we hoped to shed more light on the role of blur perception in refractive error development because, at present, there is no effective treatment (without side effects) to prevent the onset and progression of myopia. A better understanding of refractive error development will be necessary if we hope to discover a valuable myopia control therapy.

The aim of the second part of this thesis, the *Eye Movements* study, was to evaluate eye movements across refractive groups in two different lighting conditions. Previous work has indicated that individuals with myopia exhibit larger visual acuity losses at low luminance levels than those with emmetropia when wearing correction, and that this deficit is not entirely caused by optical factors (e.g., Coletta, Frericks and Groves, ARVO 2007; Coletta et al., ARVO 2008). This new study aimed to measure subjects' eye movements during VA testing in both mesopic and photopic illumination to determine if individuals with myopia have more variability in eye position in dim light conditions. We believe that greater eye movement variability could possibly be a causative factor for their acuity losses in dim lighting. While this study is not as specifically geared towards understanding refractive error development as the former, there is a paucity of literature comparing eye movements across refractive groups and perhaps our findings can contribute to a better understanding of myopia, in general. Also, our findings may provide insight that would allow eye care professionals to better care for their myopic patients (a growing population).

2. BLUR PERCEPTION STUDY

2.1 Background & Hypothesis

The term “blur” is surprisingly difficult to define. Generally, blur implies a smeared or indistinct image following low-pass filtering. Blur can either be caused naturally, by optical and/or neural elements in the eye, or simulated on an image display using mathematical functions. Some amount of blur is inherent in all visual systems and, accordingly, the perception of blur is an elemental feature of the human visual system. A blurred retinal image serves to drive the accommodation and vergence responses, allowing one to see clearly and resolve fine target details (e.g., Fisher and Ciuffreda, 1988; Kruger and Pola, 1986; Lopez-Gil et al., 2013; Schor, 1999). Blur may also provide cues about the range of depths in the visual environment (e.g., Ciuffreda, Wang and Vasudevan, 2007; Held, Cooper and Banks, 2012; Maiello et al., 2014; Mather and Smith, 2002; Vishwanath, 2012; Vishwanath and Blaser, 2010; Watt et al., 2005). As such, blur perception is crucial to one’s ability to navigate the world easily, and to accurately perform daily tasks such as reading and driving (e.g., Chung, Jarvis and Cheung, 2007; Wood et al., 2014). Additionally, and of interest to this study, research with animal models suggests that continuous retinal blur may be a causative factor in refractive error development (for a comprehensive review, see Wallman and Winawer, 2004).

Animal models have repeatedly shown that retinal blur can induce abnormal eye growth and therefore refractive error (see Wallman and Winawer, 2004). The length of the eye must match the focal length of its optics in order for images of distant objects to fall on the retinal plane and appear sharply focused (emmetropia). If the length of the eye is longer than the

focal length of its optics, images from distant objects will fall in front of the retina and appear blurred (myopia). Conversely, if the length of the eye is shorter than the focal length of its optics, and accommodation is relaxed, images will fall behind the retina and appear blurred (hyperopia). Spectacle lenses can also cause the focal plane to fall either in front of or behind the retina: positive lenses cause myopic defocus while negative lenses cause hyperopic defocus.

By manipulating animals' visual environments with lenses, diffusers, or eyelid suturing, scientists have been able to show that the eye uses visual feedback to guide its growth (e.g., Norton, Siegwart and Amedo, 2006; Smith III et al., 2007; Smith III and Hung, 1999; Wallman and Winawer, 2004; Wildsoet and Wallman, 1995; Zhu et al., 2013). In most models studied (e.g., chick, tree shrew, monkey), the eye shortens or lengthens to compensate for imposed optical blur, and it does so in two ways: by changing the rate of axial growth via scleral remodeling at the posterior pole (e.g., McBrien and Gentle, 2003; Wildsoet and Wallman, 1995) and/or by changing the thickness of the choroid (the vascular layer between the retina and the sclera) (e.g., Nickla, Sharda and Troilo, 2005; Nickla, Wildsoet and Wallman, 1998; Wallman et al., 1994; Wildsoet and Wallman, 1995). These findings suggest that the retina detects not only the presence of blur, but also the sign of blur.

In addition to changes in axial length and choroid thickness, the eye uses ocular accommodation to bring the images of near objects onto the retinal plane. Accommodation involves the relaxation and contraction of the ciliary muscle to change the thickness and effectively the refractive power of the crystalline lens. Individuals with myopia are suggested to have weaker blur-driven accommodative responses, especially while the myopia is

developing (Abbott, Schmid and Strang, 1998; Gwiazda et al., 1995; Jiang and Morse, 1999), and unstable accommodation responses to two-dimensional images (Kerber, 2016).

Excessive near-work may be a risk factor for myopia development because of this accommodative inaccuracy and subsequent defocus at the retina (e.g., Wallman and Winawer, 2004). Unlike the scleral and choroidal mechanisms, accommodation occurs within a fraction of a second, but all three circuits are similar in that they seem to rely, at least in part, on discerning the sign of defocus.

Interestingly, some of the animal studies mentioned previously have found that lenses and diffusers can act locally within the eye globe such that, if they cover only half of the retina, only that half of the eye is affected (e.g., Diether and Schaeffel, 1997; Hodos and Kuenzel, 1984; Wallman et al., 1987). For example, if a negative lens covers only the temporal retina, only the temporal eye becomes enlarged and myopic. If local eye growth is controlled by local blur, it follows that the overall shape of the eye and the eccentricity of retinal blur may be significant to the emmetropization process.

It has been shown that there is a differential elongation along the optic axis in a myopic eye such that the eye exhibits a prolate contour and the periphery is relatively hyperopic in comparison to the center (e.g., Atchison et al., 2004; Wallman and Winawer, 2004). The reverse tends to hold true in a hyperopic eye wherein the eye is oblate and the periphery is relatively myopic in comparison to the center (e.g., Wallman and Winawer, 2004).

Considering the research previously discussed, it would be expected that homeostatic signals from the peripheral retina would contradict those from the central retina (i.e. a relatively hyperopic periphery would direct the eye to elongate more while a myopic center would

direct the eye to elongate less). The fovea is the most significant retinal area in primate vision, with the highest density of neurons and greatest resolution acuity of all the areas in the retina. Given this, one might think that the central retina would have a greater influence on eye growth than the peripheral retina. While this theory is logical, it is interesting to note that the vision-dependent mechanisms that regulate eye growth appear to have evolved from fish, a species without foveas (e.g., Smith III, Hung and Huang, 2009). Also, the central retina is relatively small in terms of total retinal area. If there is spatial summation of signals from both central and peripheral retina, the peripheral signal would dominate.

In general, there has been a wide range of research that supports the idea that visual signals in the peripheral retina have considerable sway in refractive development. Selective peripheral form deprivation has been shown to produce axial myopia in infant rhesus monkeys, both in the presence of unrestricted central vision (Smith III et al., 2005; Smith III, Hung and Huang, 2009) and with total foveal ablation (Smith III et al., 2007; Smith III, Hung and Huang, 2009). Clinical observations in humans suggest that disease in the retinal periphery (e.g. retinopathy of prematurity, retinitis pigmentosa) and treatments that selectively impair the periphery (e.g., laser photocoagulation, cryotherapy) are often associated with central refractive error (e.g., Knight-Nanan and O'Keefe, 1996; Nathan et al., 1985; Sieving and Fishman, 1978). Furthermore, multifocal electroretinogram (mfERG) responses in humans have shown more significant changes in amplitude in paracentral retinal regions (up to 12°) than central regions under defocused conditions (Chin et al., 2015). Overall, it seems that a delicate ratio between peripheral and central retinal stimulation may be needed in order to derive proper emmetropization signals.

Molecular research suggests that amacrine cells and also a number of biochemical messengers (e.g., dopamine, glucagon, retinoic acid) play a role in regulating eye growth (e.g., Zhong et al., 2004; Wallman and Winawer, 2004), but we do not know conclusively what that role is. It is unclear whether these cells are acting to decode the sign and magnitude of defocus and, if they are, we do not know what mechanisms they employ to do so. Nevertheless, several possible mechanisms have been proposed, some of which involve longitudinal chromatic aberrations, monochromatic aberrations, micro-fluctuations of accommodation, or even just trial and error (e.g., Wallman and Winawer, 2004). Some researchers have looked more specifically at the qualities of visual stimuli in our natural environment (rather than elements of our ocular physiology), arguing that, in order to understand visual information processing, we must better understand the visual information available around us (e.g., Field and Brady, 1997). The visual stimuli projected onto the retina are typically rich in pattern information, comprising a wide range of spatial frequencies at different levels of contrast and at different orientations. It is not yet clear what aspects of an image are important for emmetropization, but some studies suggest that the retina has a decoding system for optical defocus that is tuned to specific spatial frequencies. Specifically, emmetropization appears to be tuned to low and middle spatial frequencies (Bartmann and Schaeffel, 1994; Chin et al., 2015; Schmid and Wildsoet, 1997; Strang et al., 2011). The retina may be able to infer that an image is blurred if the ratio of low to high spatial frequencies is greater than with typical in-focus scenes (Field and Brady, 1997). This decoding system is also likely influenced by motion, and other target attributes such as contrast, luminance, texture, and size (e.g., Christman, 1990; Paakkonen and Morgan, 1994;

Wang and Ciuffreda, 2004). Altogether, it seems that the retina may employ several different cues from its visual environment to interpret defocus and then determine the direction of eye growth.

On the whole, blur perception can be quantified as two major elements: blur detection and blur discrimination. In our context, blur detection refers to the amount of defocus necessary for one to first perceive or notice the presence of blur. Blur discrimination refers instead to the amount of defocus necessary for one to perceive an already blurry target as just noticeably blurrier. Overall, the perception of blur is a complex process that involves what many call “internal” or “intrinsic” blur. Intrinsic blur, as it is referred to in this thesis, is specific to each individual and is derived from the eye’s optical quality (e.g., aberrations, astigmatism), as well as both retinal and higher-level neurophysiology (e.g., visual attention, sharpness overconstancy, and blur adaptation) (Mather and Smith, 2002). The process of blur perception also involves “external” blur which is inherent in the visual stimulus itself.

Blur perception within central vision has been studied extensively, both with induced defocus blur in free space (e.g., creating blur levels with ophthalmic lenses - discussed more later) (e.g., Campbell, 1957; Cufflin, Mankowska and Mallen, 2007; Jacobs, Smith and Chan, 1989; Poulere et al., 2013; Radhakrishnan et al., 2004; Rosenfield and Abraham-Cohen, 1999; Wang and Ciuffreda, 2005b; Walsh and Charman, 1988) and with simulated blur on an image display (i.e. creating blur levels by blurring edges with mathematical convolutions) (for a review, see Watson and Ahumada, 2011). A handful of studies, of the former sort, have compared blur perception across refractive groups. A majority of these studies have found that myopes are less sensitive to the presence of blur than non-myopes (e.g., Cufflin,

Mankowska and Mallen, 2007; Poulere et al., 2013; Radhakrishnan et al., 2004; Rosenfield and Abraham-Cohen, 1999). Some researchers theorize that this reduced blur sensitivity at the fovea could at least partially explain why myopes have demonstrated larger lags of accommodation (e.g., Radhakrishnan et al., 2004; Rosenfield and Abraham-Cohen, 1999). Some theorize that this decreased sensitivity may cause misinterpretation of visual signals and the failure of emmetropization (e.g., Ciuffreda, Wang and Vasudevan, 2007; Radhakrishnan et al., 2004; Rosenfield and Abraham-Cohen, 1999). That said, other studies report that myopes actually do not show decreased blur sensitivity in comparison to non-myopes, only that myopes show more substantial inter-subject differences (e.g., Schmid et al., 2002).

Relative to the large breadth of research on central blur perception, there is a paucity of information about how we perceive blur throughout the peripheral field of vision (Ciuffreda, Wang and Wong, 2005; Ronchi and Molesini, 1975; Rosen, Lundstrom and Unsho, 2011; Wang and Ciuffreda, 2004, 2005a; Wang, Ciuffreda and Irish, 2006). This is surprising considering peripheral blur impacts visual function and appears to strongly impact the development of refractive error, as we discussed previously. These limited studies on peripheral blur perception suggest that sensitivity to blur progressively decreases with retinal eccentricity, which is likely due to a combination of factors, one of which is decreased cone photoreceptor and ganglion cell densities in the peripheral retina (e.g., Anderson, McDowell and Ennis, 2001; Wang and Ciuffreda, 2004).

Of the studies specifically reporting blur detection and discrimination thresholds (both in the central and peripheral retina), most show evidence that discrimination is more sensitive

than detection (e.g., Wang and Ciuffreda, 2005a, 2005b; Watson and Ahumada, 2011). In other words, subjects are better at noticing a difference in blur than the initial presence of blur (unless that initial blur exceeds a certain threshold, i.e. the blur level intrinsic to the observer's visual system). The optics of the human visual system are imperfect by nature – due to irregularities in the refractive elements of the eye (cornea, lens, vitreous, etc.), and due to inevitable diffraction through a small pupil. Even with optical correction, a certain degree of imperfections persist. Yet, we are able to perceive a retinal image with apparent sharpness and do not experience sensory hallucinations in our everyday vision. This suggests that the human visual system discounts its own imperfections (its “intrinsic” blur level) and we become conscious of blur only when it exceeds a certain threshold (for example, when we need glasses) (Morgan et al., 2008).

It is important to note that most of the blur perception studies that compare across refractive groups and into the retinal periphery do not measure sensitivity to blur directly. Rather, they infer blur sensitivity by tracking changes in their subjects' visual acuity (e.g., Poulere et al., 2013; Radhakrishnan et al., 2004) or by evaluating their subjects' depth-of-focus (for a good review, see Wang and Ciuffreda, 2006). Depth-of-focus (DOF) is often defined as the maximum level of defocus that can be applied to an optimally focused image without subjective detection. It can be measured either with ophthalmic lenses or by manually displacing the test target. A larger decrease in visual acuity or a smaller depth-of-focus implies greater blur sensitivity. It is also important to note that most of these studies have evaluated perception of blur only monocularly.

To understand how blur is employed by the visual system and how blur may contribute to the success or failure of emmetropization, it is necessary to further study the perception of blur throughout the central and peripheral retina. It is also necessary to study blur perception both monocularly and binocularly. Multiple animal studies have found that lens compensation and form deprivation myopia still occur if the optic nerve is severed or if the action potentials of the optic nerve are blocked (Norton, Essinger and McBrien, 1994; Troilo et al., 1987; Wildsoet and Pettigrew, 1988). These findings suggest that some of the signals modulating eye growth are specific to the retina, independent of the central nervous system. However, proof of interocular transfer of defocus information has been shown in guinea pig (McFadden et al., 2014) and human (Kompaniez et al., 2013) models of refractive error development. There is also an interocular transfer of accommodative responses (Flitcroft, Judge and Morley, 1992), creating a similarity in retinal image focus between the two eyes. Binocularity (the neuronal integration of information from two eyes) has been shown to improve visual performance through probability summation under blur conditions (Banton and Levi, 1991; Heravian, Jenkins and Douthwaite, 1990; Plainis et al., 2011). Binocularity improves retinal sensitivity to defocus blur and, simultaneously, defocus blur is a useful cue to increase the accuracy of binocularity (both binocular correspondence and binocular rivalry) (Arnold, Grove and Wallis, 2007; Hoffman and Banks, 2010). So, although emmetropization signals are found locally at the retinal level, binocular vision may play a significant role in retinal image focus and therefore in emmetropization.

The conclusion of a thorough literature review is that it is currently unknown whether subjects with refractive error have decreased ability to detect and/or discriminate blur under

normal viewing (binocular) conditions, and whether an abnormal perception of blur is a causative factor for refractive error development. The aim of the current study was to evaluate blur perception across the near peripheral field of vision, both monocularly and binocularly, in myopic, emmetropic and hyperopic subjects. To do so, we used naturalistic stimuli (Bordenave, Gousseau and Roueff, 2006; Lee, Mumford and Huang, 2001; Pitkow, 2010; Wallis and Bex, 2012) blurred with Gaussian blur at specific peripheral eccentricities (center up to 12°), and measured blur detection and discrimination thresholds using an adaptive 4AFC paradigm (Vul et al., 2010). Our hypothesis was that subjects with myopia would show an impaired ability to detect but not discriminate blur in the near peripheral retina.

2.2 Methods

2.2.1 Subjects

A total of 47 subjects were recruited for this study (19 myopes, 20 emmetropes, and 8 hyperopes), with the goal of obtaining useful data from 15 participants in each refractive group. These subjects were recruited primarily from students, staff, and faculty at the New England College of Optometry. Attempts were made to include approximately equal numbers of males and females and as diverse a population as was possible within the available subject pool. This study followed the tenets of the Declaration of Helsinki. Informed consent was obtained from all subjects after explanation of the nature and possible consequences of the study, and was approved by the New England College of Optometry's Institutional Review Board.

Criteria for inclusion and exclusion were: (1) within 18-32 years of age, (2) refractive error (spherical equivalent (SE) in each eye) between -12.00 DS and +6.00 DS, with no more than 1.25 D of cylinder in either eye and no more than 1.25 DS anisometropia, (3) best corrected visual acuity 20/20 or better in each eye, (4) no history of refractive surgery, (5) no history of surgery or eye disease that may have resulted in visual consequences, (6) no current binocular or accommodative dysfunction, (7) no nystagmus, (8) not using drugs that may affect vision, and (9) adequate hearing, language skills and mental ability to understand the consent process and the instructions given during the experiment.

Subjects were classified as either: (1) Myopes, defined as having a spherical equivalent in each eye between -0.50 to -12.00 D; (2) Emmetropes, SE between -0.25 to +0.50 D; or (3) Hyperopes, SE between +0.75 to +6.00 D. Refractive error was determined by dry binocular subjective refraction following objective autorefraction.

2.2.2 Study Procedure

i) The Investigator explained the purposes of the study and the potential subject read the Informed Consent Form (ICF). The Investigator then answered any questions and ensured that the procedures were well understood. Once the ICF was signed, a de-identifier form was used to assign a study number to the subject. This study number, with no identifiable information, was used from that point onward.

ii) A vision screening was performed to determine the subject's eligibility and refractive error group inclusion. The vision screening consisted of the following tests:

- a) Screening questionnaire that included ocular health and refraction history.
- b) Habitual distance and near visual acuity using a Snellen chart.
- c) Estimated cover test at distance and near.
- d) Eye dominance test using the hole-in-the-card test. (Rice et al., 2008)
- e) Autorefraction with the GrandSeiko WR-5100K open-field autorefractor.
(<http://www.grandseiko.com/en/wr-5100k-binocular-accommodation-autorefractometer>)
- f) Binocular distance subjective refraction.
- g) Slit lamp evaluation to ensure clear optical media.
- h) Axial length and anterior chamber depth measured using the Lenstar LS900 optical biometer. (<https://www.haag-streit.com/haag-streit-usa/products/haag-streit-diagnostics/lenstar-biometry/>)

iii) Once eligibility was determined, the experimental procedure took place. The subject was positioned in a chinrest/headrest assembly at 40 cm from a computer monitor upon which the experimental stimuli were presented. Testing took place in a dimly lit room so as to reduce environmental distractions. (See Figure 1. Please note that all pictures of subjects included in this thesis have been obtained and published with their permission.) The monitor subtended 73 x 46° visual angle.



Figure 1. Subjects positioned to complete the experimental procedure.

The stimuli used were modified natural images, called “dead leaves” (Bordenave, Gousseau and Roueff, 2006; Lee, Mumford and Huang, 2001; Pitkow, 2010; Wallis and Bex, 2012) created with the Psychophysics Toolbox Version 3 (Brainard, 1997; Pelli, 1997) in Matlab. The dead leaves model is based on the concept that natural images can be reduced to a collage of randomly oriented, flat objects (or “leaves”) that overlap one another. The attributes of these objects (i.e. position, size, brightness) are assigned based on pre-determined mathematical distributions so that the space-averaged luminance and contrast of dead leaves patches will match that of the natural images from which they are derived. Our stimuli were constructed from a set of 2,000 ellipses, each assigned a pseudo-random center position, orientation, aspect ratio, and luminance. Each stimulus image subtended $46 \times 46^\circ$ visual angle and was divided into four sections: top, left, right and bottom (Figure 2). All sections were blurred up to the same, specific peripheral visual field area, but one section was made blurrier than the others.

To clarify, a central circular portion of the stimulus was sharply rendered, with no blur, up to 0° , 4° , 8° , or 12° of eccentricity. Blur was presented in an annulus with its inner edge abutting the central portion at the specified retinal eccentricity (Figure 2). Blur then extended into the periphery until it reached the outer edge of the image/computer screen. Blur was applied to each quadrant by Gaussian filtering in the frequency domain. Three quadrants were blurred by the same amount of “pedestal” blur, while the fourth was blurred by a greater amount of “pedestal + increment” blur. Two green concentric circles, at 0.3° and 3° eccentricity respectively, served as the central fixation target. Examples of stimuli can be seen in Figure 2. Overall, five pedestal blur levels (0.125, 0.5, 2, 8, and 32 arc min) and four eccentricities (0° , 4° , 8° , and 12° from fixation) were tested in random order.

The subject was asked to fixate on the central target and decide which section of the presented image was the blurriest. Each image was presented for 250 milliseconds to prevent the subject from using eye movements to thoroughly inspect the stimulus before answering. She/he answered using a keyboard, and a dipper shaped threshold function was derived from the 4AFC psychophysical task, using the Functional Adaptive Sequential Testing (FAST) method (Vul et al., 2010). This is described further in Section 2.2.3.

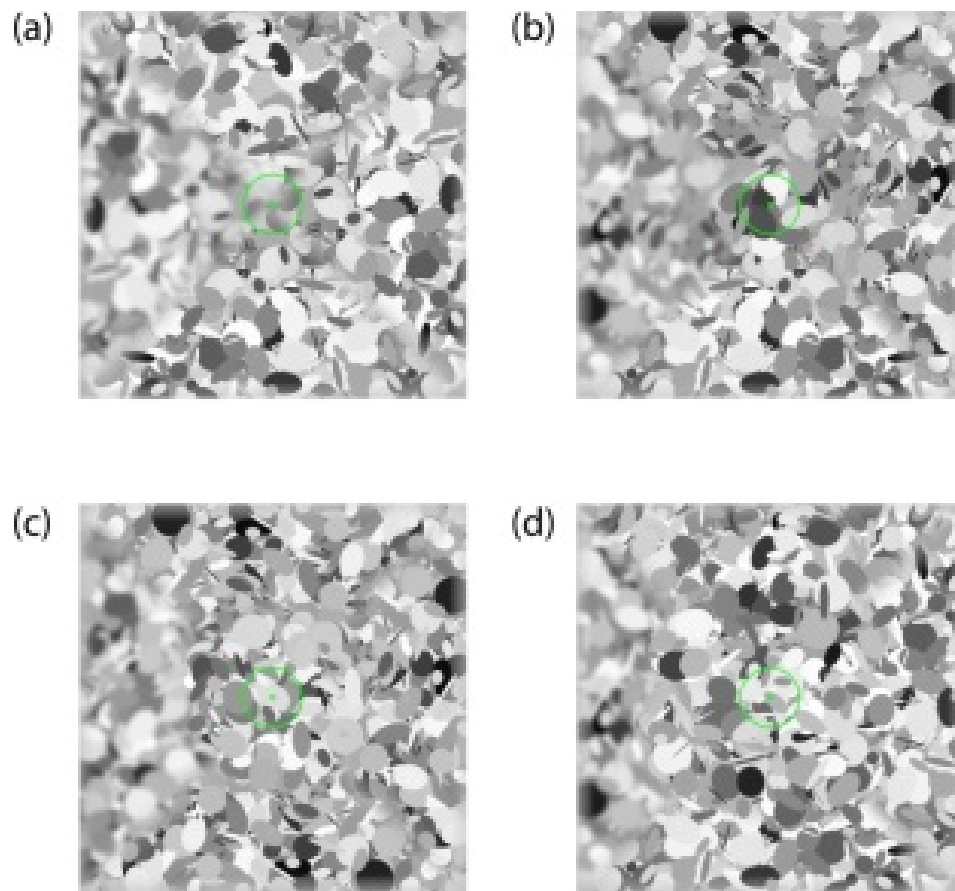


Figure 2. Examples of “dead leaves” stimuli used in the study, for each eccentricity condition: 0° (a), 4° (b), 8° (c), and 12° (d). In each of these examples, the top, right, and bottom quadrants are blurred with 0.5 arcmin of “pedestal” blur, while the left quadrant is blurred with 6.5 arcmin of “pedestal (0.5 arcmin) + increment (6 arcmin)” blur. For the 0° condition (a), blur is present throughout the entire image, from the center to the periphery. For the other conditions (b-d), the leaves within the central 4°, 8°, or 12°, respectively, are sharply rendered. Blur extends beyond the specified retinal eccentricity, to the outer edge of the image.

The subject was asked to complete two experimental sessions - once monocularly (with their non-dominant eye occluded) and once binocularly. The session order was randomized across participants. In each session, subjects completed 15 trials at each of the five pedestal blur levels for each of the four eccentricities, or 300 trials in total. The two sessions together lasted about 40 minutes. The subjects were given regular breaks to avoid fatigue.

2.2.3 Study Design

Previous work has confirmed decidedly that the ability of human subjects to discriminate between different amounts of blur varies lawfully as a function of reference (or “pedestal”) blur, and that this function is dipper shaped much like that for contrast discrimination. (For a review of these studies, see [Watson and Ahumada, 2011](#).) Blur discrimination performance first improves for small amounts of reference blur, and then, past the lowest threshold, worsens in proportion to reference blur ([Mather and Smith, 2002](#)). In other words, as small amounts of blur are added to two images, the just-noticeable difference (JND) in blur first decreases, and then increases ([Morgan et al., 2008](#)).

As such, blur perception is usually studied by measuring blur discrimination thresholds at several different levels of pedestal blur, and then fitting the threshold data with a dipper shaped function. In this study, we used the functional adaptive sequential testing (FAST) algorithm ([Vul et al., 2010](#)) to estimate dipper functions instead of measuring individual thresholds. Given the number of conditions we aimed to test in this study (five reference blur levels, four eccentricities, two viewing sessions - monocular and binocular), measuring individual thresholds as usual would have necessitated several thousand trials and multiple hours of testing per subject. The FAST algorithm allowed us to limit our testing time to one hour per subject. To our knowledge, the FAST algorithm has not been used to measure blur discrimination dipper functions prior to this study. For this reason, we ran a control experiment to verify that the procedure would produce meaningful results. We found that our estimates using the FAST method were unbiased and compared closely to estimates using

classical psychophysical methods with five interleaved staircases in the same subjects. (See Appendix II for details.)

We adopted a parameterization of the blur dipper function (Mather and Smith, 2002; Murray and Bex, 2010) with the following equation:

$$\Delta b = \sqrt{(1 + 1/S)(\sigma_i^2 + \sigma_e^2)} - \sigma_e$$

where blur increment threshold Δb varies as a function of the external (“pedestal”) blur σ_e applied to the stimulus, and is modulated by two parameters: blur sensitivity S and intrinsic blur σ_i .

Both intrinsic and external blur contribute to the total blur in a retinal image (Mather and Smith, 2002). The model’s intrinsic blur parameter takes into account that the human visual system has a baseline level of blur derived from optical and neurological sources. External blur, again, refers to the blur applied to the stimulus image (i.e. that which is added via Gaussian filtering). The dipper shape arises because, at near-zero reference blur levels, more external blur must be added to overcome the contribution of intrinsic blur. Then, as reference blur increases beyond the value of intrinsic blur, the contribution of intrinsic blur diminishes, and blur discrimination worsens in accordance with Weber’s law. The blur sensitivity parameter takes into account the proportional increase of the blur threshold with increasing external blur. An observer who is better at discriminating blur is said to have a higher sensitivity to blur and, on examination, will have globally lower thresholds.

Figure 3 illustrates how the shape of the dipper function responds to changes in the intrinsic blur and blur sensitivity parameters. Increasing the intrinsic blur parameter whilst holding the blur sensitivity parameter constant (Figure 3a) shifts the left side of the dipper

function upward but does not affect the right side of the function. Increasing the blur sensitivity parameter whilst holding the intrinsic blur parameter constant (Figure 3b) shifts the entire curve down and to the right.

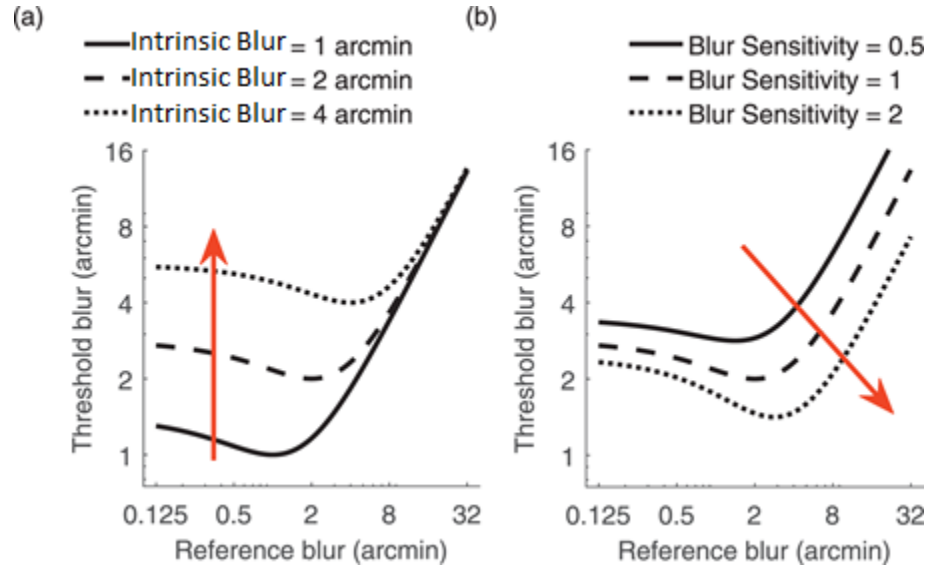


Figure 3. Representation of the effect of modifying the different parameters of the blur dipper model. (a) Effect of holding the blur sensitivity parameter fixed at a value of 1 and increasing the intrinsic blur parameter from 1 to 4 arcmin. (b) Effect of holding the intrinsic blur parameter fixed at 2 arcmin and increasing the blur sensitivity parameter from 0.5 to 2.

Figure 4 shows an example of a dipper function estimated for one representative observer in one experimental condition. For each dipper function estimate, we required the FAST algorithm to select and test 15 trials (or 15 “increment” blur levels) at each of the five pedestal blur levels (0.125, 0.5, 2, 8, and 32 arcmin). The FAST algorithm works to select the test blur levels that maximize information gain, efficiently constraining the parameter estimates of the underlying dipper function.

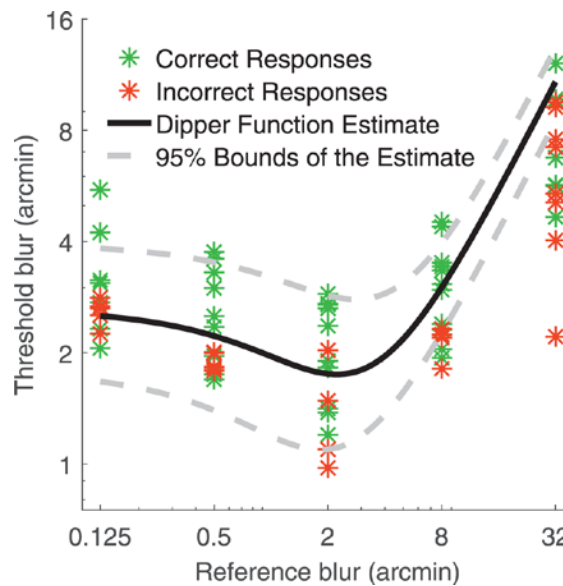


Figure 4. Example of a dipper function estimated for one representative subject in the binocular, 0° eccentricity condition. Asterisks represent individual trials: Green and red are correct and incorrect responses, respectively. The dipper function estimate is shown by the black curve, which describes how the subject’s threshold blur increment varies as a function of reference (or “pedestal”) blur. The dotted lines show the 95% bounds of the estimated curves. Note that 25% of the trials below threshold are guessed correctly in this 4AFC task.

2.2.4 Data Analysis

For each subject, we derived blur discrimination dipper functions for 0° , 4° , 8° , and 12° retinal eccentricity, both monocular and binocular. On some conditions and for certain subjects, the FAST algorithm failed to converge. Thus, we performed outlier removal by employing the following procedure: For each estimated parameter, we computed the size of the 95% confidence region of the estimate. For intrinsic blur (σ_i) and blur sensitivity (S) parameters separately, we then computed the upper 90th percentile of the size of the confidence regions. Finally, we excluded data from those dipper curves in which at least one of the parameter estimates confidence region was greater than this 90th percentile. This

procedure thus excluded parameters estimated with high uncertainty. 13% of dipper curves were excluded overall.

Estimated intrinsic blur (σ_i) and blur sensitivity (S) parameters (derived from the dipper functions) were analyzed with a 2 (refractive group, between subjects factor) x 2 (viewing condition (monocular/binocular), within subjects factor) x 4 (eccentricity, within subjects factor) mixed-design ANOVA. Blur sensitivity data did not respect the ANOVA assumption on the normality of the residuals, so blur sensitivity data was square-root transformed and ANOVA was rerun with the transformed data. We found that the results from the original and transformed data do not differ substantially, but decided to report the ANOVA results on the transformed data for statistical rigor. Post-hoc comparisons were conducted via Bonferroni corrected t tests.

2.3 Results

2.3.1 Main Findings

Complete measurements were obtained for 19 subjects with myopia (Mean (SE): $-5.88 \pm 3.35\text{DS}$), 20 emmetropic subjects (Mean (SE): $+0.15 \pm 0.24\text{DS}$), and 6 subjects with hyperopia (Mean (SE): $+1.72 \pm 0.92\text{DS}$), for a total of 45 subjects (Table 1). Given the small number of subjects with hyperopia recruited, we ran our final data analysis using only the data from subjects with myopia and emmetropia. We published these findings in the *Journal of Vision* in 2017 (Maiello et al., 2017; Appendix II). See Section 2.3.3 for a preliminary analysis of data from subjects with hyperopia.

Subject Group (n)	Rx (Mean SE) (Range)	Age (Mean) (Range)	Female (%)
Myopes (19)	-5.88 ± 3.35D (-1.50 to -10.94)	25.05 yrs (23-30 yrs)	15 (75.0%)
Emmetropes (20)	+0.15 ± 0.24D (-0.25 to +0.50)	24.80 yrs (23-27 yrs)	8 (42.1%)
Hyperopes (6)	+1.72 ± 0.92D (+0.81 to +3.25)	26.00 yrs (21-32 yrs)	5 (83.3%)

Table 1. Demographic information of subjects enrolled in the study.

Figure 5 shows group data dipper functions estimated under monocular and binocular viewing conditions, at each tested eccentricity. In both monocular and binocular viewing, blur thresholds increase (or blur sensitivity decreases) with eccentricity. Also, blur discrimination thresholds are generally lower (higher sensitivity) for the binocular testing condition.

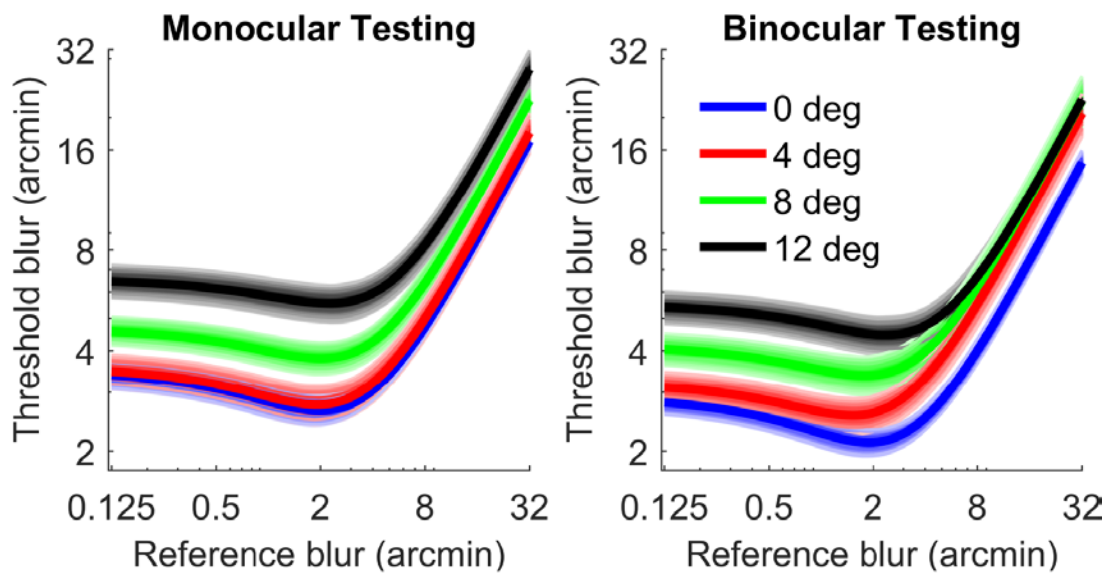


Figure 5. Blur dipper functions averaged across all subjects, under monocular (left) and binocular (right) conditions and at each eccentricity (0° blue, 4° red, 8° green, and 12° black). Shaded regions are 95% bootstrapped confidence intervals of the mean.

Figure 6 shows the intrinsic blur parameter (derived from the estimated dipper curves) as a function of retinal eccentricity in both monocular and binocular viewing conditions.

Intrinsic blur is larger under monocular than binocular conditions, $F(1, 42) = 12.75$, $p = 0.00091$, and increases with eccentricity, $F(3, 108) = 32.73$, $p = 10^{-14}$. There was no significant effect of refractive group, $F(1, 38) = 0.54$, $p = 0.47$, and no significant two or three way interactions (all $ps > 0.6$).

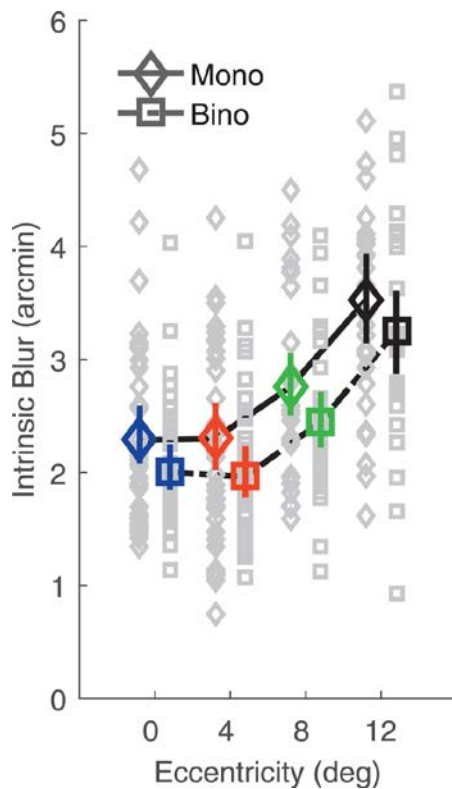


Figure 6. Intrinsic blur as a function of retinal eccentricity. Data are averaged across subjects for both monocular (diamonds) and binocular (squares) viewing conditions. Monocular and binocular data are shifted left and right, respectively, for graphical purposes. Color-coding of eccentricity conditions is as described in Figure 5. Error bars are 95% bootstrapped confidence intervals of the mean. Gray data points are individual subject data.

Figure 7a shows blur sensitivity as a function of retinal eccentricity, averaged across all subjects and both viewing conditions. Blur sensitivity decreases with eccentricity, $F(3, 109) = 11.6$, $p = 10^{-6}$. Figure 7b shows binocular sensitivity advantage as a function of

eccentricity. In comparing monocular and binocular viewing, we found that there was a significant main effect of viewing condition, $F(1, 43) = 5.88, p = 0.020$, and a significant two-way interaction between viewing condition and eccentricity, $F(3, 75) = 4.91, p = 0.0036$. Post-hoc testing revealed that blur sensitivity is higher under binocular viewing conditions at 0° eccentricity ($p = 0.012$) but that there was no significant difference in blur sensitivity between binocular and monocular viewing conditions at $4^\circ, 8^\circ$, or 12° eccentricity (all $ps > 0.25$). Figure 7b summarizes these results, where we plot the difference between blur sensitivity measured binocularly and monocularly at each tested eccentricity. If binocular viewing boosts blur sensitivity, the blur sensitivity advantage should appear positive. On average, binocular sensitivity advantage was positive, but it was significantly so only with central vision. Figure 7c plots averaged monocular and binocular blur sensitivity in emmetropes and myopes. There was no significant main effect of refractive group on blur sensitivity, $F(1, 38) = 3.49, p = 0.069$, but there was a marginally significant two-way interaction between viewing condition and refractive group, $F(1, 39) = 4.11, p = 0.049$. Bonferroni corrected t tests revealed that myopes had significantly worse blur sensitivity than emmetropes monocularly ($p = 0.037$) but not binocularly ($p = 0.66$). Lastly, there was no significant two-way interaction between eccentricity and refractive group, $F(3, 109) = 0.28, p = 0.84$, and no significant three-way interaction, $F(3, 75) = 1.09, p = 0.36$.

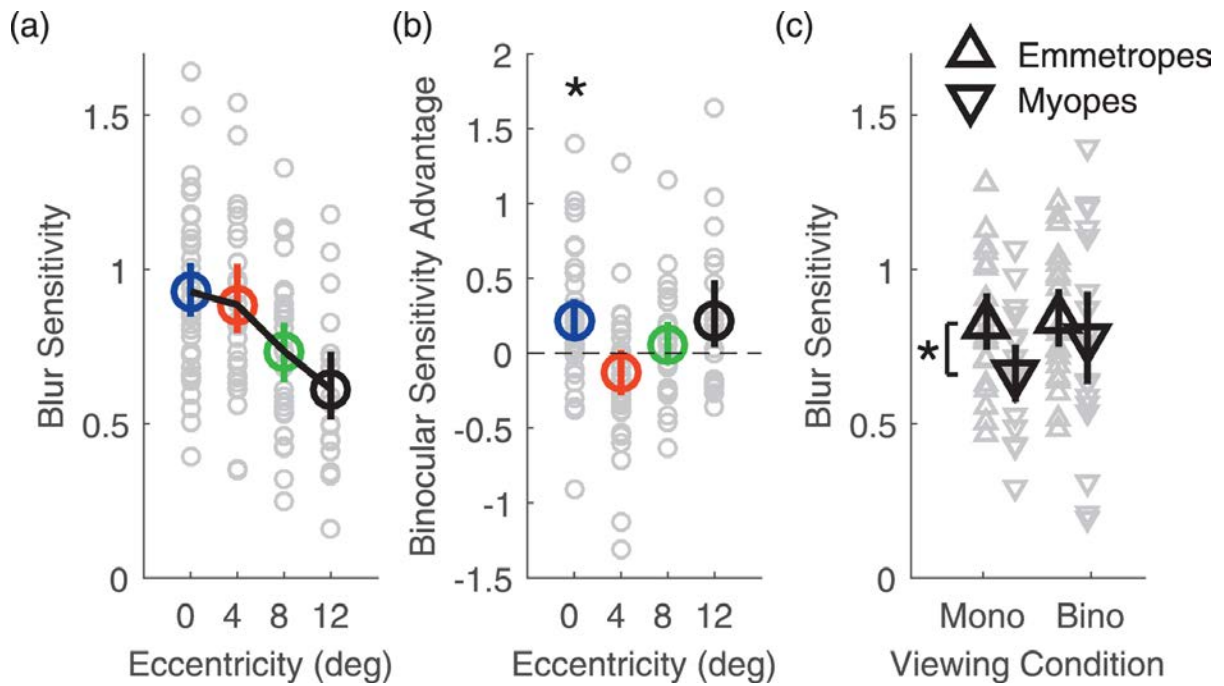


Figure 7. Blur sensitivity. (a) Blur sensitivity as a function of eccentricity, averaged across subjects and viewing conditions. (b) Blur sensitivity advantage for binocular viewing compared with monocular viewing, as a function of eccentricity, averaged across all subjects. Color-coding of eccentricity conditions in (a) and (b) is as described in Figure 5. (c) Monocular and binocular blur sensitivity in emmetropes (upward pointing triangles) and myopes (downward pointing triangles). Data are averaged across eccentricities and across subjects in each refractive group. Error bars are 95% bootstrapped confidence intervals of the mean. $*p < 0.05$.

2.3.2 Difference between “Best” and Habitual Eyeglass Prescription

As stated previously, subjects were classified into refractive groups based on dry binocular subjective refraction on the day of testing. These values are what we term the subject’s “best” refraction or prescription. If the subject habitually wore correction during near tasks, they were asked to bring and wear that correction during the experimental procedure. If subjects habitually wore no correction, they completed the experiment without correction. We noted that in some cases the “best” prescription did not match what subjects used on the day of the experiment. Because several previous studies have shown that blur

sensitivity increases after a period of blur adaptation, and that myopes demonstrate higher experience-based blur compensation (e.g., Cufflin, Mankowska and Mallen, 2007; George and Rosenfield, 2004; Ghosh et al., 2017; Poulere et al., 2013; Radhakrishnan et al., 2004; Wang, Ciuffreda and Vasudevan, 2006), we thought that it would be interesting to see whether there was an effect of best versus habitual prescription on blur perception in this experiment. In other words, we thought that the subjects who were not habitually corrected with their best prescription may have been adapted to blur and may have therefore shown different blur sensitivity responses. In plotting these comparisons, no correlations were found (R^2 values ranged from 0.0064 to 0.273), suggesting blur adaptation did not play a role in this blur perception task.

2.3.3 Preliminary Data from Subjects with Hyperopia

Because of the small number of subjects with hyperopia we were able to recruit, we did not feel it appropriate to run statistics on their data and attempt to draw conclusions. Rather, we plotted their data and evaluated it for possible trends. Figures 8 and 9 compare the mean parameter estimates described in the previous section (pooled across both myopes and emmetropes) to the mean parameter estimates calculated for our hyperopes. Figure 8 shows intrinsic blur as a function of retinal eccentricity (averaged across monocular and binocular viewing conditions) and the reduction in intrinsic blur with binocular viewing. Similarly, Figure 9 shows blur sensitivity as a function of retinal eccentricity, and the improvement in blur sensitivity (or “advantage”) with binocular viewing. Overall, hyperopes mimic the patterns reported in the previous section and in our *Journal of Vision* article (Maiello et al.,

2017). Hyperopes, like emmetropes and myopes, show: (1) increasing intrinsic blur with eccentricity, (2) a binocular reduction in intrinsic blur, (3) decreasing blur sensitivity with eccentricity, and (4) a binocular improvement in blur sensitivity.

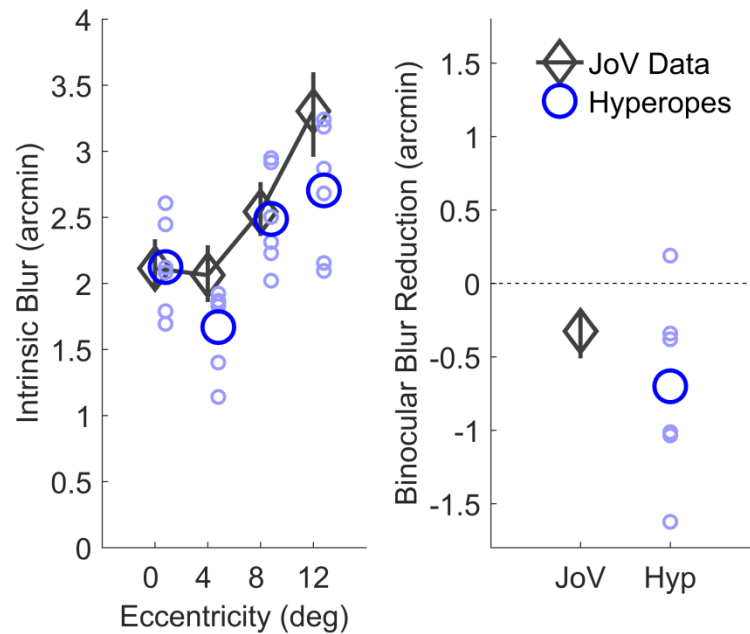


Figure 8. Intrinsic blur as a function of retinal eccentricity (left) and the reduction in intrinsic blur under binocular conditions (right). Black diamonds are the mean parameter estimates from the previous section and reported in JoV (averaged across all myopes and emmetropes). Error bars are 95% bootstrapped confidence intervals of the mean. Large blue circles are the mean parameter estimates of our hyperopes. Small blue circles are individual hyperope subject data.

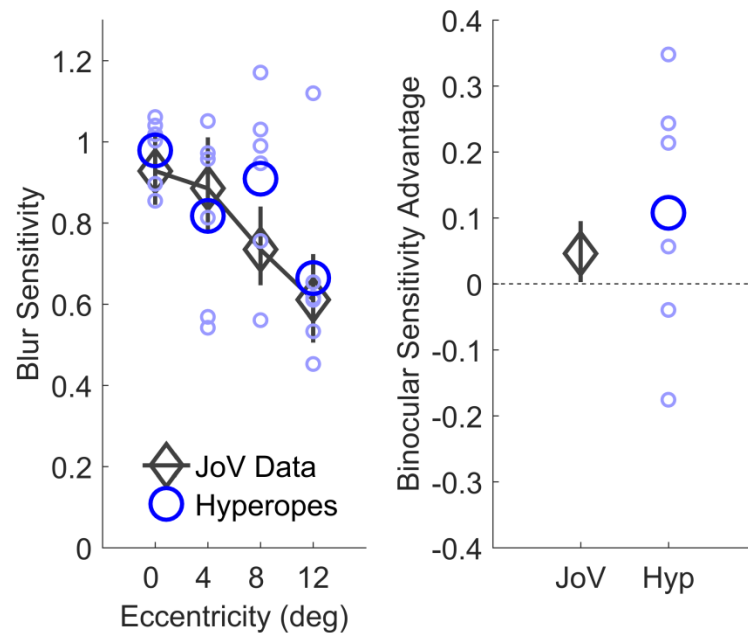


Figure 9. Blur sensitivity as a function of retinal eccentricity (left) and the improvement in blur sensitivity under binocular conditions (right). Black diamonds are the mean parameter estimates from the previous section and reported in JoV (averaged across all myopes and emmetropes). Error bars are 95% bootstrapped confidence intervals of the mean. Large blue circles are the mean parameter estimates of our hyperopes. Small blue circles are individual hyperope subject data.

On average, these pilot data show that hyperopes may have, with respect to the *Journal of Vision* subject pool of emmetropes and myopes: (1) less intrinsic blur, (2) a greater binocular reduction in intrinsic blur, (3) greater blur sensitivity, and (4) a greater binocular improvement in blur sensitivity. There is not enough statistical power with so few hyperopes to draw solid conclusions, but these trends may be worth further investigation in future studies.

2.4 Discussion

In this study, we assessed monocular and binocular blur perception in various distinct near peripheral retinal areas of subjects with myopia and emmetropia. Our hypothesis was that myopes would show an impaired ability to detect blur in the near peripheral retina. (An impaired ability to detect blur in the retinal periphery could possibly contribute to a misinterpretation of emmetropization signals and the failure of the emmetropization mechanism.) Previous studies have found that, in comparison to central vision, subjects are less sensitive to blur (i.e. show a higher tolerance to blur) in the far (out to 60° from the fovea) (e.g., Ronchi and Molesini, 1975) and near ($\leq 8^\circ$ from the fovea) (e.g., Ciuffreda, Wang and Wong, 2005; Wang and Ciuffreda, 2004, 2005a; Wang, Ciuffreda and Irish, 2006) peripheral visual field. Previous studies have also found that blur perception follows a characteristic dipper shaped curve (for a review, see Watson and Ahumada, 2011), with blur discrimination thresholds being lower than detection thresholds for small blur pedestals, and then rising in proportion to reference blur past the dipper minimum.

We have replicated both of these findings, showing that responses to blur worsen in the visual periphery and that performance can be described by a dipper shaped function. We have extended these findings to show that the increase in blur discrimination thresholds with increasing eccentricity can be attributed to two sources: (1) observers' increased intrinsic blur and (2) decreased blur sensitivity in the periphery.

We fit a variance discrimination model to our data, where intrinsic blur represents the internal noise or variance in luminance gradient (across an edge) that is due to our sensory system (Morgan et al., 2008). Intrinsic blur, then, results from the combined effects of

aberrations from the eye's optics and noise from the eye's neural machinery. We found that intrinsic blur increased with eccentricity and, specifically, that intrinsic blur increased by 56% beyond 12° in the visual periphery. We think this increase in intrinsic blur is due to a combination of a couple of different factors. First, there is an increased amount of optical aberrations in the retinal periphery (astigmatism, coma, and higher order aberrations) (e.g., Westheimer, 2006), but, on this point, it is important to note that other studies have found no improvement in peripheral visual resolution after removing these aberrations via adaptive optics (e.g., Lundstrom et al., 2007). Second, and probably most importantly, the retinal periphery experiences a decrease in cone and ganglion cell sampling density, which results in a decrease in resolution acuity (e.g., Dabir et al., 2015; Wolsley et al., 2008).

In addition to the increase in intrinsic blur into the retinal periphery, we found that blur sensitivity decreased into the periphery. Specifically, blur sensitivity decreased by 34% beyond 12°. We believe that the same factors contributing to increased intrinsic blur may also be contributing to decreased blur sensitivity, especially the decrease in neural sampling density in the peripheral retina. Additionally, two cortically-based mechanisms—a decrease in visual attention and an increase in sharpness overconstancy—may play a role in decreasing blur sensitivity into the retinal periphery (Ciuffreda, Wang and Wong, 2005; Wang and Ciuffreda, 2004).

Evidence for differences in the perception of blur across refractive groups is conflicting. Classically, blur perception experiments involve inducing blur by applying ophthalmic lenses or manipulating target distance and then inferring sensitivity to blur from changes in visual acuity or depth-of-focus. The majority of studies completed this way have found that myopes

are less sensitive to blur than emmetropes (e.g., Cufflin, Mankowska and Mallen, 2007; Poulere et al., 2013; Radhakrishnan et al., 2004; Rosenfield and Abraham-Cohen, 1999). Schmid et al. (2002), is an example of a study with different methodology. This research group induced blur in images (text and scenes) using image processing, and measured sensitivity to blur using a 2AFC task. Also, their subject population consisted of children between 8 and 12 years old. Interestingly, they found no statistically significant differences in blur sensitivity between myopic and emmetropic subjects.

Like Schmid et al. (2002), we employed a computer-based experimental procedure and found that there was no statistically significant overall effect of refractive group on either intrinsic blur or blur sensitivity. We found that there was no significant overall effect of refractive group on blur detection or blur discrimination thresholds. Perhaps the difference in methodology is important. Our assumption has been that the retinal and higher order mechanisms involved in analyzing blur remain the same (or similar) regardless of how that blur is produced, but perhaps blur induced by mathematical functions on a computer screen (e.g., Gaussian blur) is not as connected to myopia development as blur induced by lenses or distance (i.e. defocus blur). That said, Jacobs, Smith and Chan (1989) found no difference in what they called “source” and “observer” methods – the former involved viewing defocused stimuli presented on a projection screen, while the latter involved inducing defocus with lenses placed in the spectacle plane. The differences in results across studies could be attributed to a number of other factors instead, such as subject age, variations in accommodation (i.e. cycloplegia) and/or vergence responses, variations in target spatial frequency content and/or size, etc.

Several studies support the theory that visual signals in the retinal periphery have a significant influence on refractive error development (e.g., Smith III et al., 2005, 2007; Smith III, Hung and Huang, 2009; Knight-Nanan and O’Keefe, 1996; Nathan et al., 1985; Sieving and Fishman, 1978; Chin et al., 2015). Some studies have found, in particular, a strong association between relative peripheral hyperopia and the development of myopia (Hoogerheide, Rempt and Hoogenboom, 1971; Mutti et al., 2007). We do not know conclusively whether peripheral hyperopia is a risk factor for or a consequence of myopia development, but, if the former, the implication is that the peripheral retina can somehow detect the sign and magnitude of defocus and generate signals to control ocular growth. The hope is that at-risk individuals could be identified at an early age and started on a treatment option that helps to reduce hyperopic defocus in the retinal periphery. Some of the options currently being studied include spectacle lens designs that introduce peripheral myopic defocus (Sankaridurg et al., 2010), multifocal soft contact lenses (Anstice and Phillips, 2011; Lam et al., 2014), and orthokeratology (Cho and Cheung, 2012; Hiraoka et al., 2012). It is important to point out that our study did not look specifically at sensitivity to positive versus negative defocus, so we cannot contribute very much to this area of discussion. We can only repeat that we did not find any differences in sensitivity to Gaussian blur in the near-peripheral retina between refractive groups.

Our study stands apart from existing literature because we compared blur sensitivity under monocular and binocular conditions. Previous studies have shown that binocularity improves visual performance through probability summation under blur conditions (Arnold, Grove and Wallis, 2007; Banton and Levi, 1991; Hoffman and Banks, 2010; Heravian,

Jenkins and Douthwaite, 1990; Plainis et al., 2011). Plainis et al. (2011) have shown that, with visual blur induced by positive lenses, binocularity improved visual acuity (a subjective finding) and also enhanced the P100 component of visual evoked potentials (an objective, electrophysiological finding). We have found that binocularity also improves visual blur perception. Our results show that combining information from the two eyes leads to a reduction in the system's intrinsic blur, which is consistent with the notion that combining information from the two eyes reduces noise (Legge, 1984a, 1984b). Our results also show a small but statistically significant advantage in blur sensitivity at the fovea when viewing stimuli binocularly. This suggests that there may be additional binocular processing of blur in the center of the visual field.

While we did not find an overall main effect of refractive group on blur sensitivity, we did find that myopes have, on average, worse blur sensitivity than emmetropes monocularly but not binocularly. This suggests that myopes may process blur less efficiently than emmetropes under monocular conditions. We could speculate that monocular deficits in blur processing could be linked to refractive error development, but functionally these deficits are masked by binocular summation. Perhaps a better speculation is that decreased binocular processing in childhood could be a culprit in refractive error development. In other words, if a child's binocular vision is slow to fully develop, that child might suffer from decreased (i.e. a monocular level of) blur sensitivity during the emmetropization period and may be at greater risk for myopia development.

Our understanding of the role of defocus in refractive error is largely derived from animal studies, in which optical defocus induced by ophthalmic lenses has been used extensively to

induce refractive error (e.g., Schaeffel and Feldkaemper, 2015; Wallman and Winawer, 2004). It is important to realize that, for practical reasons, most of these animal studies were completed on non-primates and observations cannot be assumed totally transferable to humans. Observations in primate models are more likely to be transferable because primates have a fovea, accommodation and visual resolution similar to humans (Schaeffel and Feldkaemper, 2015). Unfortunately, the myopia studies using primate models are relatively limited and, like human studies, show conflicting results. In particular, primates show significant inter-subject variability in the response to defocus blur (for a review, see Schaeffel and Feldkaemper, 2015). It is also important to realize that most of these animal studies have been completed monocularly, which is an inadequate parallel with most naturally occurring myopia as most individuals are binocular. Considering the complexity of primate and human visual systems, and considering the results of the present study, we feel that binocularity should be examined more closely as a factor in refractive error development going forward.

As mentioned previously, a potential limitation of the present study is that we assessed blur sensitivity using only Gaussian blur. Also, we were unable to recruit an adequate number of hyperopes to compare blur sensitivity responses across all three refractive groups with sufficient statistical power. Finally, we recognize that we did not control for variations in accommodation with cycloplegia or employ a fixed pupil size.

Further investigations will be necessary to evaluate the effect of binocularity and the effect of different types of blur on blur sensitivity. Also, in regards to binocularity, blur sensitivity should be assessed both binocularly and monocularly in both eyes (not just the

dominant eye) to verify the degree to which binocular summation occurs in different refractive groups. Additionally, while mechanisms that lead to hyperopia may not be the same as those that lead to myopia, investigations involving subjects with hyperopia will be necessary if we hope to fully understand the relationship between blur sensitivity and refractive error development. Investigations with children would also shed light on the emmetropization process, and whether any differences in blur sensitivity exist prior to or result from myopia development. Finally, it could be interesting to study whether there is an effect of retinal quadrant (superior, inferior, nasal or temporal) on blur sensitivity responses, which was not possible in our study due to the limited sample size.

3. EYE MOVEMENTS STUDY

3.1 Background & Hypothesis

Previous studies have shown that myopes have lower visual acuity than emmetropes when acuity is converted from angular units in cyc/deg to retinal units in cyc/mm (this conversion compensates for larger images on the retina in longer eyes and is described in detail in Section 3.2.3) (Coletta and Watson, 2006; Strang, Winn and Bradley, 1998).

Previous studies have also shown that myopes with corrected refractive error suffer a greater deficit in visual acuity in low luminance than emmetropes (e.g., Coletta, Frericks and Groves, ARVO 2007; Coletta et al., ARVO 2008). This result was repeated with laser interference fringes as the stimuli (Coletta et al., ARVO 2008), suggesting that the deficit is not entirely caused by the potentially decreased optical quality in myopic eyes.

The question that remains is what other, non-optical factors could be causing visual acuity to be reduced to a greater extent under dim illumination in myopes than in emmetropes. One possible hypothesis for a contributing factor to this difference emerged during the measurements of acuity with letter charts in dim light, as myopes often complained that the letters of the chart were moving around or were difficult to fixate (Coletta and Moskowitz, 2003). We thought that it might be possible that subjects with myopia have more variable eye movements in dim light than other subjects.

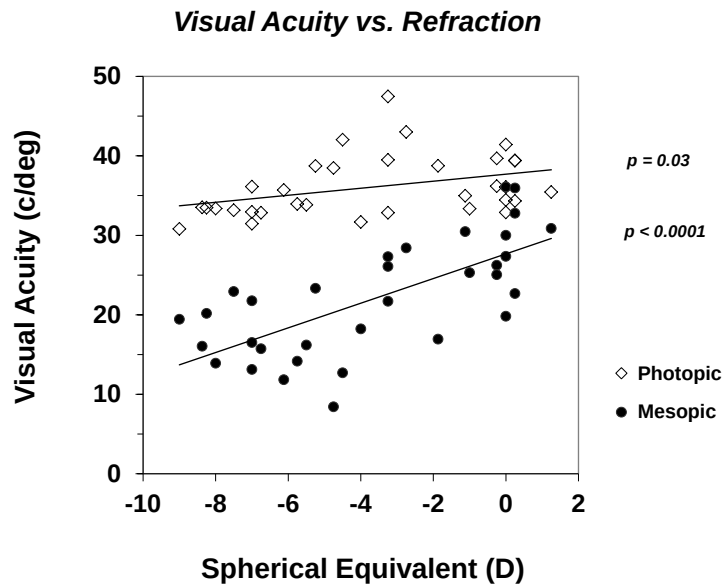


Figure 10: Findings from Coletta, Frericks, and Groves (2007), i.e. myopes' acuity deficit in low luminance. Visual acuity (in cyc/deg) measured under photopic (open symbols) and mesopic (filled symbols) light levels, plotted against spherical equivalent refraction (in Diopters).

In foveate species (e.g., primates and humans), eye movements function to place and hold images of objects onto the fovea, the central area of the retina with the highest density of photoreceptors and the best resolution acuity. Before describing our experiment in detail, it seems appropriate to define these movements, of which there are several different types. Firstly, eye movements can be broadly classified into two categories: saccades or smooth pursuits (Krauzlis, Goffart and Hafed, 2016). Saccades are rapid, ballistic movements that can be elicited voluntarily or reflexively to abruptly change the point of fixation. Smooth pursuits are much slower, continuous movements that are used to track moving visual targets. Saccadic eye movements, then, can be further classified as large saccades (with amplitudes >2 deg, peak velocities of up to >500 deg/s, and durations of 20-100 ms) or microsaccades

(with amplitudes smaller than the diameter of the foveal region, usually <2 deg, but otherwise, similar velocities and durations) (Ahissar et al., 2016).

Eye movements during fixation on an immobile target are comprised of microsaccades, as well as tremor and drifts (e.g., Martinez-Conde, Macknik and Hubel, 2004; Otero-Millan et al., 2008). Microsaccades are saccades (fast, jerk-like movements) with very small amplitudes. They are usually about 25 ms in duration and, in that time, they can carry the image of the object of interest across several dozen to several hundred photoreceptors (Martinez-Conde, Macknik and Hubel, 2004). Interestingly, microsaccades are seldom recorded in afoveate species (e.g., rabbits, frogs, goldfish), so it seems that these movements are most important in species with foveal vision (e.g., primates and humans) (Martinez-Conde and Macknik, 2008). Ocular tremor is sometimes referred to as “physiological nystagmus,” and consists of irregular, oscillatory movements with very low amplitudes (about the diameter of a cone photoreceptor in the fovea, or ~ 6 arc-seconds) and very high frequencies (~ 90 Hz) (Krauzlis, Goffart and Hafed, 2016; Martinez-Conde, Macknik and Hubel, 2004). In regards to eye movement recordings, tremor amplitudes and frequencies are typically in the range of the recording system’s noise (Martinez-Conde, Macknik and Hubel, 2004). Tremor is therefore very difficult to measure and not often studied (Krauzlis, Goffart and Hafed, 2016). It remains unclear how tremor contributes to vision/fixation. Ocular drifts occur simultaneously with tremor. These drifts are slower, meandering movements, with larger amplitudes (many arc-minutes) and lower frequencies (<40 Hz) (Krauzlis, Goffart and Hafed, 2016). During drifts, the image of the object of interest can move across a dozen photoreceptors (Martinez-Conde, Macknik and Hubel, 2004). Interestingly, drifts occur only

in the nasal direction prior to the development of binocularity (i.e. prior to binocular input from the striate cortex). Drifts may have a compensatory role in maintaining fixation when microsaccades are absent or inaccurate (Martinez-Conde, Macknik and Hubel, 2004), and they may be important to judging the orientation of the visual stimulus (Krauzlis, Goffart and Hafed, 2016). Another possibility is that drifts (and tremor, for that matter) are just noise, resulting from random neuronal firing to the ocular muscles (Martinez-Conde, Macknik and Hubel, 2004). It may be that microsaccades are actually serving the compensatory role, correcting for drifts and bringing the object/region of interest back to the fovea (Martinez-Conde and Macknik, 2008).

In regards to fixation, researchers have shown that dynamic eye movements are not just a random anomaly of the oculomotor system. Instead, these dynamic eye movements act to prevent neural adaptation and, as such, have substantial effects on visual perception (e.g., Krauzlis, Goffart and Hafed, 2016; Martinez-Conde and Macknik, 2008; Martinez-Conde, Macknik and Hubel, 2004; Martinez-Conde et al., 2006). It was found that, after stabilizing a retinal image (for example, by flashing a stimulus and testing the retinal after-image), the perception of that image fades over several seconds and can even disappear completely (e.g., Krauzlis, Goffart and Hafed, 2016). Fixational eye movements serve to counteract this visual fading by continuously shifting the position of an image on the retina (e.g., Krauzlis, Goffart and Hafed, 2016). Microsaccades have been shown to serve this purpose during prolonged fixation and also during the fixation periods in visual exploration and search (e.g., Otero-Millan et al., 2008; Snodderly, 2016).

Additionally, microsaccades may serve to optimize sampling of fine spatial detail, especially when retinal contrast is low due to optical blurring (e.g., Donner and Hemila, 2007; Snodderly, 2016). In other words, the retinal slip (i.e. the shift of the image on the retina) that counteracts visual fading may also be acting to elicit photoreceptor responses and, resultantly, may be helping to encode visual details more efficiently at the ganglion cell level and beyond (e.g., Martinez-Conde, Macknik and Hubel, 2004; Snodderly, 2016). Several findings seem to support this theory—for example, Gilchrist, Brown and Findlay (1997) found that a patient with total ophthalmoplegia (i.e. unable to make any eye movements) was able to read normally by using comparable head movements or “head-saccades” (Otero-Millan et al., 2008). This sampling mechanism could be similar to when objects are recognized via tactile information, i.e. when we run our fingers across an object with our eyes closed (Otero-Millan et al., 2008).

While microsaccades are beneficial in their ability to counteract neural adaptation and possibly to enhance spatial acuity, microsaccades also temporarily interrupt visual processing in a process called “saccadic suppression” (e.g., Hafed, Chen and Tian, 2015; Ibbotson and Krekelberg, 2011; Krauzlis, Goffart and Hafed, 2016). Saccadic suppression has been found to reduce visual sensitivity during an eye movement, but also ~100 ms before the eye movement begins and ~100 ms after it has ended (Hafed, Chen and Tian, 2015; Ibbotson and Krekelberg, 2011). Our visual system works to link the representation of objects before and after a saccade. This mechanism is necessary so that we perceive a stable environment instead of “visual jitter” when we fixate an object (i.e. when our eyes are continuously moving) (e.g., Martinez-Conde, Macknik and Hubel, 2004). However, some researchers have

looked more closely at perisaccadic perception (i.e. visual perception just before and after a microsaccade), and they have shown that, among other things, orientation discrimination is impaired and high spatial frequency letters are more difficult to identify during these perisaccadic time periods (Ibbotson and Krekelberg, 2011). Furthermore, microsaccades are also associated with misinterpretations of object locations (e.g., Krauzlis, Goffart and Hafed, 2016). Researchers have shown that there is a compression of the visual field during microsaccades such that, if a visual stimulus is flashed at the fovea just before a microsaccade, it is mistakenly localized more in the direction of the microsaccade (i.e. if the microsaccade is shifting the eye rightward, the stimulus appears to be towards the right of center) (e.g., Krauzlis, Goffart and Hafed, 2016; Ross, Morrone and Burr, 1997). If a visual stimulus is flashed in the retinal periphery just before a microsaccade, it is displaced foveally, opposite to the direction of the microsaccade (e.g., Krauzlis, Goffart and Hafed, 2016).

We are interested in the role of microsaccades and scanning eye movements in visual tasks, specifically visual acuity tasks, and how eye movements may differ across refractive groups. Previous studies into eye movements (their mechanics, associated neuronal responses, etc.) have provided valuable insight into some of the ways the visual system acquires information about the visual environment, both normally and in the presence of ocular pathology. Given our interest in the relationship between eye movement variability and visual acuity, we found a couple of studies in subjects with amblyopia to be particularly interesting. Raveendran et al. (2014) used a video based infrared eye tracker to measure fixational eye movements in subjects with strabismic amblyopia. They calculated bivariate contour ellipse areas (or BCEA, explained further in Section 3.2.3) to show that these

subjects have larger variability in eye position in their amblyopic eye (i.e. the eye with reduced visual acuity) when compared to their non-amblyopic eye. Chung et al. (2015) used retinal imaging to measure and determine the characteristics of fixational eye movements in subjects with anisometropic and/or strabismic amblyopia. Specifically, they compared fixational eye movements among amblyopic eyes, non-amblyopic fellow eyes, and normal control eyes. Similarly, they found that amblyopic eyes exhibit microsaccades with larger error magnitudes (i.e. microsaccades are less accurate in their landing positions), as well as microsaccades with increased amplitude and frequency. In regards to visual acuity, they found a significant correlation between fixational stability and visual acuity, but could not determine whether fixational stability is the limiting factor on acuity, or vice versa.

In reviewing the existing literature, it seems that there are relatively few studies that have explicitly examined eye movements in subjects with myopia. Hartwig et al. (2013) compared large saccadic eye movements (their amplitudes, peak velocities, and durations) between groups of myopes and emmetropes, and found no statistically significant differences. Alhazmi, Seidel and Gray (2014) measured large saccades as well, but they found that subjects with low ocular rigidity (myopes) had decreased peak velocities and took longer both to reach peak velocity and to respond in comparison to subjects with high ocular rigidity (hyperopes). Regarding fixational eye movements, Ghasia and Shaikh (2015) measured microsaccades during a fixation task in myopes, both with and without refractive correction (in a randomly determined sequence). They found that myopes have larger, more variable patterns of fixation when left uncorrected, suggesting that optical blur may result in decreased fixational stability or, in other words, may reduce the precision of oculomotor

control. While it can be assumed that uncorrected refractive error is associated with decreased visual acuity, this study did not specifically compare acuity and eye movements, and they did not compare eye movements across refractive groups.

The aim of this study is to measure the variability of eye movements during eye chart reading under photopic and mesopic lighting conditions, and to relate those eye movements to the subjects' refractive error and visual acuity. Our recordings are comprised mostly of larger, voluntary scanning movements. We are averaging all of these movements together to get an overall idea of eye movement variability. Our expectation was that myopes would have greater variability in eye movements compared to emmetropes, and that this might relate to a greater loss of acuity in dim light.

3.2 Methods

3.2.1 Subjects

A total of 48 subjects were recruited for this study (20 myopes, 20 emmetropes, and 8 hyperopes). Based on a prior study of visual acuity and its dependence upon refractive error (Coletta and Moskowitz, 2003), we found that a minimum sample size of 37 subjects should have provided a power of 0.8 for $\alpha=0.05$. Thus, a subject group of 48 should provide sufficient power for statistical significance in regression analysis.

These subjects were recruited primarily from students, staff, and faculty at the New England College of Optometry. Attempts were made to include approximately equal numbers of males and females and as diverse a population as was possible with the available subject pool. This study followed the tenets of the Declaration of Helsinki; informed consent was

obtained from all subjects after explanation of the nature and possible consequences of the study, and was approved by the New England College of Optometry's Institutional Review Board.

Criteria for inclusion were: (1) within 18-32 years of age, (2) refractive error between -12.00 DS and +6.00 DS spherical equivalent (SE) in each eye, with no more than 1.25 D of cylinder or 1.25 DS anisometropia, (3) best corrected visual acuity 20/20 or better in each eye, (4) no history of refractive surgery, (5) no history of surgery or eye disease that may have resulted in visual consequences, (6) no current binocular or accommodative dysfunction, (7) no nystagmus, (8) not using drugs that may affect vision, (9) contact lens wearer if distance correction was necessary, and (10) adequate hearing, language skills and mental ability to understand the consent process and the instructions given during the experiment.

Subjects were classified as either: (1) Myopes, defined as having a spherical equivalent in each eye between -0.50 to -12.00 D; (2) Emmetropes, SE between -0.25 to +0.50 D; or (3) Hyperopes, SE between +0.75 to +6.00 D. In some group analyses, myopes were further subdivided into high myopes (-6.00 D or more minus) and low/mid myopes (-0.50 D to -5.75D). Refractive error was determined by dry binocular subjective refraction following objective autorefraction.

3.2.2 Study Procedure

i) The Investigator explained the purposes of the study and the potential subject read the Informed Consent Form (ICF). The Investigator then answered any questions and ensured

that the procedures were well understood. Once the ICF was signed, a de-identifier form was used to assign a study number to the subject. This study number, with no identifiable information, was used from that point onward.

ii) A vision screening was performed to determine the subject's eligibility and refractive error group inclusion. The vision screening consisted of the following tests:

- a) Screening questionnaire that included ocular health and refraction history.
- b) Habitual distance and near visual acuity using a Snellen chart.
- c) Estimated cover test at distance and near.
- d) Eye dominance testing using hole-in-the-card test. (Rice et al., 2008)
- e) Autorefractometer with the GrandSeiko WR-5100K open-field autorefractor.
(<http://www.grandseiko.com/en/wr-5100k-binocular-accommodation-autorefractometer/>)
- f) Binocular distance subjective refraction.
- g) Slit lamp evaluation to ensure clear optical media.
- h) Central corneal power measured using the Humphrey Atlas Corneal Topography System Model 995. (<https://www.zeiss.com/meditec/us/products/ophthalmology-optometry/cornea-refractive/cornea-diagnostics/corneal-topography-system/atlas-9000.html>)
- i) Axial length and anterior chamber depth measured using the Lenstar LS900 optical biometer. (<https://www.haag-streit.com/haag-streit-usa/products/haag-streit-diagnostics/lenstar-biometry/>)

iii) Once eligibility was determined, the experimental procedure took place. The subject was positioned in a chinrest/headrest assembly four meters from a computer monitor upon which a computerized visual acuity chart was presented. This chinrest/headrest reduced the influence of head movements during the experiment. The non-dominant eye was fully occluded with a black cloth eye patch, and the subject was asked to wear contact lens correction on their dominant eye if distance correction was necessary. An EyeLink 1000 Desktop eye tracker (SR Research, Ontario, Canada; http://www.sr-research.com/EL_1000.html) was placed approximately 40 cm in front of the subject so as to record eye movements during visual acuity measurements. (See Figure 11.)



Figure 11. A subject positioned to complete the experimental procedure.

The EyeLink 1000 is a remote video-based eye tracker that records gaze position every 2 msec, with 0.6 arcmin spatial resolution. The system consists of a high-speed camera (see

Figure 12), a “host” computer which is dedicated to data collection, and a second “display” computer used to present stimuli. (The two computers are connected via an Ethernet cable.)



Figure 12. EyeLink 1000 Desktop Mount, with camera on the left and IR illuminator on the right (EyeLink 1000 User Manual).

Before recording eye movements, the camera had to be positioned so that the eye image was roughly centered in the overall camera image and focused so that the pupil was easily detectable (see Figure 13). An infrared illuminator, attached to the camera, causes a visible reflection on the subject’s cornea. The eye tracker uses changes in the subject’s pupil center and corneal reflection (CR) to deduce changes in eye movement, so a careful setup is necessary, as is a careful calibration. We had each subject slowly look along the edges of the display surface to ensure that the pupil center and corneal reflection were well established. We also required subjects needing distance correction to wear contact lenses instead of eyeglasses because eyeglasses can cause extra reflections and poor image contrast which, in turn, can cause unstable and noisy measurements.

Calibration was necessary with each subject so that the EyeLink system was able to associate pupil position on the camera image and gaze position on the display computer. This was completed using a thirteen-point calibration type, wherein thirteen different point targets

are displayed in succession on the display monitor and the subject is asked to fixate each target. The pupil-CR position was recorded for each target, and this set of target and pupil-CR positions was used to compute gaze positions during the experimental task.



Figure 13. An example of the “Camera Setup” screen on the host computer. Here, the eye is set up such that there are good pupil and corneal reflection thresholds.

The stimulus used in this study was a back-illuminated, high contrast LogMAR ETDRS visual acuity chart. A Matlab program was written to control the letter display. The letters were generated in a random order but kept to the LogMAR design (Sloan font, five letters per line, logarithmic spacing between letters and between lines, calibrated for four meters). Overall, our chart showed thirteen lines of letters, ranging from 1.0 to -0.2 logMAR (or 20/200 to 20/12.5 Snellen), but the monitor’s vertical dimension limited the number of lines that could be shown at once (Figure 14). The program was written so that the chart would shift upward during testing. The examiner asked the subject to read the letters out loud (as is conventional during visual acuity testing) and would simultaneously type in the subjects’ responses. After each line of five letters, the examiner would press the “Enter” key at which

time the chart would shift upward on the display. The chart shifted such that the line the subject was reading was always centered on the display monitor.

Eye movements were recorded during visual acuity measurements in a darkened room so that the only illumination was from the acuity display screen. Measurements were made at two illumination levels of the acuity screen:

- a) VA was first assessed under photopic illumination, with an average chart luminance of 325 cd/m^2 .
- b) Subjects then dark-adapted for 15 minutes in a darkened room.
- c) VA was assessed again under mesopic illumination, with a 3.0 ND neutral density filter over the display monitor (Figure 14). The average chart luminance was reduced by approximately a factor of 1000—to 0.276 cd/m^2 .

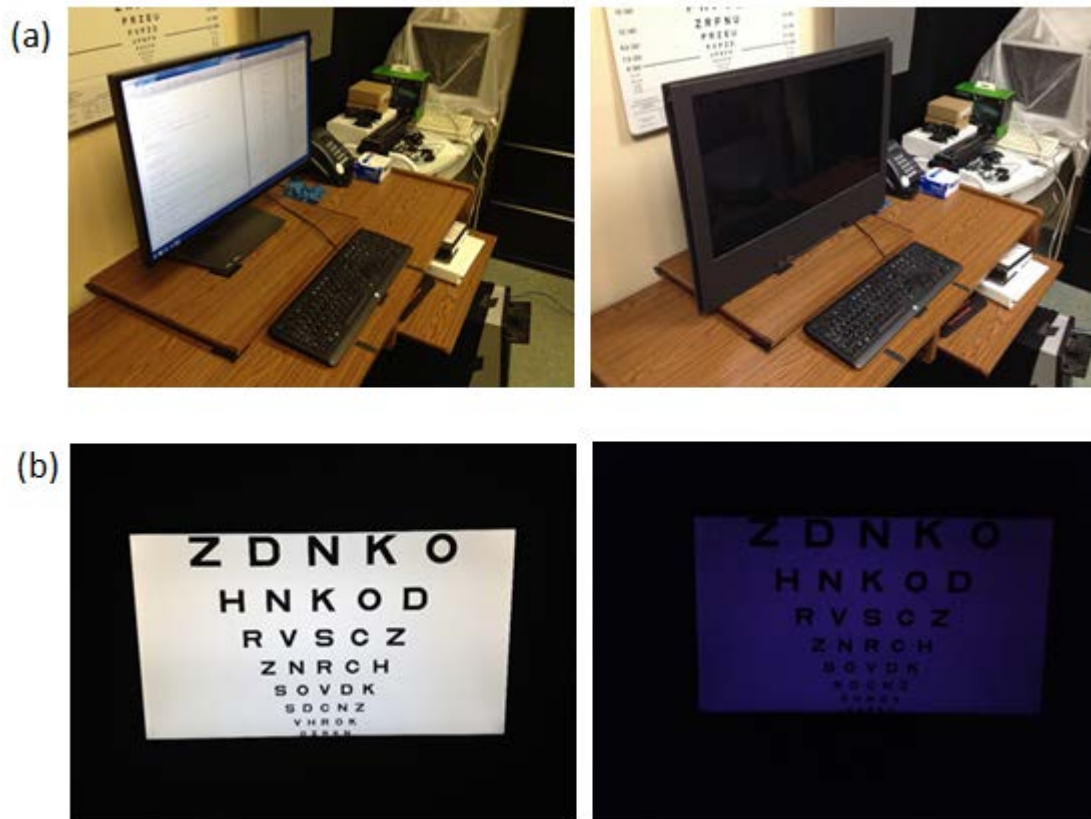


Figure 14. (a) Display monitor without (left) and with (right) the 3.0 ND neutral density filter. (b) LogMAR visual acuity chart without (left) and with (right) the filter.

3.2.3 Data Analysis

The EyeLink 1000 eye tracker uses the EyeLink Data Format (EDF) file format to record eye movements and other data, but can translate an EDF file into an ActionScript (ASC) file if desired. The ASC file includes the most important data from the EDF file in a text format that is more easily accessible ([EyeLink 1000 User Manual](#)). Eye position is given as horizontal and vertical coordinates on the display monitor, in pixels, for every 2 msec. Our first step for data analysis was to copy the ASC file into Microsoft Excel, and then to isolate the eye movements we were interested in.

Eye movement recordings were taken for all lines read on the visual acuity chart, but we decided to analyze only the movements corresponding to each subject's photopic and mesopic acuity levels. Specifically, we analyzed movements when subjects read letters at their (1) mesopic VA limit, (2) photopic VA limit, and (3) when subjects read the line of letters corresponding to their mesopic VA in the photopic condition. For each visual acuity line, we analyzed movements for the entire duration of line reading and also during only the first two seconds of line reading. After isolating those three lines for each subject, we removed “noisy” data points associated with blinks (see Figure 15), and then assessed their eye movement variability two ways: by determining (1) the standard deviation (SD) of vertical eye position and (2) the bivariate contour ellipse area (BCEA) (explained below). A larger SD and a larger BCEA signify greater variability in eye movements.

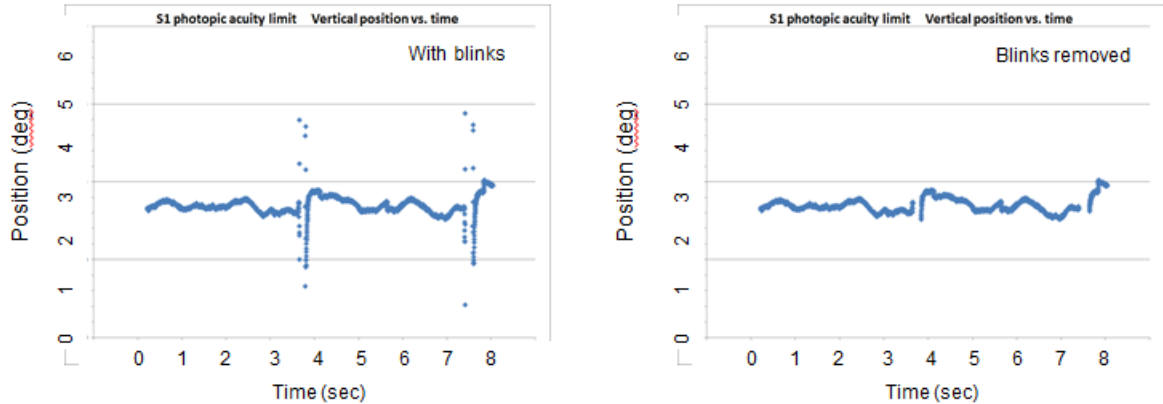


Figure 15. Example graphs of vertical eye position (in degrees) plotted against time (in seconds) for our first subject during line reading at their photopic visual acuity limit. The graph on the left shows all data points recorded, while the graph on the right shows remaining data points after removal of “noise” associated with blinks.

For each subject, during each of the three conditions described above, we derived the standard deviation of vertical eye position (in degrees). We then plotted vertical SD as a

function of refractive error and used least square linear regression to determine if there was a significant positive correlation between eye movement variability and amount of myopia as we had hypothesized. We used single factor ANOVA to determine if there were significant differences in vertical SD between the refractive groups (high myopes, myopes, emmetropes and hyperopes, as defined previously, run with and without the hyperopes). We also used a two sample t-test to compare all myopes together and emmetropes.

Bivariate contour ellipse area (BCEA) has been defined as the area of fixation for 68.2% of the time and is calculated using the following equation:

$$BCEA = \pi \chi^2 \sigma_x \sigma_y \sqrt{1 - \rho^2}$$

where σ_x and σ_y are standard deviation of the horizontal and vertical eye position, respectively, and ρ is the Pearson correlation between the horizontal and vertical eye positions during the trial, and $\chi^2 = 2.291$ is the chi-square value (2 degrees of freedom) corresponding to a probability value of 0.682 (i.e. ± 1 SD) (Raveendran et al., 2014). In our context, BCEA serves as a measure of variability in fixational as well as scanning eye movements (averaged together). BCEA has the added advantage over vertical SD in that it considers contributions from horizontal eye movements. Again, the larger the BCEA value, the larger the eye movement variability. As we did with vertical SD, we plotted BCEA in degrees²) as a function of refractive error and used least square linear regression to determine if there was a significant positive correlation between eye movement variability and amount of myopia. We used single factor ANOVA to determine if there were significant differences in BCEA between the refractive groups (high myopes, myopes, emmetropes and hyperopes, as defined previously, run with and without the hyperopes). We used a two sample t-test to

compare all myopes together and emmetropes. Additionally, we compared BCEA as a function of retinal acuity using least square linear regression.

Retinal acuity computes the limit of acuity in terms of actual distance on the retina (i.e. cycles/mm) as opposed to conventional angular measurements (i.e. cycles/deg). This is important in comparing acuity across subjects with different axial lengths, since a larger eye will form a larger retinal image of an object that has a certain angular dimension. In other words, one degree of angular subtense corresponds to a larger dimension on a long myopic eye than on a shorter emmetropic eye. In addition to comparing BCEA as a function of retinal acuity, we wanted to assess whether subjects with higher amounts of myopia had lower retinal acuity than emmetropes, as has been shown in previous studies (Coletta and Watson, 2006; Strang, Winn and Bradley, 1998). For these analyses, our first step was to use biometry and refraction data to construct a computational eye model for each subject, in Excel. This schematic eye was used to compute the subject's Retinal Magnification Factor in mm/deg, and the RMF was then used to convert acuity data in cyc/deg to retinal units of cyc/mm (Figure 16). This conversion allowed comparison of acuity across subjects as it compensated for variation in eye sizes. Both mesopic and photopic retinal acuity were compared to refractive error by least square linear regression. Additionally, acuity deficits in the mesopic condition, relative to the photopic condition, were compared across refractive error by two sample t-test and least square linear regression.

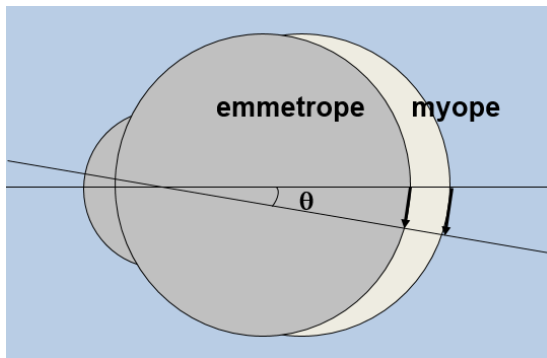


Figure 16. Retinal image size is larger in axial myopia. Acuity in angular units (cyc/deg) can be converted to retinal units (cyc/mm) using the Retinal Magnification Factor.

A previous study by Kanonidou, Proudlock, and Gottlob (2010) reported that slower reading speed is associated with more regressive saccades and longer fixation durations in people with amblyopia. This report inspired us to also assess reading duration in our subjects, both in the photopic and mesopic conditions, and to compare these durations to refractive error, visual acuity (in cpd), and eye movement variability, again, with least square linear regressions.

3.3 Results

Useful measurements were completed for 16 subjects with myopia (Mean (SE): $-5.51 \pm 3.47\text{DS}$), 14 subjects with emmetropia (Mean (SE): $+0.25 \pm 0.22\text{DS}$), and 4 subjects with hyperopia (Mean (SE): $+1.69 \pm 1.13\text{DS}$), for a total of $n=34$ subjects. Myopes were further classified into Low/Mid Myopes ($n=11$; Mean (SE): $-3.36 \pm 1.31\text{DS}$) and High Myopes ($n=5$; Mean (SE): $-10.23 \pm 0.61\text{DS}$). (See Table 2.)

Subject Group (n)	Rx (Mean SE) (Range)	Age (Mean) (Range)	Female (%)
High Myopes (5)	-10.23 ± 0.61D (-9.25 to -10.88)	25.00 yrs (24-28 yrs)	5 (100.0%)
Low/Mid Myopes (11)	-3.36 ± 1.31D (-1.50 to -5.38)	25.36 yrs (23-30 yrs)	7 (63.6%)
Emmetropes (14)	+0.25 ± 0.22D (-0.13 to +0.50)	24.64 yrs (23-27 yrs)	5 (35.7%)
Hyperopes (4)	+1.68 ± 1.13D (+0.63 to +3.00)	25.75 yrs (22-30 yrs)	3 (75.0%)

Table 2. Demographic information of subjects enrolled in the study.

Altogether, we excluded 14 of our 48 recruited subjects. The majority (eleven) of these subjects (n=3 myopes, n=4 emmetropes, and n=4 hyperopes) were excluded because we discovered during data analysis that they failed to read the Snellen equivalent of 20/20 during the experimental photopic acuity measurement. We did not expect this hiccup because all eleven of these subjects easily read the 20/20 Snellen line during our baseline vision screening. We attribute the difference in acuity measurements (vision screening vs. experimental procedure) to two factors: memorization and difference in chart design. In regards to the former, almost all of the subjects recruited for this study were optometry students and, as such, it is likely that they were very familiar with the classic Snellen visual acuity chart and may have had the 20/20 line memorized. In regards to the latter, it is well known that Snellen and ETDRS visual acuity charts exhibit several design differences – e.g., a Snellen chart has a variable number of letters per line, and variable distances between letters and rows, leading to different contour interactions. Many studies have found differences in visual acuity measured with these two charts (e.g., Kaiser, 2009). While we

preferred not to exclude such a substantial percentage of our subject pool, our IRB protocol specified an inclusion criterion of best corrected visual acuity 20/20 or better in each eye. Also, we did not want sub-optimal distance correction to confound our eye movement or mesopic acuity deficit calculations and decided that excluding these eleven subjects would provide more accurate results. (Please note that this exclusion did not apply to the *Blur Perception* experiment because that experimental procedure was completed at a distance of 40 cm.) The remaining three subjects (n=1 myope, n=1 emmetrope, and n=1 hyperope) were excluded due to poor quality eye movement data (the EyeLink failed to continuously track eye movements, possibly losing the subject's pupil center and/or corneal reflex because of misalignment, small palpebral apertures, excessive blinking, etc.).

We have summarized our results below, but want to preface this section by acknowledging that we only have a small number of subjects with high myopia and with hyperopia. Statistically, this makes for weaker conclusions. We also want to acknowledge that we did not acquire useful data from subjects with refractive errors between -5.38 and -9.25 D. This gap drove us to refine our definition of high myopia: instead of classifying subjects with ≤ -5.00 D of refractive error as high myopes (like Holden et al. (2016)), we decided to use ≤ -6.00 D.

3.3.1 Acuity vs. Refractive Error

We found that there was a strong correlation between axial length and refractive error in this group of subjects (Figure 17), which suggests that the myopia in this group of subjects

was primarily axial in nature, and, resultantly, that the longer myopic eyes should have larger retinal image sizes than the shorter, more emmetropic/hyperopic eyes.

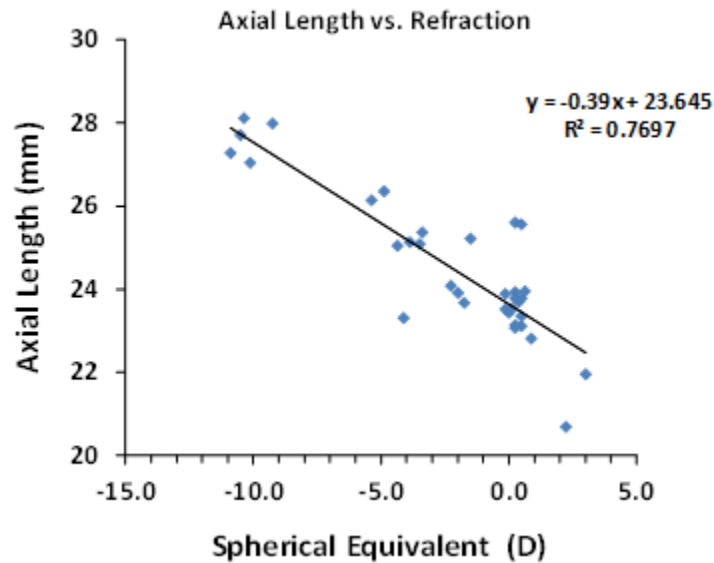


Figure 17. Axial length (in mm) plotted against spherical equivalent refraction (in Diopters) for our group of subjects.

With acuity expressed in retinal units of log cycles per mm on the retina, we found that acuity is significantly reduced in myopes in both the photopic ($p=0.002$) and mesopic ($p=0.0028$) conditions (Figure 18). With acuity expressed in conventional angular units (logMAR), there was no reduction in photopic acuity with increasing myopia ($p=0.45$) as we expected (considering our exclusion criteria), but there was a trend of decreased mesopic acuity with increasing myopia that did not reach statistical significance ($p=0.09$).

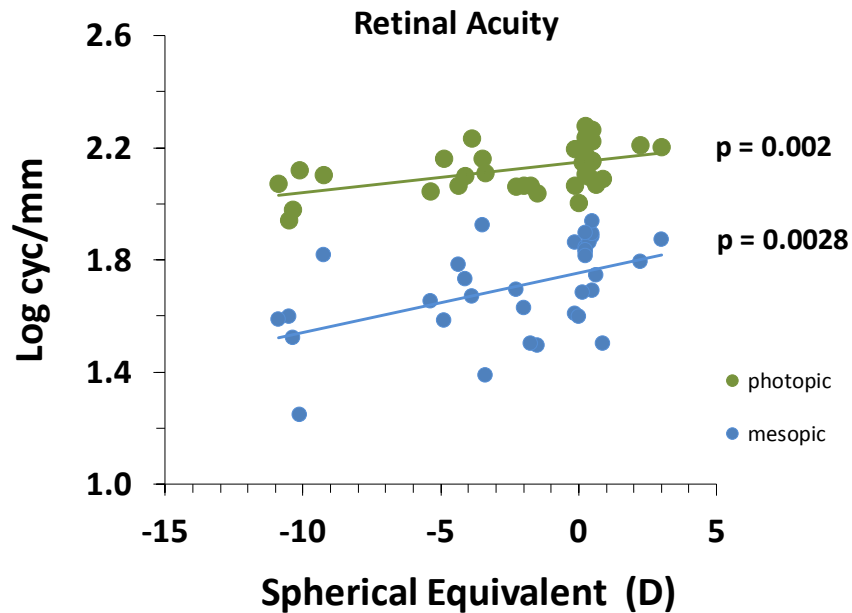


Figure 18. Retinal acuity (in log cyc/mm) plotted against spherical equivalent refraction (in Diopters), for photopic acuity (green) and mesopic acuity (blue). P-values are for the linear regressions.

Overall, subjects with higher photopic acuity had higher mesopic acuity ($p=0.0011$).

Myopes showed a relatively greater log unit loss of acuity in dim light than emmetropes (i.e. the difference between mesopic and photopic acuity increased with myopia). Figure 19 shows the mean log unit loss in mesopic acuity for all 16 myopes (high and low/mid myopes together) and for the 14 emmetropes. A two sample t-test showed that the difference in mean log unit acuity loss between myopes and emmetropes is significant ($p=0.02$). A linear regression of the relative log unit loss of mesopic acuity against refraction showed a trend of increasing acuity loss with increasing myopia but this effect did not reach significance ($p=0.09$).

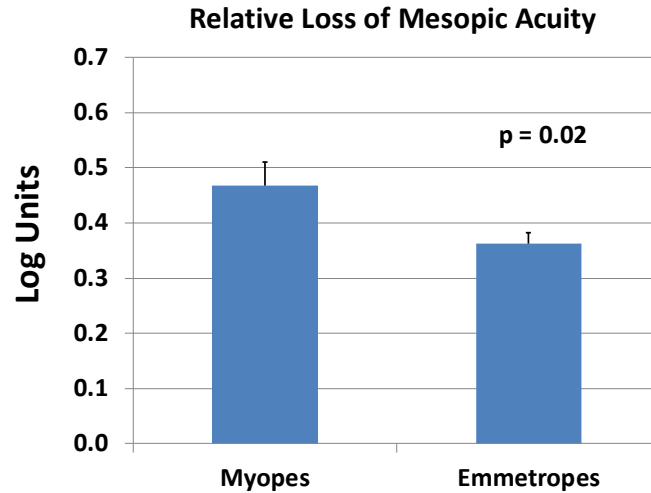


Figure 19. Mean loss of acuity in the mesopic condition relative to the photopic condition, in log units. Data are shown for all 16 myopes and 14 emmetropes. Error bars are one standard error of the mean.

3.3.2 Eye Movement Variability vs. Refractive Error

As mentioned previously, we analyzed movements when subjects read letters at their (1) mesopic VA limit, (2) photopic VA limit, and (3) when subjects read the line of letters corresponding to their mesopic VA in the photopic condition, both (a) for the entire duration of VA line reading and (b) for the duration up to the first two seconds of VA line reading. We thought that a subject's variability in eye position could possibly be influenced by the time taken to read the acuity line, so we decided to look at a shorter duration in addition to entire duration for comparison. For each subject, during each of these six conditions, we derived the standard deviation of vertical eye position (vertical SD) and bivariate contour ellipse area (BCEA). We then compared these vertical SD and BCEA values across refractive error with least squares linear regression.

For the entire duration of VA line reading, vertical SD increased significantly with increasing myopia for all three conditions: mesopic VA limit ($p=0.038$), photopic VA limit ($p=0.026$), and mesopic VA limit with photopic illumination ($p=0.0002$). BCEA also increased significantly with increasing myopia for all three conditions: mesopic VA limit ($p=0.048$), photopic VA limit ($p=0.036$), and mesopic VA limit with photopic illumination ($p=0.036$).

Similarly, for the first two seconds of VA line reading, vertical SD increased significantly with increasing myopia for all three conditions: mesopic VA limit ($p=0.013$), photopic VA limit ($p=0.029$), and mesopic VA limit with photopic illumination ($p=0.0008$). BCEA also increased significantly with increasing myopia for all three conditions: mesopic VA limit ($p=0.01$), photopic VA limit ($p=0.016$), and mesopic VA limit with photopic illumination ($p=0.028$).

The standard deviation of vertical eye position (in degrees) is plotted as means for the four refractive groups in Figure 20. Results are shown for the first 2 sec of data, for letters at the mesopic acuity limit, viewed both in mesopic (blue) and photopic (red) conditions, and for letters at the photopic acuity limit (green). High myopes appear to have much greater variability in eye movements than the other refractive groups. A single factor ANOVA for each of the three conditions showed significant differences among the four refractive groups (mesopic VA, $p=0.007$; mesopic letter at photopic, $p=0.0002$; photopic VA, $p=0.022$). A single factor ANOVA run with all myopes together in one refractive group (three refractive groups total) also showed significant differences. We realize that we cannot derive solid conclusions with so few subjects in our high myopia and hyperopia groups, and without post-

hoc testing, but we assume the significant differences found in this preliminary analysis is due to the high myopes (again, see Figure 20). A two-sample t-test comparing all myopes (high and low/mid myopes together) to emmetropes (no hyperopes included) shows no significant difference between groups ($p>0.05$).

Figure 21 shows a comparable plot for the BCEA parameter (in degrees²) for the four refractive groups, with high myopes showing much greater variability in eye movements than the other refractive groups. A single factor ANOVA showed significant difference among refractive groups for the mesopic letter size read at the photopic light level ($p=0.037$). Again, a two-sample t-test comparing all myopes to emmetropes (no hyperopes included) shows no significant difference between groups ($p>0.05$).

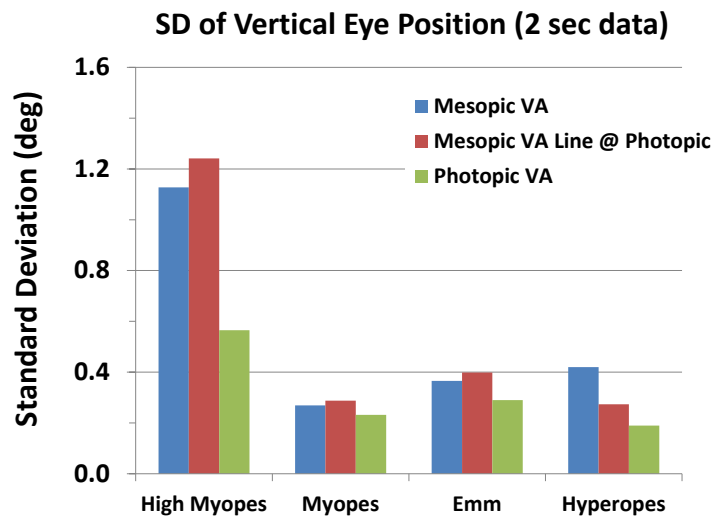


Figure 20. Mean vertical SD (in degrees) for three acuity line conditions: letters read at the mesopic acuity limit (blue), letters read at the mesopic acuity limit in photopic illumination (red), and letters read at the photopic acuity limit (green). Subjects were divided into refractive groups as detailed in Table 2.

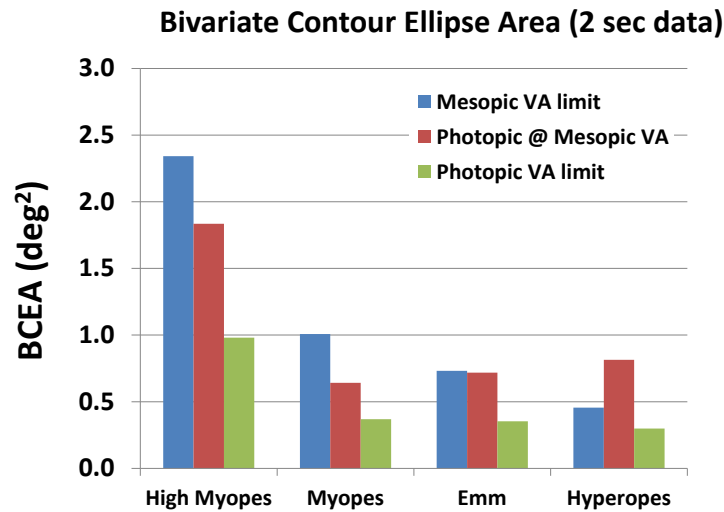


Figure 21. Mean BCEA (in degrees²) for three acuity line conditions: letters read at the mesopic acuity limit (blue), letters read at the mesopic acuity limit in photopic illumination (red), and letters read at the photopic acuity limit (green). Subjects were divided into refractive groups as detailed in Table 2.

Because we read letters in the horizontal dimension (left to right), we were concerned that subjects with worse visual acuities would have larger horizontal standard deviations simply because the letters at their acuity limit are larger and span more distance horizontally. We did not plan to report results using only the standard deviation of horizontal eye position (horizontal SD), however, we did complete this analysis. We found that horizontal SD increased significantly with increasing myopia only if averaged across the entire duration of VA line reading for the mesopic VA limit with photopic illumination ($p=0.02$). Horizontal SD was not significantly correlated with refractive error for any condition when averaged across only the first two seconds of VA line reading.

3.3.3 Eye Movement Variability and Mesopic Acuity

Subjects who exhibited less variability in eye movements under photopic conditions (i.e. smaller BCEA) had better mesopic Snellen acuity ($p=0.04$ for BCEA at photopic VA letter size; $p=0.01$ for BCEA at mesopic VA letter size) and better mesopic retinal acuity in log cyc/mm ($p=0.023$ for BCEA at photopic VA letter size; $p=0.009$ for BCEA at mesopic VA letter size).

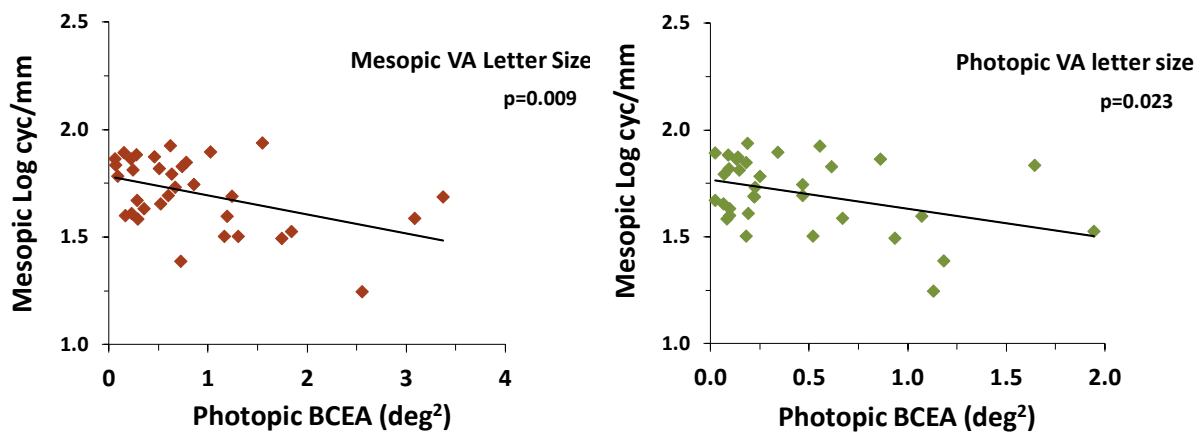


Figure 22. Mesopic retinal acuity (in log cyc/mm) plotted against photopic BCEA (in degrees²) for the letters at the mesopic acuity limit (left) and at the photopic acuity limit (right).

3.3.4 Reading Duration

We also examined the relationship between reading duration (i.e. the time taken by the subject to read each acuity line) and refractive error, acuity, and eye movement variability. First of all, the time taken to read the mesopic VA line was not correlated with the time taken to read the photopic VA line ($p=0.42$), but the time taken to read the mesopic VA line was positively correlated with the time taken to read the same line under photopic illumination ($p=0.0067$). No correlation was found between reading duration and refractive error, in any

of the three conditions (mesopic VA limit ($p=0.73$), photopic VA limit ($p=0.19$), and mesopic VA limit with photopic illumination ($p=0.33$)). In regards to reading duration vs. acuity, subjects who took longer to read the mesopic VA line had higher mesopic acuity, whether acuity was expressed in angular units (cyc/deg; $p=0.001$, as shown in Figure 23) or in retinal units (cyc/mm; $p=0.0062$). Similarly, subjects who took longer to read the mesopic VA line had less loss of acuity in dim light relative to their photopic visual acuity ($p=0.022$). Subjects who took longer to read the mesopic VA line with photopic illumination also had less relative loss of acuity in dim light ($p=0.049$).

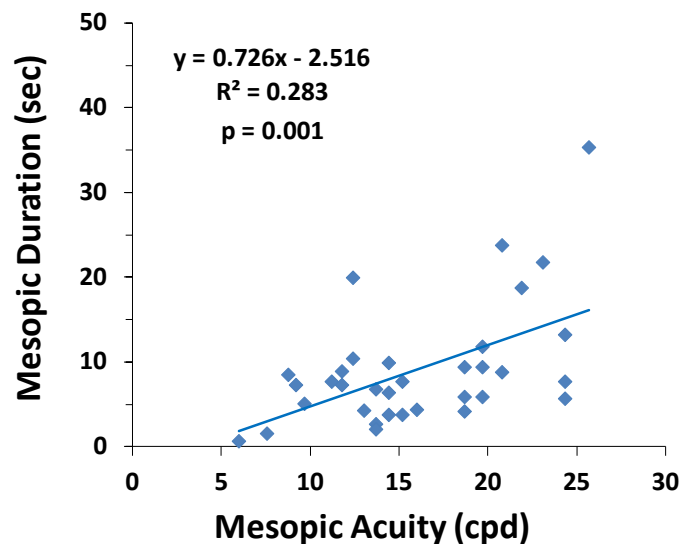


Figure 23. Duration taken to read the mesopic VA line (in seconds) plotted against mesopic acuity (in cyc/deg).

Finally, in regards to reading duration vs. eye movement variability, subjects who took longer to read the mesopic VA line under photopic illumination had less variability as measured by vertical SD ($p=0.01$), BCEA ($p=0.024$), or horizontal SD ($p=0.03$).

3.4 Discussion

In this study, we assessed eye movements during a visual acuity task under photopic and mesopic lighting conditions, and then related those eye movements to refractive error and visual acuity. Our hypothesis was that subjects with myopia would show a greater variability in eye movements compared to emmetropes and hyperopes. We also predicted that myopes would show a greater loss of visual acuity in the mesopic condition relative to the photopic condition, as has been demonstrated in previous studies. While it is more likely that decreased visual acuity (i.e. impaired sensory control) is causing larger variability in eye movements in myopes, we think that it could be possible that greater variability in eye movements could be contributing to their greater loss of visual acuity in dim illumination.

Our main finding was that vertical eye position (as measured by standard deviation) was more variable in subjects with high myopia than in subjects with other refractive errors in all conditions and, similarly, that the bivariate contour ellipse area of eye movement was larger in subjects with high myopia in all conditions. Additionally, myopes tended to show a greater log unit loss of acuity in dim illumination as we expected, consistent with earlier findings (e.g., Coletta, Frericks and Groves, ARVO 2007; Coletta et al., ARVO 2008). In relating eye movements to acuity, we found that subjects with less variability in eye movements (i.e. smaller BCEA) under photopic conditions had better mesopic Snellen acuity and better mesopic retinal acuity (in cyc/mm). This suggests that greater variability in eye position is associated with greater loss of acuity in dim light.

In reviewing the existing eye movements literature, there does not seem to be a previous study that is comparable to ours. In fact, there seems to be a scarcity of research on eye

movements across refractive groups, in general. Consequently, we cannot say for sure why myopes would show greater variability in eye position during an acuity task. Researchers have shown that amblyopic eyes (with reduced visual acuity) show a greater variability in eye position than fellow non-amblyopic eyes and normal control eyes (Chung et al., 2015; Raveendran et al., 2014). We acknowledge that subjects with amblyopia are not a reasonable model for subjects with myopia, as the former suffer from a developmental anomaly and have poor spatial vision. Still, we wonder if these findings are in some way analogous to our findings in subjects with high myopia. There is a definite association between eye movement stability and visual acuity, but the question that remains is whether eye movement variability is causing reduced visual acuity or if reduced visual acuity is causing eye movement variability.

Chung et al. (2015) list reasons to believe the former (eye movement variability causes reduced visual acuity). Namely, Chung and Bedell (1995) found that incessant retinal image motion degrades acuity in subjects with congenital nystagmus and that random jittering of an acuity target (which simulates retinal image motion) also degrades acuity in observers with normal vision. The assumption behind these findings is that, with unsteady eye movements, the acuity target falls on several different locations on the retina, causing positional uncertainty and rendering it difficult for the observer to integrate information over time and space (Chung et al., 2015).

On the other hand, Hess (1977) compared the grating acuity of two strabismic amblyopes under stabilized (using afterimages) and unstabilized conditions, and found that eye movements did not play a large role in reducing acuity. As we mentioned previously, it could

be possible that microsaccades actually improve the sampling efficiency of fine spatial detail. It follows, then, that greater eye movement variability could be a result of the visual system attempting to overcome reduced visual acuity (i.e. reduced visual acuity causes greater eye movement variability). In regards to myopes, it is well established that cone photoreceptor packing density is lower in myopic eyes (i.e. there are larger spaces between cones) (e.g., Chui, Song and Burns, 2008; Coletta and Watson, 2006). Perhaps the visual system is required to use larger eye movements in order to project the target image adequately across a coarser neural grain. Or, perhaps retinal stretching causes some amount of damage to inner retinal neurons in myopic eyes, requiring larger eye movements to refresh perception. In other words, eye movements with larger amplitudes may be required in myopes (in comparison to emmetropes and hyperopes) so that they may integrate a similar amount of information and form a similar (but perhaps imperfect) overall perception of the target. Perhaps this mechanism is more evident in situations that place higher demands on the visual system (e.g., dim lighting conditions). Indeed, Otero-Millan et al. (2008) found that microsaccade generation increases as the difficulty of the visual task increases (e.g., there were increased rates of microsaccades in a Where's Waldo visual search than in free visual exploration).

If we suppose that eye movement variability is the limiting factor on visual acuity, we must consider other reasons (other than visual acuity or coarser neural grain) for why eye movements are more variable with increasing amounts of myopia. Interestingly, Alhazmi, Seidel and Gray (2014) found that subjects with low ocular rigidity (myopes) had saccades with decreased peak velocities and longer total response times in comparison to subjects with

high ocular rigidity (hyperopes). This suggests that there are differences in the physics behind moving a larger, softer eyeball (i.e. the eyeball of an axial myope). Perhaps eye movement variability in high myopes is due, at least in part, to structural characteristics of the eyeballs themselves. It is important to note that eye movement variability due to ocular size and rigidity does not explain the greater acuity loss in mesopic conditions seen by myopes in comparison to emmetropes.

In addition to relating eye movements to refractive error and visual acuity, we explored whether there were associations between reading duration and refractive error, visual acuity, and eye movement variability. There was no correlation between reading duration and refractive error, but we did find that subjects who took longer to perform the mesopic acuity task generally had better mesopic acuity and also a smaller acuity loss in the mesopic condition relative to the photopic condition. Unsurprisingly, this implies that spending more time to read letters in dim light may assist in increasing acuity.

Additionally, we found that subjects who took longer to perform the mesopic acuity task in photopic illumination had less variability in eye movements. A previous study by Kanonidou, Proudlock, and Gottlob (2010) reported that slower reading speed is associated with more regressive saccades and longer fixation durations in people with amblyopia. Our findings show the opposite, implying that faster reading speed in an acuity task (instead of slower) is associated with larger variabilities in eye movements. Perhaps this difference in findings is due to the task itself. Visual strategies during an acuity task may not be the same as during a normal text reading task.

To our knowledge, there have been a handful of previous studies that have examined eye movements in dark environments (though, none during an acuity task and none comparing across refractive groups). Most of these studies measured eye movements in humans in complete darkness, and found that microsaccades are larger and less frequent without a visual target to guide fixation (e.g., Martinez-Conde, Macknik and Hubel, 2004). This finding does not entirely apply to our study, as we had appreciable visual stimuli in our mesopic condition, but it might be interesting to investigate the frequency of microsaccades per acuity line across refractive groups in future studies. There have also been a couple of studies that have measured eye movements in humans and monkeys while varying the background luminance behind a fixation spot (Barash et al., 1998; Snodderly, 1987). These studies found that dark backgrounds lead to a fixational upshift (i.e. the eyes tend to fixate above the fixation target), perhaps so that the line of gaze falls on a retinal area with a greater distribution of rod photoreceptors (Barash et al., 1998; Snodderly, 1987). This suggests another interesting avenue for future studies—that is, analyzing eye movements for consistent directional shifts during an acuity task in dim illumination and comparing findings across refractive groups.

As mentioned previously, a limitation of the present study is that we only have a small number of subjects with high myopia and with hyperopia, and we did not acquire useful data from subjects with refractive errors between -5.38 and -9.25 D. Statistically, this makes for weaker conclusions. We are confident that there is a significant trend in our data showing that high myopes have greater eye movement variability than the other subjects, but further

investigations will still be necessary (with larger numbers of high myopic and hyperopic subjects) to confirm this finding.

We recognize that our eye movements data may have been affected by a number of different factors: EyeLink calibration, fatigue, level of interest (i.e. attention), dryness with contact lens wear, etc. Special care was taken to calibrate the EyeLink machine as carefully as possible, and to give identical and specific instructions to all subjects before the visual acuity task. We also had lubricating drops on hand to offer our subjects should they experience subjective dryness.

Another potential limitation of this study is that we only assessed eye movements monocularly. We did so to match the conditions of previous studies showing corrected myopes show a greater deficit in visual acuity in low luminance than emmetropes (e.g., Coletta, Frericks and Groves, ARVO 2007; Coletta et al., ARVO 2008). Multiple studies, using different recording systems, have found that microsaccades are generally conjugate between the two eyes (e.g., Martinez-Conde, Macknik and Hubel, 2004; Otero-Millan, Macknik and Martinez-Conde, 2014). That is, most microsaccades have the same direction in both eyes (unless they are correcting for errors in vergence) and similar magnitudes (Otero-Millan, Macknik and Martinez-Conde, 2014). So, it may be that our monocular eye movement recordings are good estimates of overall binocular eye movements, but we cannot say for sure. It is more likely that microsaccades are conjugate in order to maintain binocular alignment and that there may be functional differences in eye movements monocularly. Further investigations will be necessary to evaluate the effect of binocularity on eye movements across refractive groups.

4. GENERAL CONCLUSIONS & SUMMARY

Our *Blur Perception* study shows that, for all subjects, responses to blur worsen in the visual periphery due to the observers' (1) increased intrinsic blur and (2) decreased blur sensitivity in the periphery. Our study stands apart from existing literature because we compared blur sensitivity under monocular and binocular conditions. We have found that binocularity improves visual blur perception, both by reducing the amount of intrinsic blur in the visual system, and by improving blur sensitivity at the fovea. This latter point suggests that there may be additional binocular processing of blur in the center of the visual field. Overall, we did not find a significant effect of refractive group on blur detection or blur discrimination thresholds, but we did find that myopes have, on average, worse blur sensitivity than emmetropes monocularly but not binocularly. This suggests that myopes may process blur less efficiently than emmetropes under monocular conditions, and we could speculate that, if a child's binocular vision is slow to fully develop, that child might suffer from decreased blur sensitivity during the emmetropization period and may be at greater risk for myopia development. Further studies will be necessary to evaluate the effect of binocularity and the effect of different types of blur on blur sensitivity. Further studies with more hyperopic subjects and children will be necessary if we hope to fully understand the relationship between blur sensitivity and refractive error development.

Our *Eye Movements* study shows that eye movement variability (as measured by vertical SD and BCEA) increases with increasing amounts of myopia, and is most substantial in the

high myopia subject group (≤ -6.00 D). Additionally, myopes tend to show a greater log unit loss of acuity in dim illumination in comparison to emmetropes and hyperopes. In relating eye movements to acuity, we found that subjects with less eye movement variability (i.e. smaller BCEA) under photopic conditions had better mesopic Snellen acuity and better mesopic retinal acuity (in cyc/mm). This suggests that greater variability in eye position is associated with greater loss of acuity in dim light, but the question that remains is whether reduced visual acuity is causing eye movement variability or if eye movement variability is causing reduced visual acuity. Further studies, with a larger number of high myopic and hyperopic subjects, will be necessary to confirm our findings, and further studies will be necessary to evaluate the effect of binocularity on eye movements across refractive groups.

5. BIBLIOGRAPHY

- Abbott, M., Schmid, K., & Strang, N. (1998). Differences in the accommodation stimulus response curves of adult myopes and emmetropes. *Ophthalmic and Physiological Optics*, 18(1): 13-20.
- Ahissar, E., Arieli, A., Fried, M., & Bonneh, Y. (2016). On the possible roles of microsaccades and drifts in visual perception. *Vision Research*, 118, 25-30.
- Alhazmi, M., Seidel, D., & Gray, L.S. (2014). The effect of ocular rigidity upon the characteristics of saccadic eye movements. *Investigative Ophthalmology & Visual Science*, 55(3): 1251-1258.
- Anderson, R.S., McDowell, D.R., & Ennis, F.A. (2001). Effect of localized defocus on detection thresholds for different sized targets in the fovea and periphery. *Acta Ophthalmologica Scandinavica*, 79, 60-63.
- Anstice, N., & Phillips, J. (2011). Effect of dual-focus soft contact lens wear on axial myopia progression in children. *Ophthalmology*, 118(6): 1152-1161.
- Arnold, D.H., Grove, P.M., & Wallis, T.S.A. (2007). Staying focused: A functional account of perceptual suppression during binocular rivalry. *Journal of Vision*, 7(7): 7.
- Atchison, D., Jones, C., Schmid, K., Pritchard, N., Pope, J., Strugnell, W., & Riley, R. (2004). Eye shape in emmetropia and myopia. *Investigative Ophthalmology & Visual Science*, 45(10): 3380-3386.
- Banton, T., & Levi, D.M. (1991). Binocular summation in vernier acuity. *Journal of the Optical Society of America A*, 8(4): 673-680.
- Barash, S., Melikyan, A., Sivakov, A., & Tauber, M. (1998). Shift of visual fixation dependent on background illumination. *Journal of Neurophysiology*, 79(5): 2766-2781.
- Bartmann, M., & Schaeffel, F. (1994). A simple mechanism for emmetropization without cues from accommodation or colour. *Vision Research*, 34(7): 873-876.
- Bordenave, C., Gousseau, Y., & Roueff, F. (2006). The dead leaves model: a general tessellation modeling occlusion. *Advances in Applied Probability*, 38(1): 31-46.
- Bourne, R., Stevens, G., White, R., Smith, J., Flaxman, S., Price, H., Jonas, J., Keeffe, J., Leasher, J., Naidoo, K., Pesudovs, K., Resnikoff, S., & Taylor, H. (2013). Causes of vision loss worldwide, 1990-2010: a systematic analysis. *The Lancet*, 1, e339-e349.

- Campbell, F.W. (1957). The depth of field of the human eye. *Journal of Modern Optics*, 4(4): 157-164.
- Chin, M., Chu, P., Cheong, A., & Chan, H. (2015). Human electroretinal responses to grating patterns and defocus changes by global flash multifocal electroretinogram. *PLOS One*, 10(4): 1-21.
- Cho, P., & Cheung, S. (2012). Retardation of myopia in orthokeratology (ROMIO) study: A 2-Year randomized clinical trial. *Investigative Ophthalmology & Visual Science*, 53(11): 7077-7085.
- Christman, S. (1990). Effects of luminance and blur on hemispheric asymmetries in temporal integration. *Neuropsychologia*, 28(4): 361-374.
- Chui, T.Y.P., Song, H., & Burns, S.A. (2008). Individual variations in human cone photoreceptor packing density: Variations with refractive error. *Investigative Ophthalmology & Visual Science*, 49(10): 4679-4687.
- Chung, S.T.L., & Bedell, H.E. (1995). Effect of retinal image motion on visual acuity and contour interaction in congenital nystagmus. *Vision Research*, 35, 3071-3082.
- Chung, S.T.L., Jarvis, S., & Cheung, S. (2007). The effect of dioptric blur on reading performance. *Vision Research*, 47(12): 1584-1594.
- Chung, S.T.L., Kumar, G., Li, R.W., & Levi, D.M. (2015). Characteristics of fixational eye movements in amblyopia: Limitations on fixational stability and acuity? *Vision Research*, 114, 87-99.
- Ciuffreda, K.J., Wang, B., & Vasudevan, B. (2007). Conceptual model of human blur perception. *Vision Research*, 47(9): 1245-1252.
- Ciuffreda, K.J., Wang, B., & Wong, D. (2005). Central and near peripheral retinal contributions to the depth-of-focus using naturalistic stimulation. *Vision Research*, 45, 2650-2658.
- Coletta, N.J., Frericks, M., & Groves, R. (2007). Mesopic visual acuity in myopia. *Investigative Ophthalmology & Visual Science*, 48 (ARVO E-abstract 1009).
- Coletta, N., & Moskowitz, A. (2003). Wavefront aberrations and mesopic visual performance following soft contact lens removal. *Journal of Vision*, 3(12): 37a.

- Coletta, N.J., Raghuram, A., Nguyen, T., & Rondon, M. (2008). Neural contribution to the mesopic acuity deficit in myopia. *Investigative Ophthalmology & Visual Science*, 49 (ARVO E-abstract 1434).
- Coletta, N. & Watson, T. (2006). Effect of myopia on visual acuity measured with laser interference fringes. *Vision Research*, 46(5): 636-651.
- Cufflin, M.P., Mankowska, A., & Mallen, E.A. (2007). Effect of blur adaptation on blur sensitivity and discrimination in emmetropes and myopes. *Investigative Ophthalmology & Visual Science*, 48(6): 2932-2939.
- Dabir, S., Mangalesh, S., Schouten, J.S., Berendschot, T.T., Kurian, M.K., Kumar, A.K., Yadav, N.K., & Shetty, R. (2015). Axial length and cone density as assessed with adaptive optics in myopia. *Indian Journal of Ophthalmology*, 63(5): 423-426.
- Diether, S., & Schaeffel, F. (1997). Local changes in eye growth induced by imposed local refractive error despite active accommodation. *Vision Research*, 37(6): 659-668.
- Dolgin, E. (2015). The myopia boom. *Nature*. 519, 276-278.
- Donner, K. & Hemilä, S. (2007). Modelling the effect of microsaccades on retinal responses to stationary contrast patterns. *Vision Research*. 47, 1166-1177.
- EyeLink 1000 User Manual. SR Research Ltd., Mississauga, Ontario, Canada. Version 1.5.0, 2005-2009.
- Fan, Q., Wojciechowski, R., Ikram, M., Cheng, C., Chen, P., Zhou, X., Pan, C., Khor, C., Tai, E., Aung, T., Wong, T., Teo, Y., & Saw, S. (2014). Educational influences the association between genetic variants and refractive error: a meta-analysis of five Singapore studies. *Human Molecular Genetics*, 23(2): 546-554.
- Field, D., & Brady, N. (1997). Visual sensitivity, blur and the sources of variability in the amplitude spectra of natural scenes. *Vision Research*, 37(23): 3367-3383.
- Fisher, S.K., & Ciuffreda, K.J. (1988). Accommodation and apparent distance. *Perception*, 17(5): 609-621.
- Flitcroft, D., Judge, S., & Morley, J. (1992). Binocular interactions in accommodation control: effects of anisometric stimuli. *The Journal of Neuroscience*, 12(1): 188-203.
- Fricke, T., Holden, B., Wilson, D., Schlenther, G., Naidoo, K., Resnikoff, S., & Frick, K. (2012). Global cost of correcting vision impairment from uncorrected refractive error. *Bulletin of the World Health Organization*. 90, 728-738.

- George, S., & Rosenfield, M. (2004). Blur adaptation and myopia. *Optometry and Vision Science*, 81(7): 543-547.
- Ghasia, F.F., & Shaikh, A.G. (2015). Uncorrected myopic refractive error increases microsaccade amplitude. *Investigative Ophthalmology & Visual Science*, 56(4): 2531-2535.
- Ghosh, A., Zheleznyak, L., Barbot, A., Jung, H., & Yoon, G. (2017). Neural adaptation to peripheral blur in myopes and emmetropes. *Vision Research*. 132, 69-77.
- Gilchrist, I.D., Brown, V., & Findlay, J.M. (1997). Saccades without eye movements. *Nature*. 390, 130-131.
- Grosvenor, T. (2003). Why is there an epidemic of myopia? *Clinical and Experimental Optometry*, 86(5): 273-275.
- Gwiazda, J., Bauer, J., Thorn, F., & Held, R. (1995). A dynamic relationship between myopia and blur-driven accommodation in school-aged children. *Vision Research*, 35(9): 1299-1304.
- Hafed, Z., Chen, C., & Tian, X. (2015). Vision, perception, and attention through the lens of microsaccades: Mechanisms and implications. *Frontiers in Systems Neuroscience*. 9, 1-16.
- Hartwig, A., Gowen, E., Charman, W.N., & Radhakrishnan, H. (2013). Binocular saccades in myopes and emmetropes. *Optometry and Vision Science*. 90(9): 980-987.
- Held, R., Cooper, E., & Banks, M. (2012). Blur and disparity are complementary cues to depth. *Current Biology*, 22(5): 426-431.
- Heravian J., Jenkins, T., & Douthwaite, W. (1990). Binocular summation in visually evoked responses and visual acuity. *Ophthalmic and Physiological Optics*, 10(3): 257-261.
- Hess, R.F. (1977). Eye movements and grating acuity in strabismic amblyopia. *Ophthalmic Research*. 9, 225-237.
- Hiraoka, T., Kakita, T., Okamoto, F., Takahashi, H. & Oshika, T. (2012). Long-term effect of overnight orthokeratology on axial length elongation in childhood myopia: A 5-year follow-up study. *Investigative Ophthalmology & Visual Science*, 53(7): 3913-3919.
- Hodos, W., & Kuenzel, W. (1984). Retinal-image degradation produces ocular enlargement in chicks. *Investigative Ophthalmology & Visual Science*, 25(6): 652-659.

- Hoffman, D.M., & Banks, M.S. (2010). Focus information is used to interpret binocular images. *Journal of Vision*, 10(5): 13, 1-17.
- Holden, B., Fricke, T., Wilson, D., Jong, M., Naidoo, K., Sankaridurg, P., Wong, T., Naduvilath, T., & Resnikoff, S. (2016). Global prevalence of myopia and high myopia and temporal trends from 2000 through 2050. *Ophthalmology*, 123(5): 1036-1042.
- Hoogerheide, J., Rempt, F., & Hoogenboom, W.P. (1971). Acquired myopia in young pilots. *Ophthalmologica*. 163, 209-215.
- Ibbotson, M., & Kregelberg, B. (2011). Visual perception and saccadic eye movements. *Current Opinion in Neurobiology*. 21, 1-6.
- Jacobs, R., Smith, G., & Chan, C. (1989). Effect of defocus on blur thresholds and on thresholds of perceived change in blur: Comparison of source and observer methods. *Optometry and Vision Science*, 66(8): 545–553.
- Jiang, B., & Morse, S.E. (1999). Oculomotor functions and late-onset myopia. *Ophthalmic and Physiological Optics*, 19(2): 165-172.
- Kaiser, P. (2009). Prospective evaluation of visual acuity assessment: A comparison of Snellen versus ETDRS charts in clinical practice (An AOS thesis). *Transactions of the American Ophthalmological Society*. 107, 311-324.
- Kanonidou, E., Proudlock, F.A., & Gottlob, I. (2010). Reading strategies in mild to moderate strabismic amblyopia: An eye movement investigation. *Investigative Ophthalmology & Visual Science*, 51(7): 3502-3508.
- Kerber, K.L. (2016). Peripheral vision, accommodation and blur perception in myopia (Master's thesis). New England College of Optometry, Boston, Massachusetts, USA.
- Knight-Nanan, D., & O'Keefe, M. (1996). Refractive outcome in eyes with retinopathy of prematurity treated with cryotherapy or diode laser: 3 year follow up. *British Journal of Ophthalmology*. 80, 998-1001.
- Kompaniez, E., Sawides, L., Marcos, S., & Webster, M.A. (2013). Adaptation to interocular differences in blur. *Journal of Vision*, 13(6): 19, 1-14.
- Krauzlis, R.J., Goffart, L., & Hafed, Z.M. (2016). Neuronal control of fixation and fixational eye movements. *Philosophical Transactions of the Royal Society B*. 372, 1-12.
- Kruger, P., & Pola, J. (1986). Stimuli for accommodation: blur, chromatic aberration and size. *Vision Research*, 26(6): 957-971.

- Lam, C.S.Y., Tang, W.C., Tse, D.Y., Tang, Y.Y., & To, C.H. (2014). Defocus incorporated soft contact (DISC) lens slows myopia progression in Hong Kong Chinese schoolchildren: A 2-year randomised clinical trial. *British Journal of Ophthalmology*, 98, 40-45.
- Lee, A.B., Mumford, D., & Huang, J. (2001). Occlusion models for natural images: A statistical study of scale-invariant dead leaves model. *International Journal of Computer Vision*, 41(1-2): 35-59.
- Legge, G.E. (1984a). Binocular contrast summation—I. Detection and discrimination. *Vision Research*, 24(4): 373-383.
- Legge, G.E. (1984b). Binocular contrast summation—II. Quadratic summation. *Vision Research*, 24(4): 385-394.
- Lopez-Gil, N., Martin, J., Liu, T., Bradley, A., Diaz-Munoz, D., & Thibos, L.N. (2013). Retinal image quality during accommodation. *Ophthalmic and Physiological Optics*, 33(4): 497-507.
- Lundström, L., Manzanera, S., Prieto, P.M., Ayala, D.B., Gorceix, N., Gustafsson, J., Unsbo, P., & Artal, P. (2007). Effect of optical correction and remaining aberrations on peripheral resolution acuity in the human eye. *Optics Express*, 15(20): 12654-12661.
- Maiello, G., Chessa, M., Solari, F., & Bex, P.J. (2014). Simulated disparity and peripheral blur interact during binocular fusion. *Journal of Vision*, 14(8): 13, 1-14.
- Maiello, G., Walker, L., Bex, P.J., & Vera-Diaz, F.A. (2017). Blur perception throughout the visual field in myopia and emmetropia. *Journal of Vision*, 17(5): 3, 1-13.
- Martinez-Conde, S., & Macknik, S.L. (2008). Fixational eye movements across vertebrates: Comparative dynamics, physiology, and perception. *Journal of Vision*, 8(14): 28, 1-16.
- Martinez-Conde, S., Macknik, S.L., & Hubel, D.H. (2004). The role of fixational eye movements in visual perception. *Nature Reviews Neuroscience*, 5, 229-240.
- Martinez-Conde, S., Macknik, S.L., Troncoso, X.G., & Dyar, T.A. (2006). Microsaccades counteract visual fading during fixation. *Neuron*, 49, 297-305.
- Mather, G., & Smith, D.R. (2002). Blur discrimination and its relation to blur-mediated depth perception. *Perception*, 31(10): 1211-1219.
- McBrien, N., & Gentle, A. (2003). Role of the sclera in the development and pathological complications of myopia. *Progress in Retinal and Eye Research*, 22, 307-338.

- McFadden, S.A., Tse, D.Y., Bowrey, H.E., Leotta, A.J., Lam, C.S., Wildsoet, C.F., & To, C.H. (2014). Integration of defocus by dual power Fresnel lenses inhibits myopia in the mammalian eye. *Investigative Ophthalmology & Visual Science*, 55(2): 908-917.
- Morgan, M., Chubb, C., & Solomon, J.A. (2008). A 'dipper' function for texture discrimination based on orientation variance. *Journal of Vision*, 8(11): 9, 1-8.
- Murray, S., & Bex, P.J. (2010). Perceived blur in naturally contoured images depends on phase. *Frontiers in Psychology*. 1, 1-12.
- Mutti, D.O., Mitchell, G.L., Moeschberger, M.L., Jones, L.A., and Zadnik, K. (2002). Parental myopia, near work, school achievement, and children's refractive error. *Investigative Ophthalmology & Visual Science*. 43, 3633-3640.
- Nathan, J., Kiely, P., Gillard Crewther, S., & Crewther, D. (1985). Disease-associated visual image degradation and spherical refractive errors in children. *American Journal of Optometry & Physiological Optics*, 62(10): 680-688.
- Nickla, D., Sharda, V., & Troilo, D. (2005). Temporal integration characteristics of the axial and choroidal responses to myopic defocus induced by prior form deprivation versus positive spectacle lens wear in chickens. *Optometry and Vision Science*, 82(4): 318-327.
- Nickla, D., Wildsoet, C., & Wallman, J. (1998). Visual influences on diurnal rhythms in ocular length and choroidal thickness in chick eyes. *Experimental Eye Research*. 66, 163-181.
- Norton, T.T., Essinger, J.A., & McBrien, N.A. (1994). Lid-suture myopia in tree shrews with retinal ganglion cell blockade. *Visual Neuroscience*. 11, 143-153.
- Norton, T.T., Siegwart, J.T., & Amedo, A.O. (2006). Effectiveness of hyperopic defocus, minimal defocus, or myopic defocus in competition with a myopiagenic stimulus in tree shrew eyes. *Investigative Ophthalmology & Visual Science*, 47(11): 4687-4699.
- Otero-Millan, J., Macknik, S.L., & Martinez-Conde, S. (2014). Fixational eye movements and binocular vision. *Frontiers in Integrative Neuroscience*, 8(52): 1-10.
- Otero-Millan, J., Troncoso, X.G., Macknik, S.L., Serrano-Pedraza, I., & Martinez-Conde, S. (2008). Saccades and microsaccades during visual fixation, exploration, and search: Foundations for a common saccadic generator. *Journal of Vision*, 8(14): 21, 1-18.
- Päakkönen, A.K., & Morgan, M.J. (1994). Effects of motion on blur discrimination. *Journal of the Optical Society of America A*, 11(3): 992-1002.

- Pan, C., Ramamurthy, D., & Saw, S. (2012). Worldwide prevalence and risk factors for myopia. *Ophthalmic and Physiological Optics*, 32, 3-16.
- Pitkow, X. (2010). Exact feature probabilities in images with occlusion. *Journal of Vision*, 10(14): 42, 1-20.
- Plainis, S., Petratos, D., Giannakopoulou, T., Atchison, D.A., & Tsilimbaris, M.K. (2011). Binocular summation improves performance to defocus-induced blur. *Investigative Ophthalmology & Visual Science*, 52(5): 2784-2789.
- Poulere, E., Moschandreas, J., Kontadakis, G.A., Pallikaris, I.G., & Plainis, S. (2013). Effect of blur and subsequent adaptation on visual acuity using letter and Landolt C charts: differences between emmetropes and myopes. *Ophthalmic and Physiological Optics*, 33(2): 130-137.
- Radhakrishnan, H., Pardhan, S., Calver, R., & O'Leary, D. (2004). Unequal reduction in visual acuity with positive and negative defocusing lenses in myopes. *Optometry and Vision Science*, 81(1): 14-17.
- Raveendran, R.N., Babu, R.J., Hess, R.F., & Bobier, W.R. (2014). Transient improvements in fixational stability in strabismic amblyopes following bifoveal fixation and reduced interocular suppression. *Ophthalmic and Physiological Optics*, 34, 214-225.
- Ronchi, L., & Molesini, G. (1975). Depth of focus in peripheral vision. *Ophthalmic Research*, 7(3): 152-157.
- Rose, K., French, A., & Morgan, I. (2016). Environmental factors and myopia: Paradoxes and prospects for prevention. *Asia-Pacific Journal of Ophthalmology*, 5(6): 403-410.
- Rosen, R., Lundstrom, L., & Unsbo, P. (2011). Influence of optical defocus on peripheral vision. *Investigative Ophthalmology & Visual Science*, 52(1): 318-323.
- Rosenfield, M., & Abraham-Cohen, J.A. (1999). Blur sensitivity in myopes. *Optometry and Vision Science*, 76(5): 303-307.
- Ross, J., Morrone, M.C., & Burr, D.C. (1997). Compression of visual space before saccades. *Nature*, 386, 598-601.
- Sankaridurg, P., Donovan, L., Varnas, S., Ho, A., Chen, X., Martinez, A., Fisher, S., Lin, Z., Smith, E.L., III, Ge, J., & Holden, B. (2010). Spectacle lenses designed to reduce progression of myopia: 12-month results. *Optometry and Vision Science*, 87(9): 631-641.

- Schaeffel, F., & Feldkaemper, M. (2015). Animal models in myopia research. *Clinical and Experimental Optometry*. 98, 507-517.
- Schmid, K.L., Iskander, D.R., Li, R.W., Edwards, M.H., & Lew, J.K. (2002). Blur detection thresholds in childhood myopia: single and dual target presentation. *Vision Research*, 42(2): 239-247.
- Schmid, K.L., & Wildsoet, C.F. (1997). Contrast and spatial-frequency requirements for emmetropization in chicks. *Vision Research*, 37(15): 2011-2021.
- Schor, C. (1999). The influence of interactions between accommodation and convergence on the lag of accommodation. *Ophthalmic and Physiological Optics*, 19(2): 134-150.
- Sieving, P.A., & Fishman, G.A. (1978). Refractive errors of retinitis pigmentosa patients. *British Journal of Ophthalmology*. 62, 163-167.
- Smith E.L., III, & Hung, L. (1999). The role of optical defocus in regulating refractive development in infant monkeys. *Vision Research*. 39, 1415-1435.
- Smith E.L., III, Hung, L., & Huang, J. (2009). Relative peripheral hyperopic defocus alters central refractive development in infant monkeys. *Vision Research*. 49, 2386-2392.
- Smith E.L., III, Kee, C., Ramamirtham, R., Qiao-Grider, Y., & Hung, L. (2005). Peripheral vision can influence eye growth and refractive development in infant monkeys. *Investigative Ophthalmology & Visual Science*, 46(11): 3965-3972.
- Smith E.L., III, Ramamirtham, R., Qiao-Grider, Y., Hung, L., Huang, J., Kee, C., Coats, D., & Paysse, E. (2007). Effects of foveal ablation on emmetropization and form-deprivation myopia. *Investigative Ophthalmology & Visual Science*, 48(9): 3914-3922.
- Smith, T., Frick, K., Holden, B., Fricke, T., & Naidoo, K. (2009). Potential lost productivity resulting from the global burden of uncorrected refractive error. *Bulletin of the World Health Organization*. 87, 431-437.
- Snodderly, D.M. (1987). Effects of light and dark environments on macaque and human fixational eye movements. *Vision Research*, 27(3): 401-415.
- Snodderly, D.M. (2016). A physiological perspective on fixational eye movements. *Vision Research*. 118, 31-47.
- Strang, N.C., Day, M., Gray, L.S., & Seidel, D. (2011). Accommodation steps, target spatial frequency and refractive error. *Ophthalmic and Physiological Optics*, 31(5): 444-455.

- Strang, N.C., Winn, B., & Bradley, A. (1998). The role of neural and optical factors in limiting visual resolution in myopia. *Vision Research*, 38, 1713-1721.
- Troilo, D., Gottlieb, M.D., & Wallman, J. (1987). Visual deprivation causes myopia in chicks with optic nerve section. *Current Eye Research*, 6, 993-999.
- Vishwanath, D. (2012). The utility of defocus blur in binocular depth perception. *i-Perception*, 3(8): 541-546.
- Vishwanath, D., & Blaser, E. (2010). Retinal blur and the perception of egocentric distance. *Journal of Vision*, 10(10): 26, 1-16.
- Vul, E., Bergsma, J., & MacLeod, D.I. (2010). Functional adaptive sequential testing. *Seeing and Perceiving*, 23(5): 483-515.
- Wallis T.S., & Bex, P.J. (2012). Image correlates of crowding in natural scenes. *Journal of Vision*, 12(7): 6, 1-19.
- Wallman, J., Gottlieb, M.D., Rajaram, V., & Fugate-Wentzek, L.A. (1987). Local retinal regions control local eye growth and myopia. *Science*, 237, 73-77.
- Wallman, J., Wildsoet, C., Xu, A., Gottlieb, M.D., Nickla, D.L., Marran, L., Krebs, W., & Christensen, A.M. (1994). Moving the retina: Choroidal modulation of refractive state. *Vision Research*, 35(1): 37-50.
- Wallman, J., & Winawer, J. (2004). Homeostasis of eye growth and the question of myopia. *Neuron*, 43(4): 447-468.
- Walsh, G., & Charman, W. (1988). Visual sensitivity to temporal change in focus and its relevance to the accommodation response. *Vision Research*, 28(11): 1207-1221.
- Wang, B., & Ciuffreda, K.J. (2004). Depth-of-focus of the human eye in the near retinal periphery. *Vision Research*, 44, 1115-1125.
- Wang, B., & Ciuffreda, K.J. (2005a). Blur discrimination of the human eye in the near retinal periphery. *Optometry and Vision Science*, 82(1): 52-58.
- Wang, B., & Ciuffreda, K.J. (2005b). Foveal blur discrimination of the human eye. *Ophthalmic and Physiological Optics*, 25(1): 45-51.
- Wang, B., & Ciuffreda, K.J. (2006). Depth-of-focus of the human eye: theory and clinical implications. *Survey of Ophthalmology*, 51(1): 75-85.

- Wang, B., Ciuffreda, K.J., & Irish, T. (2006). Equiblur zones at the fovea and near retinal periphery. *Vision Research*, 46(21): 3690-3698.
- Wang, B., Ciuffreda, K.J., & Vasudevan, B. (2006). Effect of blur adaptation on blur sensitivity in myopes. *Vision Research*. 46, 3634-3641.
- Watson, A.B., & Ahumada, A.J. (2011). Blur clarified: A review and synthesis of blur discrimination. *Journal of Vision*, 11(5): 10, 1-23.
- Watt, S.J., Akeley, K., Ernst, M.O., & Banks, M.S. (2005). Focus cues affect perceived depth. *Journal of Vision*, 5(10): 7, 834-862.
- Westheimer, G. (2006). Specifying and controlling the optical image on the human retina. *Progress in Retinal and Eye Research*, 25(1): 1-24.
- Wildsoet, C.F., & Pettigrew, J.D. (1988). Experimental myopia and anomalous eye growth patterns unaffected by optic nerve section in chickens: Evidence for local control of eye growth. *Clinical Vision Sciences*. 3, 99-107.
- Wildsoet, C., & Wallman, J. (1995). Choroidal and scleral mechanisms of compensation for spectacle lenses in chicks. *Vision Research*, 35(9): 1175-1194.
- Wolsley, C.J., Saunders, K.J., Silvestri, G., & Anderson, R.S. Investigation of changes in the myopic retina using multifocal electroretinograms, optical coherence tomography and peripheral resolution acuity. *Vision Research*. 48, 1554-1561.
- Wood, J., Collins, M., Chaparro, A., Marszalek, R., Carberry, T., Lacherez, P., & Sun Chu, B. (2014). Differential effects of refractive blur on day and nighttime driving performance. *Investigative Ophthalmology & Visual Science*, 55(4): 2284-2289.
- World Health Organization. (2015). The impact of myopia and high myopia: Report of the Joint World Health Organization—Brien Holden Vision Institute Global Scientific Meeting on Myopia, University of New South Wales, Sydney, Australia, 16-18 March 2015.
- Zhong, X., Ge, J., Smith, E.L., III, & Stell, W. (2004). Image defocus modulates activity of bipolar and amacrine cells in macaque retina. *Investigative Ophthalmology & Visual Science*, 45(7): 2065-2074.
- Zhu, X., McBrien, N.A., Smith, E.L., III, Troilo, D., & Wallman, J. (2013). Eyes in various species can shorten to compensate for myopic defocus. *Investigative Ophthalmology & Visual Science*, 54(4): 2634-2644.

APPENDIX I: Conference Presentations

- 1) **Association for Research in Vision and Ophthalmology (ARVO)** Annual Meeting, Seattle, WA. May 2016.
 - A) *Ability to Perceive Blur in Central and Near-Peripheral Retina in Myopia*
(Poster Section)
 - B) *Fixational Instability in Myopia*
(Poster Section)
- 2) The **Optical Society (OSA)** Fall Vision Meeting, Rochester, NY. October 2016.

Fixational Eye Movements in a Visual Acuity Task
(Symposium Lecture)
- 3) **American Academy of Optometry (AAO)** Annual Meeting, Anaheim, CA. November 2016.

Blur Perception in Near-Peripheral Retina
(Poster Section)
- 4) **Vision Sciences Society (VSS)** Annual Meeting, St. Pete Beach, FL. May 2017.

Reading Speed During a Mesopic Visual Acuity Task
(Poster Section)



Ability to Perceive Blur in Central and Near-Peripheral Retina in Myopia

lennawalker18@neco.edu

197 – B0096



Lenna Walker¹, Guido Maiello^{2,3}, Nancy Coletta¹, Peter J. Bex², Fuensanta A. Vera-Diaz¹

¹New England College of Optometry, ²Northeastern University, Boston, MA, ³UCL Inst. of Ophthalmology, University College London, UK

Background

- Human and animal studies suggest that an ability to accurately detect and respond to blur is essential to emmetropization.
- Furthermore, a delicate balance between peripheral and central retinal stimulation may be important in the retina's ability to derive proper blur signals.
- Previous studies have evaluated blur sensitivity across refractive groups but have done so indirectly, e.g., in the form of changes in accommodative response, or changes in visual acuity.
- There is no consensus as to whether myopes have a decreased ability to perceive normally occurring blur under normal viewing (binocular) conditions.

Study Purpose / Hypothesis

- To directly evaluate sensitivity to blur using a 4AFC task with blur presented at various near peripheral retina eccentricities (0 to 12 degrees), monocularly and binocularly and using more natural conditions.
- We hypothesize that myopic subjects will show an impaired ability to perceive blur in the near peripheral retina.

Methods

Subjects

- 37 young adults (23-30 years old)
- Refraction (SE each eye) range: +0.50 to -10.94 (<1.50DC)
- Myopes (n=18; Mean SE: -5.76 ± 3.40D), wearing contact lenses
- Emmetropes (n=19; Mean SE: +0.16 ± 0.24D)

Vision Screening

- Screening questionnaire (refractive, ocular and medical history)
- LogMAR BCVA
- Eye dominance test ("hole-in-card")
- Autorefractor & Binocular subjective refraction
- Slit lamp evaluation (optical media)

Stimuli

- Images 50deg in diameter @ 40cm
- "Dead leaves" naturalistic stimuli (Wallace & Bex, 2012)
- Gaussian blur pedestal applied to all quadrants: 0.125, 0.5, 2, 8, or 32 arc min
- Blur increment applied to only one quadrant
- Blur only in the periphery, starting at a specific eccentricity: 0deg, 4deg, 8deg, or 12deg
- 200 images, each presented for 250msec

Methods (cont)

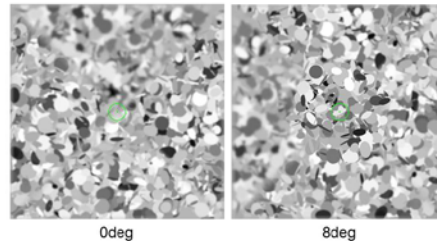
Procedure

- Subjects corrected with soft contact lenses
- Spatial 4AFC psychophysical paradigm
- Functional adaptive sequential testing (FAST) (Vul et al., 2010)

- Two conditions (randomized):
(a) Monocular (dominant eye), (b) Binocular

- Subjects asked to fixate at center and respond with keypad:

"Which quadrant is blurriest?"



Data Analysis

- Linear mixed model (SAS software) to analyze effects of:

- Retinal Eccentricity (0deg/4deg/8deg/12deg)
- Viewing Condition (Monocular/Binocular)
- Refractive Group (Myope/Emmetrope)

on

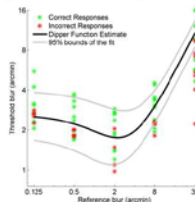
- Intrinsic Blur
- Blur Sensitivity

- Spearman rho correlations were used to analyze the relationship between intrinsic blur/blur sensitivity and refractive error, both monocularly and binocularly.

- Threshold blur data for each reference blur level were fit with dipper functions (Mather & Smith, 2002):

$$\Delta b = \sqrt{(1 + \frac{1}{S})(\sigma_i^2 + \sigma_e^2)} - \sigma_e$$

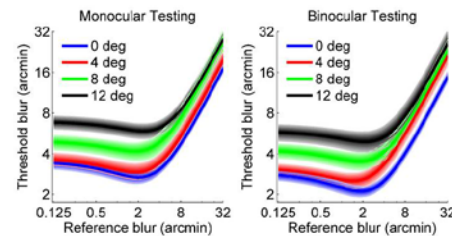
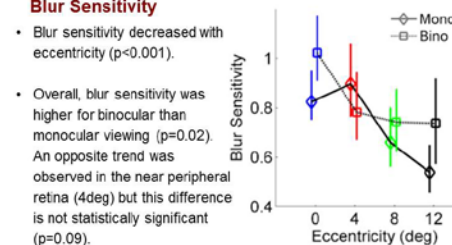
where:
 Δb is Threshold Blur
 S is Blur Sensitivity
 σ_i is Intrinsic Blur
 σ_e is External Blur



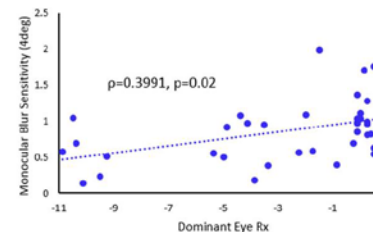
Results

Blur Sensitivity

- Blur sensitivity decreased with eccentricity ($p < 0.001$).
- Overall, blur sensitivity was higher for binocular than monocular viewing ($p = 0.02$). An opposite trend was observed in the near peripheral retina (4deg) but this difference is not statistically significant ($p = 0.09$).



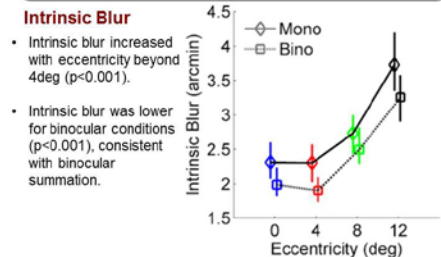
- There was a trend towards lower blur sensitivity in myopes compared to emmetropes for all conditions, although a significant difference was not found ($p = 0.08$).
- A positive correlation was found between monocular blur sensitivity and subjective refraction at 4deg eccentricity ($p = 0.3991$, $p = 0.02$). No other correlations were found between blur sensitivity and refractive error.



Results (cont'd)

Intrinsic Blur

- Intrinsic blur increased with eccentricity beyond 4deg ($p < 0.001$).
- Intrinsic blur was lower for binocular conditions ($p < 0.001$), consistent with binocular summation.
- Refractive error did not have an effect on intrinsic blur at any eccentricity tested, for monocular or binocular conditions. Myopes and emmetropes did not have statistically significant differences in intrinsic blur ($p = 0.90$).



Conclusions/Future Directions

- Intrinsic blur increases and blur sensitivity decreases with retinal eccentricity.
- No statistically significant differences were found between myopes and emmetropes in regards to intrinsic blur or blur sensitivity. However, a trend was found that suggests myopes may experience a greater difficulty discriminating blur at all retinal eccentricities. Binocular viewing seems to ameliorate some of this difficulty, but the trend still persists.
- Further investigations that include hyperopes are necessary to elicit if there is truly a significant difference in blur sensitivity between refractive groups.

References

- Cuffin et al. IOVS. 2007; 48(8):2922-39.
- Malher & Smith. Perception. 31(10): 1211-1219.
- Norton et al. IOVS. 2006; 47(11): 4687-99.
- Polare & Moschandreass. OPO. 2013; 33(2).
- Rosenfield & Abraham-Cohen. OVS. 1999;76(5): 303-7.
- Schmid et al. VR. 2002; 42(2):239-47.
- Smith et al. IOVS. 2007 Sep; 48(9): 3914-22.
- Strang et al. OPO. 2011 Sep; 31(5): 444-55.
- Taylor et al. J Vis. 2009; 9(1):1-14.
- Vera-Diaz et al. (2015, May). ARVO Poster.
- Jul et al. Seeing Perceiving. 2010; 23: 483-515.
- Walls and Bex. J Vis. 2012; 12(7).
- Waltman and Winawer. Neuron. 2004 Aug 19; 43(4): 447-68.
- Widdsoet and Waltman. VR. 1995; 35(9):1175-94.

Acknowledgments

Lenna Walker was supported by NEI T35 EY007149 to the New England College of Optometry, additional support was provided by the New England College of Optometry.



Blur Perception in Near-Peripheral Retina

lennawalker18@neco.edu

AAO Poster Board #177



Lenna Walker¹, Guido Maiello^{2,3}, Nancy Coletta¹, Peter J. Bex², Fuensanta A. Vera-Diaz¹

¹New England College of Optometry, ²Northeastern University, Boston, MA, ³UCL Inst. of Ophthalmology, University College London, UK

Background

- Human and animal studies suggest that continuous retinal defocus may be a causative factor in the failure of emmetropization.
- The interaction between peripheral and central retina may be significant to the retina's ability to derive proper blur signals and provide accurate visual feedback.
- Previous studies evaluated blur perception across refractive groups but indirectly (evaluating DOF, changes in accommodative response, or changes in VA). Also, most studies were monocular and restricted to the fovea.
- There is no consensus as to whether myopes have a decreased ability to perceive blur under normal viewing (binocular) conditions.

Purpose/Hypothesis

- To directly (using a 4AFC task) evaluate the ability of observers with emmetropia and myopia to detect and discriminate blur in the central and peripheral retina, under monocular and binocular viewing conditions.
- We hypothesize that myopic subjects will show an impaired ability to perceive blur in the near peripheral retina.

Methods

Subjects

- 39 young adults (23-30 yrs old; Mean age: 24.8 ± 3.8 yrs)
- Refraction (SE) range: +0.50 to -10.94DS (±1.50DC)
- Myopes (n=19; Mean SE: -5.88 ± 3.35DS)
- Emmetropes (n=20; Mean SE: +0.15 ± 0.24DS)

Vision Screening

- Screening questionnaire (refractive, ocular and medical hx)
- Snellen BCVA
- Eye dominance test ("hole-in-card")
- Autorefractometer & Binocular subjective refraction

Stimuli

- 46x46deg images @ 40cm
- "Dead leaves" naturalistic stimuli (Wallis & Bex, 2012)
- Gaussian blur pedestal applied to all quadrants: 0.125, 0.5, 2, 8, or 32 arc min
- Blur increment applied to only one quadrant
- Blur only in the periphery, starting at a specific eccentricity: 0deg, 4deg, 8deg, or 12deg
- 200 images, each presented for 250ms

Acknowledgements

Lenna Walker was supported by NEI T35 EY007149 to the New England College of Optometry (NECO) and by Beta Sigma Kappa (BSK); additional support was provided by internal funds from NECO.

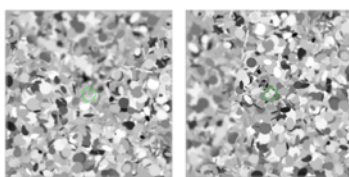
Methods (cont)

Procedure

- Subjects corrected with soft contact lenses
- Spatial 4AFC psychophysical paradigm
- Functional adaptive sequential testing (FAST) (Vul et al., 2010)

- Subjects asked to fixate at center and respond with keypad:

"Which quadrant is blurriest?"



- Two conditions (randomized):
(a) Monocular (dominant eye), (b) Binocular

Data Analysis

- The blur discrimination function is dipper shaped.
- Threshold blur data for each reference blur level were fit with dipper functions (Mather & Smith, 2002):

$$\Delta b = \sqrt{(1 + 1/5)(\sigma_e^2 + \sigma_s^2)} - \sigma_e$$

where:
 Δb is Threshold Blur
 S is Blur Sensitivity
 σ_e is Intrinsic Blur
 σ_s is External Blur

Example of a dipper function estimated for one subject in the binocular, 0deg condition.

- Blur Sensitivity and Intrinsic Blur parameters were analyzed with:
2 (refractive status, between subjects factor) x 2 (viewing condition, within subjects factor) x 4 (eccentricity, within subjects factor) mixed design ANOVA.
- Post-hoc Bonferroni corrections were performed

Results

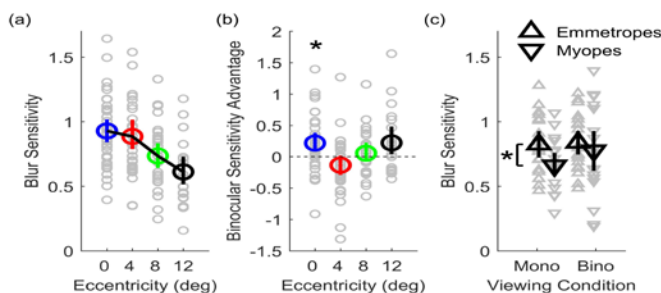
Intrinsic Blur

- Intrinsic Blur larger under monocular conditions ($p < 0.01$) and increases with eccentricity ($p = 10^{-14}$).
- No significant effect of refractive group ($p = 0.47$). No significant two- or three-way interactions (all $p > 0.6$).

Monocular and binocular data are shifted left and right for graphical purposes.

Results (cont)

Blur Sensitivity



Error bars are 95% bootstrapped confidence intervals of the mean. Gray data points are individual subject data. * $p < 0.05$

- Blur Sensitivity decreases with eccentricity under both monocular and binocular viewing ($p = 10^{-6}$).
- Significant main effect of viewing condition ($p = 0.02$) and significant two-way interaction between viewing condition and eccentricity ($p < 0.01$).
- On average, Binocular Sensitivity Advantage was positive, but post-hoc analysis revealed that Blur Sensitivity was significantly higher under binocular viewing conditions only at the fovea ($p = 0.01$).
- Significant two-way interaction between viewing condition and refractive status ($p = 0.049$).
- Post-hoc analysis revealed that Myopes have significantly worse Blur Sensitivity than Emmetropes monocularly ($p = 0.0377$) but not binocularly ($p = 0.66$).
- No significant two- or three-way interaction between eccentricity and refractive status.

Conclusions/Future Directions

- Blur perception worsens in the visual periphery because of degraded optics, sampling and neural processing.
- Binocularity improves visual blur perception – it reduces intrinsic blur and there is a small but statistically significant sensitivity advantage at the fovea.
- We found no statistically significant differences in the amount of intrinsic blur between myopic and emmetropic subjects, nor in binocular blur sensitivity.
- However, myopes exhibit a monocular impairment in blur perception which may be involved in the development of refractive error.
- Future investigations should include hyperopic subjects as well as progressing myopes to further study the relationship between blur sensitivity and refractive error development. They should also assess the differences in blur perception with different types of blur.

References

- Cufflin et al. IOVS. 2007; 48(6):2932-39.
- Fisher & Ciuffreda. Perception. 1998; 17: 609-21.
- Jacobs et al. OVS. 1989; 66: 545-53.
- Maher & Smith. Perception. 2002; 31(10): 1211-19.
- Norton et al. IOVS. 2006; 47(11): 4687-99.
- Plainis et al. IOVS. 2011; 52: 2784-89.
- Pouliere & Moschandreass. OPO. 2013; 33(2).
- Ronchi & Moleisini. Ophth Research. 1975; 7: 152-57.
- Rosenfield & Abraham-Cohen. OVS. 1999; 76(5): 303-7.
- Schmid et al. VR. 2002; 42(2):239-47.
- Smith et al. IOVS. 2007 Sep; 48(9): 3914-22.
- Strang et al. OPO. 2011 Sep; 31(5): 444-55.
- Taylor et al. J Vis. 2009; 9(1):1-14.
- Vera-Diaz et al. (2015, May). ARVO Poster.
- Vul et al. Seeing Perceiving. 2010; 23: 483-515.
- Wallis and Bex. J Vis. 2012; 12(7).
- Wallman and Winawer. Neuron. 2004 Aug 19; 43(4): 447-68.
- Wang & Ciuffreda. VR. 2006; 46: 3690-98.
- Wildsoet and Wallman. VR. 1995; 35(9):1175-94.

Reading Speed During a Mesopic Visual Acuity Task

Nancy J. Coletta, Lenna Walker, Fuensanta A. Vera-Diaz
New England College of Optometry, Boston, MA

colettan@neco.edu

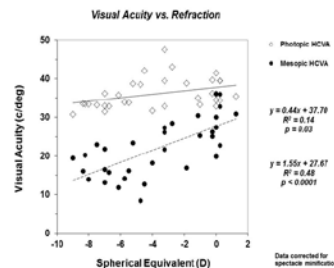
36.3032



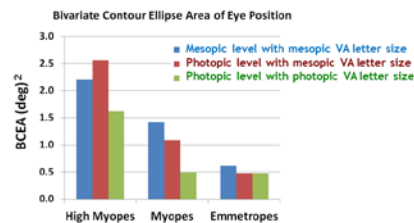
New England
College of Optometry

Introduction

Visual acuity (VA) worsens under dim illumination. Myopic subjects exhibit larger VA losses at low luminance compared to emmetropes.^{1,2}



Subjects with myopia also show less stable fixational eye movements, i.e., larger bivariate contour ellipse area (BCEA) of eye position, when reading letters on a VA chart.³



Reduced acuity in myopia may be related to fixation instability, perhaps analogous to amblyopia, where less stable eye movements are associated with reductions in acuity and reading speed.⁴

Purpose

To evaluate whether a subject's acuity and fixation stability were related to the time they spent to read an acuity line.

Methods

Subjects

Measurements were made on 31 subjects with normal vision, mean age 25.7 years.

Inclusion criteria were best corrected visual acuity of 20/20 (0.00 LogMAR) or better in each eye, with less than 1.50 D astigmatism, no history of refractive surgery or eye disease, no current binocular or accommodative dysfunction, and no nystagmus.

Spectacle plane spherical equivalent (SE) refractions ranged from +2.25 to -10.88 D. Measurements were made on the dominant eye.

Visual Acuity Measurement

High contrast VA was measured with letters displayed on an LCD panel viewed at 4 meters.



The largest letter size was 20/200 or 1.0 log MAR; each line was 0.1 log unit smaller than the preceding line, to 20/12.5 or -0.2 log MAR.

Mesopic (0.28 cd/m²) and photopic (325 cd/m²) acuity was measured. Subjects sat at a chin and head rest and wore contact lenses if correction was needed.

Statistics are based on linear regressions.

Eye Movement Recording

Eye position was recorded at 500 Hz using an EyeLink 1000 video-based eye tracker.



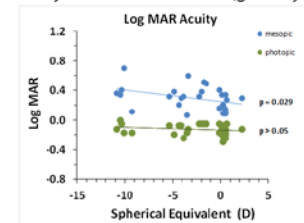
Fixations were analyzed for letter sizes corresponding to the mesopic and photopic acuity limits.

Fixation stability is reported as the bivariate contour ellipse area (BCEA) in deg², taken over a 2-sec interval, representing the area of fixation for 68% of the time.⁵

Results

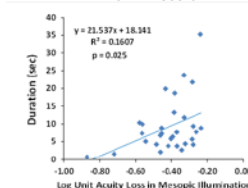
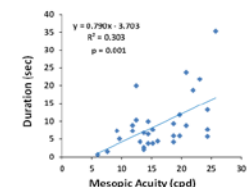
Visual Acuity

VA is shown as a function of the SE refractive error. Acuity at the mesopic condition worsened significantly with increasing myopia (blue symbols). Photopic acuity did not vary with refractive error (green symbols).



Visual Acuity and Duration to Read VA Line

At the mesopic condition, subjects who took longer to read a line at their acuity limit had higher mesopic acuity (upper figure; $p=0.001$) and smaller loss of acuity relative to their photopic acuity (lower figure; $p=0.025$).

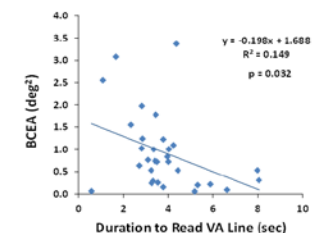


There was no correlation between reading duration at the photopic acuity limit and photopic acuity ($p>0.05$), nor between reading duration and refraction ($p>0.05$).

Results

Fixation Stability and Reading Duration

When the mesopic acuity letter size was read at the photopic light level, BCEA decreased with increasing reading duration ($p=0.032$).



Conclusions

Longer reading duration, and thus slower reading speed, in a mesopic acuity task was associated with higher visual acuity and more stable fixations.

Reading speed was not associated with refractive error. Thus fixation instability observed in high myopia is not associated with reduced reading speed during acuity measures.

These results are unlike those reported for amblyopia, where reduced acuity and fixation instability are associated with slower reading speed.

References

1. Coletta NJ, Friericks M, Groves R. (2007) Mesopic visual acuity in myopia. *Investigative Ophthalmology and Visual Science*, 48 (ARVO E-abstract 1099).
2. Coletta NJ, Moskowitz A. (2003) Wavefront aberrations and mesopic visual performance following soft contact lens removal. *Journal of Vision*, 3(12), p. 37a.
3. Coletta NJ, Walker L, Vera-Diaz FA. (2014) Fixation instability in myopia. *Investigative Ophthalmology and Visual Science*, 57 (ARVO E-abstract 199).
4. Kanonidou E, Proudlock FA, Gottlieb I. (2010) Reading strategies in mild to moderate strabismic amblyopia: an eye movement investigation. *Invest Ophthalmol Vis Sci*, 51(7):1502-8.
5. Raveendran R. N., Babu R. J., Hess R. F., Bobler W. R. (2014) Transient improvements in fixation stability in strabismic amblyopes following binocular fixation and reduced interocular suppression. *Optical. Physiol. Optics*, 34 pp 214-225.

Acknowledgements

Grant support from NIH T35 EY007149; we thank Peter Bex for loan of the EyeLink 1000.

APPENDIX II: Publications

1) “Blur perception throughout the visual field in myopia and emmetropia”

Citation:

Guido Maiello, Lenna Walker, Peter J. Bex, Fuensanta A. Vera-Diaz; Blur perception throughout the visual field in myopia and emmetropia. *Journal of Vision* 2017; 17(5):3. Doi: 10.1167/17.5.3.

Link:

<http://jov.arvojournals.org/article.aspx?articleid=2626043>

Also included:

Supplementary Material to:

“Blur perception throughout the visual field in myopia and emmetropia”

Blur perception throughout the visual field in myopia and emmetropia

Guido Maiello

University College London Institute of Ophthalmology,
London, UK
Northeastern University, Boston, MA, USA

Lenna Walker

New England College of Optometry, Boston, MA, USA

Peter J. Bex

Northeastern University, Boston, MA, USA

Fuensanta A. Vera-Diaz

New England College of Optometry, Boston, MA, USA

We evaluated the ability of emmetropic and myopic observers to detect and discriminate blur across the retina under monocular or binocular viewing conditions. We recruited 39 young (23–30 years) healthy adults ($n = 19$ myopes) with best-corrected visual acuity 0.0 LogMAR (20/20) or better in each eye and no binocular or accommodative dysfunction. Monocular and binocular blur discrimination thresholds were measured as a function of pedestal blur using naturalistic stimuli with an adaptive 4AFC procedure. Stimuli were presented in a 46° diameter window at 40 cm. Gaussian blur pedestals were confined to an annulus at either 0° , 4° , 8° , or 12° eccentricity, with a blur increment applied to only one quadrant of the image. The adaptive procedure efficiently estimated a dipper shaped blur discrimination threshold function with two parameters: intrinsic blur and blur sensitivity. The amount of intrinsic blur increased for retinal eccentricities beyond 4° ($p < 0.001$) and was lower in binocular than monocular conditions ($p < 0.001$), but was similar across refractive groups ($p = 0.47$). Blur sensitivity decreased with retinal eccentricity ($p < 0.001$) and was highest for binocular viewing, but only for central vision ($p < 0.05$). Myopes showed worse blur sensitivity than emmetropes monocularly ($p < 0.05$) but not binocularly ($p = 0.66$). As expected, blur perception worsens in the visual periphery and binocular summation is most evident in central vision. Furthermore, myopes exhibit a monocular impairment in blur sensitivity that improves under binocular conditions. Implications for the development of myopia are discussed.

Introduction

Blur perception is an elemental feature of the human visual system. A blurred retinal image serves to drive the accommodation and vergence responses, allowing one to see clearly and resolve fine target details (Ciuffreda, 1991, 1998; Ciuffreda, Wang, & Vasudevan, 2007; Fisher & Ciuffreda, 1988; Horwood & Riddell, 2009; Lin et al., 2013; López-Gil et al., 2013; Schor, 1999; Yamaguchi et al., 2013). Retinal blur also may provide information about the range of depths in one's environment (Maiello, Chessa, Solari, & Bex, 2014; Mather, 1997; Mather & Smith, 2002; Vishwanath, 2012; Vishwanath & Blaser, 2010; Watt, Akeley, Ernst, & Banks, 2005) (but see Langer & Siciliano, 2015; Maiello, Chessa, Solari, & Bex, 2015). As such, blur perception is crucial to one's ability to navigate the world easily, and to accurately perform daily tasks such as reading and driving (Poulere, Moschandreas, Kontadakis, Pallikaris, & Plainis, 2013; Wood et al., 2014). Furthermore, it has been suggested that continuous retinal defocus may be a causative factor in refractive error development, although the evidence is conflicting (Cufflin, Mankowska, & Mallen, 2007; Flitcroft, 1998; Hess, Schmid, Dumoulin, Field, & Brinkworth, 2006; Norton, Siegwart, & Amedo, 2006; Rosenfield & Abraham-Cohen, 1999; Schmid, Iskander, Li, Edwards, & Lew, 2002; Smith III & Li-Fang, 1999; Smith III, Li-Fang, & Harwerth, 1994; Strang, Day, Gray, & Seidel, 2011; Taylor, Charman, O'Donnell, & Radhakrishnan, 2009; Vera-Diaz, Maiello, Kerber, Thorn, & Bex, 2015; Wallman & Winawer, 2004; Wildsoet & Wallman, 1995).

Citation: Maiello, G., Walker, L., Bex, P. J., & Vera-Diaz, F. A (2017). Blur perception throughout the visual field in myopia and emmetropia. *Journal of Vision*, 17(5):3, 1–13, doi:10.1167/17.5.3.

doi: 10.1167/17.5.3

Received October 6, 2016; published May 5, 2017

ISSN 1534-7362 Copyright 2017 The Authors



This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.

Downloaded From: <http://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/936220/> on 05/29/2017

There are two major components in the perception of blur: blur detection and blur discrimination (Ciuffreda et al., 2007; Wang, Ciuffreda, & Irish, 2006). Blur detection refers to the amount of defocus necessary for an observer to first perceive or notice the presence of blur. Blur discrimination refers to the amount of defocus necessary for an observer to perceive an already blurry target as just noticeably blurrier. Both aspects of blur contribute to our perception of image quality (Wang & Ciuffreda, 2006). Overall, the perception of blur is a complex process that depends on the eye's optical quality (i.e., aberrations) as well as both retinal and higher level neurophysiology (Ciuffreda et al., 2007; Mather & Smith, 2002; Wang & Ciuffreda, 2004, 2005a, 2005b). Motion, visual attention, sharpness overconstancy, and target attributes such as luminance, contrast, texture, and size also contribute to the perception of image blur (Christman, 1990; Galvin, O'Shea, Squire, & Hailstone, 1999; Pääkkönen & Morgan, 1994; Wang & Ciuffreda, 2004, 2005b).

The perception of blur within central vision has been studied extensively (Campbell, 1957; Jacobs, Smith, & Chan, 1989; Oshima, 1958; Rosenfield & Abraham-Cohen, 1999; Walsh & Charman, 1988), but there is relatively limited information about how we perceive blur throughout the peripheral field of vision (Ronchi & Molesini, 1975; Wang & Ciuffreda, 2004, 2005a; Wang et al., 2006), even though peripheral blur strongly impacts peripheral visual function (Maiello, Harrison, Vera-Diaz, & Bex, 2015; Rosén, Lundström, & Unsbo, 2011). Altogether, the limited studies on peripheral blur perception suggest that blur detection and discrimination thresholds increase progressively with retinal eccentricity, and that blur detection may be less sensitive than blur discrimination to eccentric viewing. However, most of these studies do not measure blur thresholds directly, rather they infer blur sensitivity by evaluating the subject's depth-of-focus, either with ophthalmic lenses or by manually displacing the test target. Additionally, most of these studies have evaluated perception of blur only monocularly (Wang & Ciuffreda, 2004, 2005a; Wang et al., 2006).

To understand how blur is employed by the visual system it is necessary to further study blur perception throughout the peripheral field. Studying blur perception at different eccentricities may also shed light on emmetropization and its failure, as the interaction between peripheral and central vision may be significant to this process (Huang, Hung, & Smith III, 2012; Smith III, Campbell, & Irving, 2013; Smith III et al., 2007; Vera-Diaz, Kerber, Thorn, & Bex, 2013; Wallman & Winawer, 2004; Yamaguchi et al., 2013). Binocularity (the neuronal integration of information from the two eyes) needs to also be considered when investigating perception of blur. Previous studies have

found that binocularity improves visual performance through probability summation under blur conditions (Banton & Levi, 1991; Heravian, Jenkins, & Douthwaite, 1990; Plainis, Petratou, Giannakopoulou, Atchison, & Tsilimbaris, 2011).

Binocularity improves retinal sensitivity to defocus blur, and defocus blur is a useful cue to increase the accuracy of binocularity (Hoffman & Banks, 2010; Mather, 1997), including binocular rivalry (Arnold, Grove, & Wallis, 2007). In addition, proof of interocular transfer of defocus information has been shown in guinea pig (McFadden et al., 2014) and human (Kompaniez, Sawides, Marcos, & Webster, 2013) models of refractive error development. There is also interocular transfer of accommodative responses (Flitcroft, Judge, & Morley, 1992), creating similarity in retinal image focus. Therefore, although emmetropization signals are found locally at the retinal level, binocular vision may play a significant role in retinal image focus and therefore in emmetropization.

Psychophysical studies on the perception of blur have repeatedly shown that blur discrimination follows a typical “dipper” shape (for a comprehensive review see Watson & Ahumada, 2011), meaning that performance in blur discrimination tasks is best with a nonzero amount of reference blur. These data are often described using a variance discrimination model (e.g., Mather & Smith, 2002), since blur perception can be conceptualized as variance discrimination of luminance gradients (Morgan, Chubb, & Solomon, 2008). The variance discrimination model of blur assumes that the visual system is attempting to estimate the local variance of the luminance profile of an image from a set of luminance samples. Each of these samples is, however, perturbed by some level of internal noise or intrinsic blur. This intrinsic blur arises from optical sources (the optical aberrations of the eye) and neural sources (neural noise within the visual pathways). At near-zero levels of reference blur, in order to discriminate blur, the system has to overcome this level of intrinsic blur. As the reference level of blur increases, blur discrimination is initially facilitated owing to the additivity of variance (hence the dipper shape). Finally, for levels of reference blur much greater than intrinsic blur, discrimination performance worsens in accordance with Weber's law. This model well describes the dipper data and is grounded in signal detection theories of sensory discrimination and decision making (Green & Swets, 1966).

How the visual system represents and computes blur is actually a matter of current scientific debate. Watson and Ahumada (2011) provide a thorough overview of the models that have been proposed in the literature to explain the discrimination of blurred edges and provide support for a model in which blur discrimination is accomplished by discriminating local image contrast

energy after filtering by the contrast sensitivity function. Georgeson, May, Freeman, and Hesse (2007) propose instead a scale-space model that employs Gaussian derivative filters arranged in a structure that resembles the organization of simple and complex cells in visual cortex.

Here, we study blur perception throughout the visual field using the variance discrimination model of the blur dipper function that is agnostic to how the visual system computes and encodes blur. Using this model we ask how blur perception changes in the periphery and whether these changes are due to an increase in intrinsic noise (that combines all sources of visual blur, including optics and sampling) or because of different neural resources allotted to blur perception throughout the visual field (which would lead to changes in decision making—i.e., the Weber fraction of blur discrimination). We differentiate these accounts by estimating both intrinsic blur and blur sensitivity as a function of eccentricity, refractive status, and monocular or binocular viewing conditions.

The aim of the current study was to assess blur perception in the near peripheral field of vision, both monocularly and binocularly, in emmetropic and myopic subjects. To do so, we used naturalistic stimuli (Bordenave, Gousseau, & Roueff, 2006; Lee, Mumford, & Huang, 2001; Wallis & Bex, 2012) blurred at fixed eccentricities (up to 12°) and measured blur detection and discrimination threshold with an adaptive 4AFC paradigm (Vul, Bergsma, & MacLeod, 2010).

Methods

Subjects

A total of 39 young adult subjects (mean $\pm$ SD age: 24.8 $\pm$ 3.8 years; n = 19 myopes) were recruited from staff and students of the New England College of Optometry to participate in this study. Following a vision screening that comprised an ocular health evaluation and an ocular history questionnaire, subjects who met all inclusion criteria were enrolled in the study. Criteria for subjects' inclusion were: (1) within 18 and 32 years of age, (2) best-corrected visual acuity (BCVA) 20/20 or better in each eye, (3) refractive error (spherical equivalent, SE) between +0.75 hyperopia and −14.00DS myopia with $\leq$ 1.50DC of astigmatism or $\leq$ 1.00D anisometropia, (4) contact lens wearer if myopic refractive correction was needed, (5) no current binocular vision or accommodative dysfunction, (6) not using drugs that may affect their vision, (7) no history of surgery or eye disease that may have resulted in visual consequences, and (8) adequate hearing, lan-

guage skills, and mental ability to understand the consent process and the instructions given during the experiment.

Subjects' refractive error for each eye was determined by objective refraction with an open-field autorefractor (Grand Seiko WR5100K, Grand Seiko, Hiroshima, Japan) followed by binocular subjective refraction with binocular balancing and evaluated by the observer's best-corrected visual acuity. Axial length measurements were performed with a Haag–Streit Lenstar LS900 optical biometer (Haag-Streit AG, Koeniz, Switzerland; <http://www.haag-streit.com/>). Subjects were grouped based on their refractive error. Myopia (n = 19) was defined as a SE in each eye between −0.50DS and −11.00DS (mean: −5.88 $\pm$ 3.35DS). Emmetropia (n = 20) was defined as SE in each eye between −0.25DS and +0.50DS (mean: +0.15 $\pm$ 0.24DS).

This research followed the tenets of the Declaration of Helsinki; informed consent was obtained from all subjects after explanation of the nature and possible consequences of the study, and was approved by the New England College of Optometry's Institutional Review Board.

Stimuli and apparatus

The experiment was programmed with the Psychophysics Toolbox Version 3 (Brainard, 1997; Pelli, 1997) in Matlab. Stimuli were presented on a gamma-corrected ROG SWIFT PG278Q Asus monitor (Asus-Tek Computer Inc., Taipei, Taiwan) with a resolution of 2560 $\times$ 1440 pixels (display dot pitch: 0.233 mm) running at 120 Hz from an Nvidia GeForce GTX 780 graphics processing unit (Nvidia Corporation, Santa Clara, CA).

Subjects were seated 40 cm in front of the monitor with their heads stabilized in a chin and forehead rest. The monitor subtended 73 $\times$ 46°/visual angle. Stimuli were 46 $\times$ 46°/visual angle degree patches of “dead leaves” (Bordenave et al., 2006; Lee et al., 2001); examples can be seen in Figure 1. Stimuli were constructed from a set of 2,000 ellipses each assigned a center position, orientation, aspect ratio, and luminance drawn from pseudo-random uniform distributions. The length of each ellipse semi-axis was randomly selected to be between 0.1 and 10°/visual angle. Each image was divided in four sectors: upper, right, lower, and left. Blur was applied to each sector by Gaussian filtering in the frequency domain by an amount under the control of the adaptive algorithm described as follows. Three sectors were blurred by the same amount of “pedestal” blur, whereas the fourth was blurred by a greater amount of “pedestal +

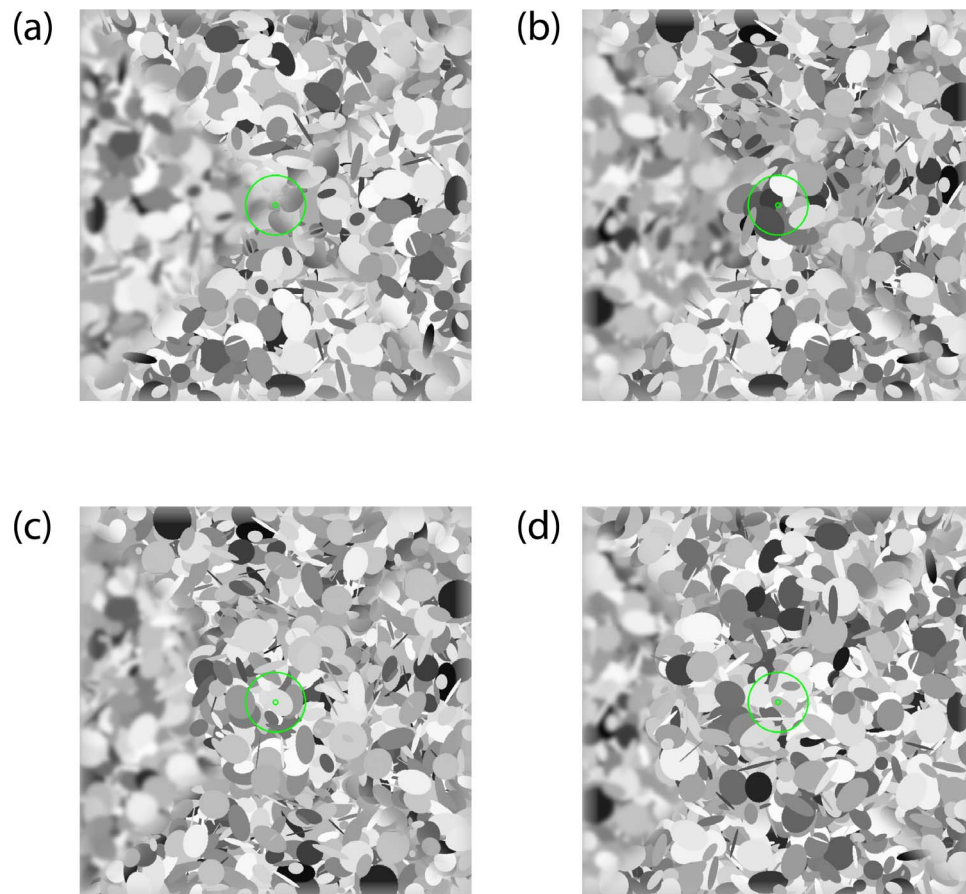


Figure 1. Example of “dead leaves” stimuli employed in the study for each eccentricity condition (a–d). For each of these four example stimuli, the top, right, and bottom quadrants are blurred with 0.5 arcmin of “pedestal” blur, whereas the left quadrant is blurred by a greater amount of blur (0.5 + 6 arcmin of “pedestal” + “increment” blur). For the 0° condition (a), blur is present throughout the entire image from the center to the periphery. In the peripheral blur testing conditions (b–d), the image within the central 4°, 8°, or 12°, respectively, were sharply rendered, and blur was present only at an eccentricity beyond 4° (b), 8° (c), or 12° (d).

increment” blur. To measure blur discrimination throughout the selected visual field, a circular central portion of the stimulus up to 0°, 4°, 8°, or 12° of eccentricity was sharply rendered, with no blur (Figure 1a–d). Two green concentric circles of 0.3° and 3°, respectively, were presented in the middle of each stimulus image to serve as target for central fixation.

Design

It is known that the ability of human observers to discriminate differences in blur varies lawfully as a function of the amount of reference blur, and that this blur discrimination function is dipper shaped (Hamerly & Dvorak, 1981; Pääkkönen & Morgan, 1994; Watt & Morgan, 1983, 1984; for a review see Watson & Ahumada, 2011). Thus, blur perception is typically investigated by measuring blur discrimination thresholds at multiple levels of pedestal blur, and then fitting

the threshold data with a dipper shaped function. Instead of measuring individual thresholds, in this study we employed an adaptive testing procedure (Vul et al., 2010) to estimate blur dipper functions at 0°, 4°, 8°, and 12° in the visual field both monocularly and binocularly.

We adopted a parameterization of the blur dipper function (Mather & Smith, 2002; Murray & Bex, 2010) with equation:

$$\Delta b = \sqrt{\left(1 + 1/S\right)(\sigma_i^2 + \sigma_e^2)} - \sigma_e \quad (1)$$

where blur increment threshold Δb varies as a function of the external (pedestal) blur σ_e applied to the stimulus and is modulated by two parameters: blur sensitivity S and intrinsic blur σ_i . The model’s intrinsic blur parameter takes into account that a human observer’s visual system has a baseline level of intrinsic blur arising from all optical and neurological sources. The blur sensitivity parameter takes into account the proportional increase of the blur threshold with

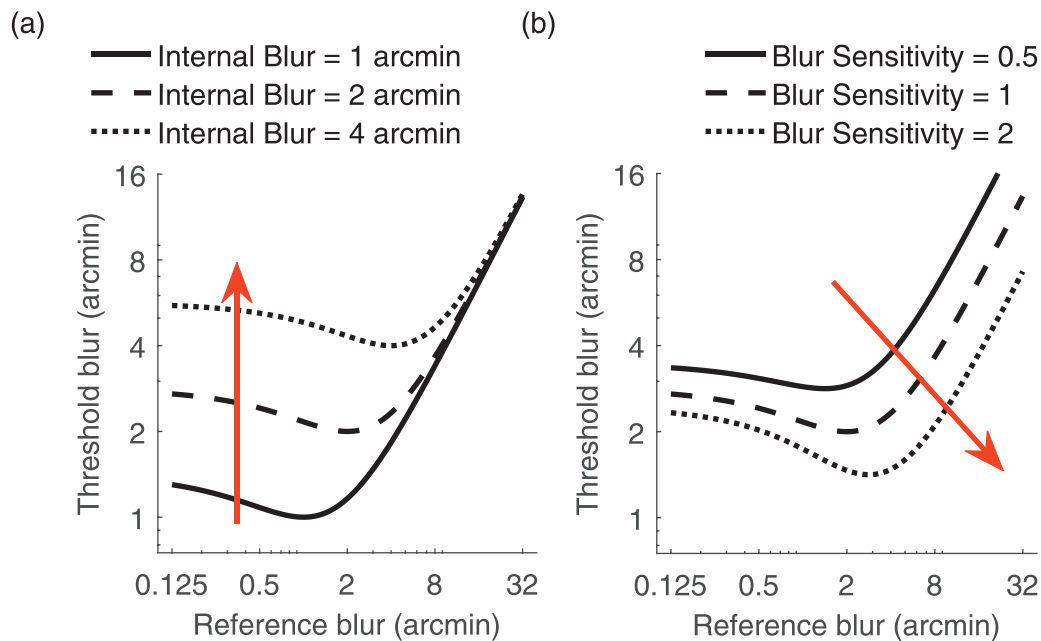


Figure 2. Representation of the effect of modifying the various parameters of the blur dipper model. (a) Effect of holding the blur sensitivity parameter fixed at a value of 1 and increasing the internal blur parameter from 1 to 4 arcmin. (b) Effect of holding the internal blur parameter fixed at 2 arcmin and increasing the blur sensitivity parameter from 0.5 to 2.

increasing external blur: an observer with high sensitivity will have globally lower thresholds and will thus be overall better at discriminating blur. Figure 2 illustrates the effects of changing these two parameters on the shape of the dipper function. Increasing the internal blur parameter whilst holding constant the blur sensitivity parameter (Figure 2a) shifts the left side of the function upward but does not affect the rightward side of the function. Increasing blur sensitivity while holding internal blur constant (Figure 2b) shifts the entire curve downward and to the right.

We employed the functional adaptive sequential testing (FAST) (Vul et al., 2010) algorithm to obtain dipper function blur estimates. We validated the use of the FAST method by comparing estimates of the dipper function parameters estimated with FAST with estimates of the dipper function based on classical psychophysical methods with five interleaved staircases in the same observers; see Appendix 1 for details. An example of a dipper function estimated for one representative observer in one experimental condition is shown in Figure 3. Specifically, for each dipper function estimate we required the algorithm to select 15 trials at each of five pedestal blur levels [0.125, 0.5, 2, 8, 32] arcmin. At these reference blur levels, each trial the FAST algorithm selected test blur levels that maximized information gain, efficiently constraining the parameter estimates of the underlying dipper function.

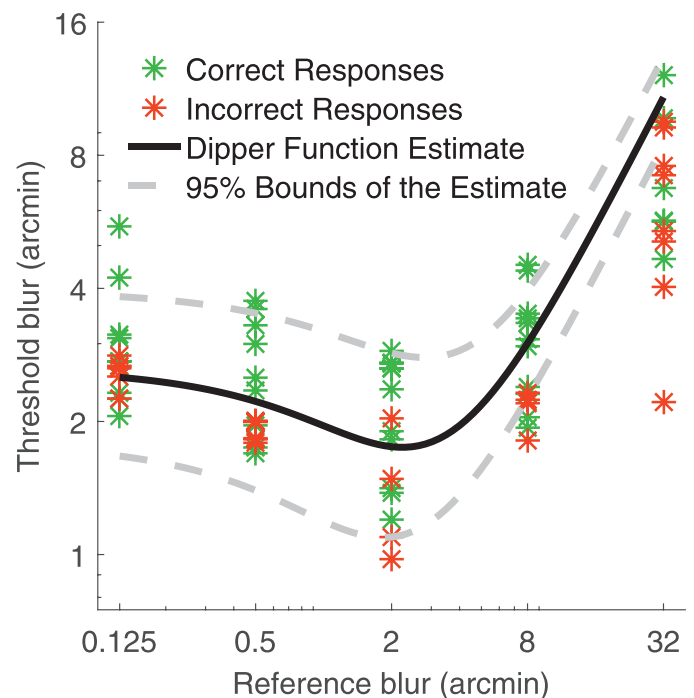


Figure 3. Example of a dipper function estimated for one representative observer in the binocular, 0° eccentricity condition. Asterisks represent individual trials: Green and red are correct and incorrect responses, respectively. Black curve is the estimated dipper function describing how the observer's threshold blur increment varies as a function of reference blur. Note that in this 4AFC task, 25% trials below threshold are guessed correctly (green asterisks). Dotted lines are the 95% bounds of the estimated curve.

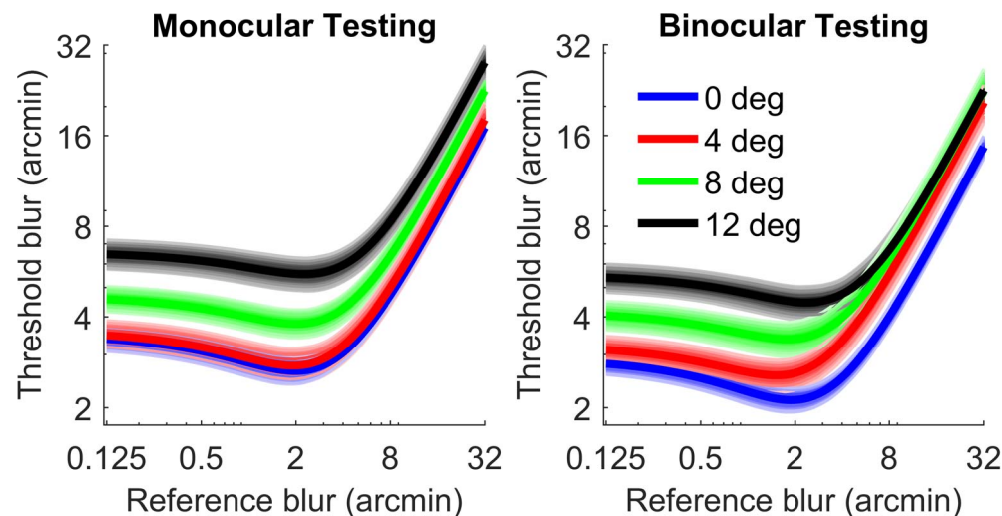


Figure 4. Blur dipper functions under monocular (left) and binocular (right) conditions. Curves are averaged across all subjects at each eccentricity (0° blue, 4° red, 8° green, and 12° black). Shaded regions are 95% bootstrapped confidence intervals of the mean.

Procedure

Subjects were tested both binocularly and monocularly (with their nondominant eye occluded) in two separate sessions. The session order was randomized across participants. Each session, subjects completed 15 trials at each of five pedestal blur levels for each of the four eccentricity conditions. Thus each subject completed 300 trials per sessions. When necessary, subjects were corrected with soft contact lenses.

Each trial, subjects were required to fixate the central fixation target. Stimuli were shown for 250 ms, which is too brief for subjects to initiate any stimulus driven changes in fixation. The 4AFC task was to identify, via button press on the keyboard placed in front of them, which of the four image sections (upper, left, lower or right) was most blurred. Visual feedback was provided by the fixation target, which was green following a correct response, or red following an incorrect response.

Data analyses

On some conditions and for certain subjects, the FAST algorithm failed to converge. Thus, we performed outlier removal by employing the following procedure. For each estimated parameter, we computed the size of the 95% confidence region of the estimate. For intrinsic blur (σ_i) and Blur Sensitivity (S) parameters separately, we then computed the upper 90th percentile of the size of the confidence regions. Finally, we excluded data from those dipper curves in which at least one of the parameter estimates confi-

dence region was greater than this 90th percentile. This procedure thus excluded parameters estimated with high uncertainty (13% of dipper curves were excluded overall).

Estimated intrinsic blur (σ_i) and blur sensitivity (S) parameters were analyzed with a 2 (refractive status, between subjects factor) $\times$ 2 (viewing condition, within subjects factor) $\times$ 4 (eccentricity, within-subjects factor) mixed-design ANOVA. Blur sensitivity data did not respect the ANOVA assumption on the normality of the residuals. Thus blur sensitivity data was square-root transformed, and ANOVA was rerun on these transformed data that conformed to the ANOVA assumptions on the normality of the residuals. ANOVA results on the original and transformed data did not substantially differ; we report the ANOVA results on the transformed data for statistical rigor. Post-hoc comparisons were conducted via Bonferroni corrected t tests.

Results

Figure 4 shows group data dipper functions estimated under monocular and binocular testing conditions at each tested eccentricity. In both monocular and binocular viewing, blur thresholds increase with eccentricity. Also blur discrimination thresholds are generally lower in the binocular testing condition.

Figure 5 shows the intrinsic blur parameter of the estimated dipper curves. Intrinsic blur is larger under monocular than binocular conditions, $F(1, 42) = 12.75$, $p = 0.00091$, and increases with eccentricity, $F(3, 108) = 32.73$, $p = 10^{-14}$. There was no significant effect of

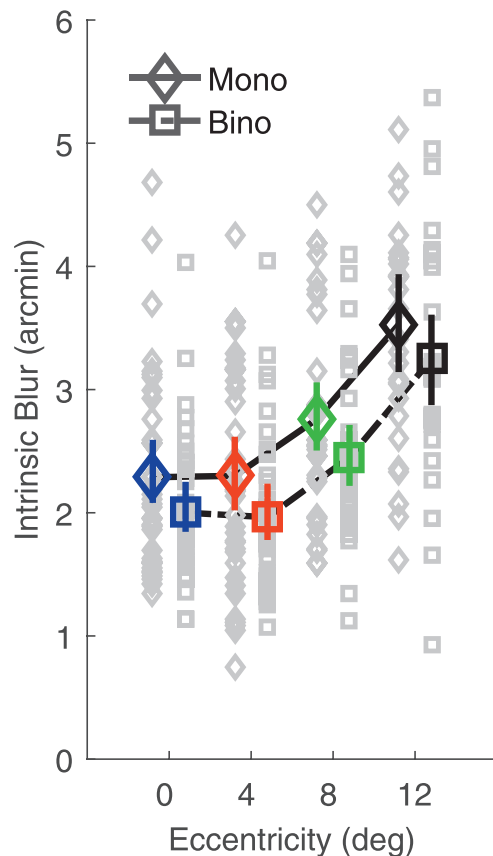


Figure 5. Intrinsic blur as a function of eccentricity in monocular and binocular viewing. Data are averaged across subjects for both monocular (diamonds) and binocular (squares) viewing conditions. Color-coding of eccentricity conditions is as in Figure 3. Error bars are 95% bootstrapped confidence intervals of the mean. Gray data points are individual subject data. Monocular and binocular data are shifted left and right for graphical purposes.

refractive group, $F(1, 38) = 0.54$, $p = 0.47$, and no significant two or three way interactions (all $ps > 0.6$).

Figure 6a shows blur sensitivity under monocular and binocular viewing. Blur sensitivity decreases with eccentricity, $F(3, 109) = 11.6$, $p = 10^{-6}$. Comparing monocular and binocular viewing, there was a significant main effect of viewing condition, $F(1, 43) = 5.88$, $p = 0.020$, and a significant two-way interaction between viewing condition and eccentricity, $F(3, 75) = 4.91$, $p = 0.0036$. Post-hoc test following the significant interaction between viewing condition and eccentricity revealed that blur sensitivity is higher under binocular viewing conditions at 0° eccentricity ($p = 0.012$). However, there was no significant difference in blur sensitivity between binocular and monocular viewing conditions at 4° , 8° , and 12° of eccentricity (all $ps > 0.25$). To summarize these results, in Figure 6b we plot binocular sensitivity advantage as a function of eccentricity. That is, we plot the difference between blur sensitivity measured binocularly and monocularly at

each tested eccentricity. If binocular viewing boosts blur sensitivity, we would expect the binocular sensitivity advantage to be positive. We can see that on average, binocular sensitivity advantage was positive, but significantly so only with central vision.

There was no significant main effect of refractive group on blur sensitivity, $F(1, 38) = 3.49$, $p = 0.069$, but a significant two-way interaction between viewing condition and refractive status, $F(1, 39) = 4.11$, $p = 0.049$. Bonferroni-corrected independent samples t tests revealed that myopes had significantly worse blur sensitivity than emmetropes monocularly ($p = 0.037$) but not binocularly ($p = 0.66$), as shown in Figure 5c. Lastly, there was no significant two-way interaction between eccentricity and refractive status, $F(3, 109) = 0.28$, $p = 0.84$, and no significant three-way interaction, $F(3, 75) = 1.09$, $p = 0.36$.

Discussion

We assessed monocular and binocular blur perception in the near peripheral vision in emmetropic and myopic subjects. It is known that the tolerance of blur increases in the far (Ronchi & Molesini, 1975) and near (Wang & Ciuffreda, 2004, 2005a) peripheral visual field. Blur perception is also known to follow a typical dipper shaped curve (Watson & Ahumada, 2011), with blur discrimination thresholds being lower than detection thresholds for small blur pedestals, and subsequently increasing with increasing levels of reference blur. This pattern is known to be maintained in the visual periphery, where blur discrimination thresholds with detectable levels of blur are lower than blur detection thresholds (Wang et al., 2006). We have replicated these findings by showing that blur perception worsens in the visual periphery and that performance can be described by a dipper-shaped function.

We have extended these findings to show that the increase in blur discrimination thresholds with increasing eccentricity can be attributed to two sources: (1) observers' increased intrinsic blur and (2) decreased blur sensitivity.

In the variance discrimination model we fit to our data, intrinsic blur represents the internal noise or the variance in luminance gradient due to the sensory system (Morgan et al., 2008). The intrinsic blur is thus due to the combined effects of aberrations in the eye's optics and to the noise in the neural transducer machinery. Intrinsic blur increased by 56% beyond 12° in the visual periphery. Part of this increase is likely due to the fact that the retinal surface is curved. Thus, when the eye is accommodating to place the flat surface of the monitor in focus at the fovea, the peripheral retina will experience defocus due to the curvature of the retina.

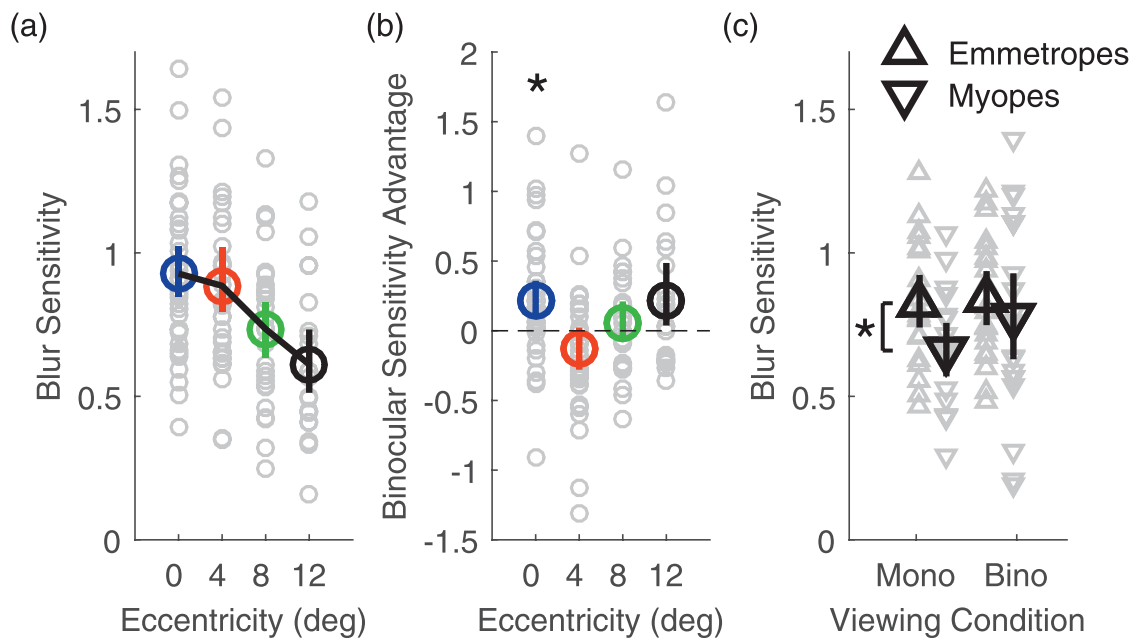


Figure 6. Blur sensitivity. (a) Blur sensitivity as a function of eccentricity averaged across subjects and viewing conditions. (b) Blur sensitivity advantage for binocular viewing compared with monocular viewing as a function of eccentricity averaged across all subjects. Color-coding of eccentricity conditions in (a) and (b) is as in Figure 4. (c) Monocular and binocular blur sensitivity in emmetropes (upwards pointing triangles) and myopes (downward pointing triangles). Data are averaged across eccentricities and across subjects in each refractive group. Error bars are 95% bootstrapped confidence intervals of the mean. Gray data points are individual subject data. * $p < 0.05$.

Other aberrations, (astigmatism, coma, and higher order aberrations) also increase in the visual periphery and might contribute to increased intrinsic blur, although removing these aberrations via adaptive optics does not improve peripheral visual resolution (Lundström et al., 2007). Subsampling and consequent aliasing (Artal, Derrington, & Colombo, 1995; Thibos, Walsh, & Cheney, 1987; Williams, Artal, Navarro, McMahon, & Brainard, 1996) due to the decrease in sampling density occurring throughout the peripheral retina (Lindsay & Norman, 1972) are also likely responsible for the observed increase in Intrinsic Blur. Overall, Intrinsic Blur estimates with our “dead leaves” stimuli were greater than those reported for border blur discrimination (Watson & Ahumada, 2011) or for blur discrimination with fractal patterns (Mather, 1997), suggesting that blur perception with naturalistic stimuli may be mediated by receptive fields with larger space constants (Mather & Smith, 2002).

Blur sensitivity decreased by 34% beyond 12° in the visual periphery and was overall quite poor if compared with, for example, spatial frequency discrimination (Hirsch & Hylton, 1982) or even stereoscopic disparity (e.g., Badcock & Schor, 1985), a fair comparison given that blur is an important cue to depth (Langer & Siciliano, 2015; Maiello et al., 2014; Maiello, Chessa et al., 2015; Mather, 1997; Mather & Smith, 2002; Vishwanath, 2012; Vishwanath & Blaser,

2010; Watt et al., 2005). For discrimination of more fundamental image properties such as contrast, dipper functions are thought to arise from the derivative of a sigmoidal transduction response function (Solomon, 2009; Wilson, 1980). Given the observers’ poor performance, it is unlikely that blur is represented in the human visual system by an analogous transducer function for image blur. The mechanisms employed for blur perception are a matter of debate. Watson and Ahumada (2011) criticize the variance discrimination model for not providing a mechanistic explanation of blur perception and propose an alternative model based on visible contrast energy detection in which the characteristic dipper shape of the blur discrimination function arises from the shape of the contrast sensitivity function (Campbell & Robson, 1968). Murray and Bex (2010), on the other hand, show that the contrast detection model cannot fit blur discrimination of Gaussian and Sinc-blurred images with the same contrast sensitivity function for the two different types of blur. Models based on luminance slope (such as the MIRAGE model, R. J. Watt & Morgan, 1985) rather than spatial frequency better predicted the data presented in Murray and Bex (2010).

Plainis et al. (2011) have shown that with visual blur induced by positive lenses, binocularity improved visual acuity and enhanced the P100 component of visual evoked potentials. We extend these findings by

showing that binocularity also improves visual blur perception. Our results show that combining the information from the two eyes leads to a reduction in the system's internal blur, which is consistent with the notion that combining information from the two eyes reduces noise (Legge, 1984a, 1984b). We also observed a small but statistically significant advantage in blur sensitivity when viewing stimuli binocularly with central vision. This suggests there may be additional binocular processing of blur in the center of the visual field.

Evidence for differences in the perception of blur across refractive groups is conflicting. Rosenfield and Abraham-Cohen (1999) found that thresholds for blur detection are impaired in myopes, whereas Cufflin et al. (2007) found that early onset myopes adapt more strongly to optical blur, yet Schmid et al. (2002) found no statistically significant differences between myopic and emmetropic children in the ability to detect blur. In the current study we have found no differences in the amount of intrinsic blur between myopic and emmetropic subjects. We have found instead that myopes have, on average, worse blur sensitivity than emmetropes monocularly but not binocularly. This suggests that myopes may process blur less efficiently than emmetropes monocularly but not binocularly. We could speculate that monocular deficits in blur processing may be linked to refractive error, but functionally these deficits are masked by binocular summation. In future work it might be informative to assess blur sensitivity both binocularly and monocularly in each eye, not only the dominant eye, to verify the degree to which binocular summation occurs in different refractive groups. Future investigations should also include hyperopic subjects as well as progressing myopes to further study the relationship between blur sensitivity and refractive error development. However, it is thought that the mechanisms that lead to hyperopia are not the same as those that lead to myopia (Borchert et al., 2011; Llorente, Barbero, Cano, Dorronsoro, & Marcos, 2004). Thus hyperopia and myopia should be investigated separately as different processes within the failure of emmetropization. In the current study we assessed blur perception using rendered Gaussian blur. It is probable that blur perception would differ with different kinds of blur, and that the specific type of defocus blur arising from an observer's own optics may have a role in emmetropization. Future studies should thus assess the differences in blur perception with different kinds of blur, such as defocus blur through an observer's own optics (Akeley, Watt, Girshick, & Banks, 2004; Love et al., 2009; Sebastian, Burge, & Geisler, 2015) or sync blur, which contains phase reversals typical of the modulation transfer function of an optical system with

a circular aperture such as the human pupil (Murray & Bex, 2010).

Keywords: blur perception, peripheral visual field, myopia, binocular vision

Acknowledgments

This research was supported by National Institutes of Health grant R01EY021553. Lenna Walker was supported by NEI T35 EY007149 to the New England College of Optometry; additional support was provided by internal funds from the New England College of Optometry.

Commercial relationships: Prevention and Treatment of Myopia Patent Application US 20160212404 A1 (GM, PJB, FAV).

Corresponding author: Guido Maiello.

Email: guido_maiello@yahoo.it.

Address: Department of Experimental Psychology, Justus-Liebig University, Gießen, Germany.

References

- Akeley, K., Watt, S. J., Girshick, A. R., & Banks, M. S. (2004). A stereo display prototype with multiple focal distances. Paper presented at the ACM Transactions on Graphics (TOG).
- Arnold, D. H., Grove, P. M., & Wallis, T. S. A. (2007). Staying focused: A functional account of perceptual suppression during binocular rivalry. *Journal of Vision*, 7(7):7, 1–8, doi:10.1167/7.7.7. [PubMed] [Article]
- Artal, P., Derrington, A. M., & Colombo, E. (1995). Refraction, aliasing, and the absence of motion reversals in peripheral vision. *Vision Research*, 35(7), 939–947, doi:10.1016/0042-6989(94)00180-T.
- Badcock, D. R., & Schor, C. M. (1985). Depth-increment detection function for individual spatial channels. *Journal of the Optical Society of America A*, 2(7), 1211–1216, doi:10.1364/JOSAA.2.001211.
- Banton, T., & Levi, D. M. (1991). Binocular summation in vernier acuity. *Journal of the Optical Society of America A*, 8(4), 673–680.
- Borchert, M. S., Varma, R., Cotter, S. A., Tarczy-Hornoch, K., McKean-Cowdin, R., Lin, J. H., . . . Ibironke, J. (2011). Risk factors for hyperopia and myopia in preschool children: The Multi-Ethnic Pediatric Eye Disease and Baltimore Pediatric Eye

- Disease Studies. *Ophthalmology*, 118(10), 1966–1973, doi:10.1016/j.ophtha.2011.06.030.
- Bordenave, C., Gousseau, Y., & Roueff, F. (2006). The dead leaves model: A general tessellation modeling occlusion. *Advances in Applied Probability*, 31–46.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, 10, 433–436.
- Campbell, F. W. (1957). The depth of field of the human eye. *Journal of Modern Optics*, 4(4), 157–164.
- Campbell, F. W., & Robson, J. G. (1968). Application of fourier analysis to the visibility of gratings. *The Journal of Physiology*, 197(3), 551–566.
- Christman, S. (1990). Effects of luminance and blur on hemispheric asymmetries in temporal integration. *Neuropsychologia*, 28(4), 361–374.
- Ciuffreda, K. J. (1991). Accommodation and its anomalies. In W.N. Charman (Ed.), *Vision and visual dysfunction: Visual optics and instrumentation* (pp. 231–279). London: MacMillan.
- Ciuffreda, K. J. (1998). Accommodation, pupil and presbyopia. In W.J. Benjamin (Ed.), *Borish's clinical refraction: Principles and practice* (pp. 77–20). Philadelphia: Saunders.
- Ciuffreda, K. J., Wang, B., & Vasudevan, B. (2007). Conceptual model of human blur perception. *Vision Research*, 47(9), 1245–1252.
- Cufflin, M. P., Mankowska, A., & Mallen, E. A. (2007). Effect of blur adaptation on blur sensitivity and discrimination in emmetropes and myopes. *Investigative Ophthalmology & Visual Science*, 48(6), 2932–2939. [PubMed] [Article]
- Fisher, S. K., & Ciuffreda, K. J. (1988). Accommodation and apparent distance. *Perception*, 17(5), 609–621.
- Flitcroft, D. (1998). A model of the contribution of oculomotor and optical factors to emmetropization and myopia. *Vision Research*, 38(19), 2869–2879.
- Flitcroft, D., Judge, S., & Morley, J. (1992). Binocular interactions in accommodation control: Effects of anisometric stimuli. *The Journal of Neuroscience*, 12(1), 188–203.
- Galvin, S. J., O'Shea, R. P., Squire, A. M., & Hailstone, D. S. (1999). Sharpness overconstancy: The roles of visibility and current context. *Vision Research*, 39(16), 2649–2657.
- Georgeson, M. A., May, K. A., Freeman, T. C. A., & Hesse, G. S. (2007). From filters to features: Scale-space analysis of edge and blur coding in human vision. *Journal of Vision*, 7(13):7, 1–21, doi:10.1167/7.13.7. [PubMed] [Article]
- Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.
- Hamerly, J. R., & Dvorak, C. A. (1981). Detection and discrimination of blur in edges and lines. *Journal of the Optical Society of America A*, 71(4), 448–452.
- Heravian, J., Jenkins, T., & Douthwaite, W. (1990). Binocular summation in visually evoked responses and visual acuity. *Ophthalmic and Physiological Optics*, 10(3), 257–261.
- Hess, R. F., Schmid, K. L., Dumoulin, S. O., Field, D. J., & Brinkworth, D. R. (2006). What image properties regulate eye growth? *Current Biology*, 16(7), 687–691.
- Hirsch, J., & Hylton, R. (1982). Limits of spatial-frequency discrimination as evidence of neural interpolation. *Journal of the Optical Society of America*, 72(10), 1367–1374, doi:10.1364/JOSA.72.001367.
- Hoffman, D. M., & Banks, M. S. (2010). Focus information is used to interpret binocular images. *Journal of Vision*, 10(5):13, 1–17, doi:10.1167/10.5.13. [PubMed] [Article]
- Horwood, A. M., & Riddell, P. M. (2009). Receding and disparity cues aid relaxation of accommodation. *Optometry and Vision Science*, 86(11), 1276.
- Huang, J., Hung, L.-F., & Smith E. L. III, (2012). Recovery of peripheral refractive errors and ocular shape in rhesus monkeys (*Macaca mulatta*) with experimentally induced myopia. *Vision Research*, 73, 30–39.
- Jacobs, R., Smith, G., & Chan, C. (1989). Effect of defocus on blur thresholds and on thresholds of perceived change in blur: Comparison of source and observer methods. *Optometry & Vision Science*, 66(8), 545–553.
- Kompaniez, E., Sawides, L., Marcos, S., & Webster, M. A. (2013). Adaptation to interocular differences in blur. *Journal of Vision*, 13(6):19, 1–14, doi:10.1167/13.6.19. [PubMed] [Article]
- Langer, M. S., & Siciliano, R. A. (2015). Are blur and disparity complementary cues to depth? *Vision Research*, 107, 15–21.
- Lee, A. B., Mumford, D., & Huang, J. (2001). Occlusion models for natural images: A statistical study of a scale-invariant dead leaves model. *International Journal of Computer Vision*, 41(1-2), 35–59.
- Legge, G. E. (1984a). Binocular contrast summation—I. Detection and discrimination. *Vision Research*, 24(4), 373–383.
- Legge, G. E. (1984b). Binocular contrast summation—

- II. Quadratic summation. *Vision Research*, 24(4), 385–394.
- Lin, Z., Vasudevan, B., Liang, Y. B., Zhang, Y. C., Zhao, S. Q., Yang, X. D., . . . Ciufreda, K. J. (2013). Nearwork-induced transient myopia (NITM) in anisometropia. *Ophthalmic and Physiological Optics*, 33(3), 311–317.
- Lindsay, P. H., & Norman, D. A. (1972). *Human information processing: An introduction to psychology*. New York: Academic Press.
- Llorente, L., Barbero, S., Cano, D., Dorronsoro, C., & Marcos, S. (2004). Myopic versus hyperopic eyes: Axial length, corneal shape and optical aberrations. *Journal of Vision*, 4(4):5, 288–298, doi:10.1167/4.4.5. [PubMed] [Article]
- López-Gil, N., Martín, J., Liu, T., Bradley, A., Díaz-Muñoz, D., & Thibos, L. N. (2013). Retinal image quality during accommodation. *Ophthalmic and Physiological Optics*, 33(4), 497–507.
- Love, G. D., Hoffman, D. M., Hands, P. J., Gao, J., Kirby, A. K., & Banks, M. S. (2009). High-speed switchable lens enables the development of a volumetric stereoscopic display. *Optics Express*, 17(18), 15716–15725.
- Lundström, L., Manzanera, S., Prieto, P. M., Ayala, D. B., Gorceix, N., Gustafsson, J., . . . Artal, P. (2007). Effect of optical correction and remaining aberrations on peripheral resolution acuity in the human eye. *Optics Express*, 15(20), 12654–12661, doi:10.1364/OE.15.012654.
- Maiello, G., Chessa, M., Solari, F., & Bex, P. J. (2014). Simulated disparity and peripheral blur interact during binocular fusion. *Journal of Vision*, 14(8):13, 1–14, doi:10.1167/14.8.13. [PubMed] [Article]
- Maiello, G., Chessa, M., Solari, F., & Bex, P. J. (2015). The (in) effectiveness of simulated blur for depth perception in naturalistic images. *PloS One*, 10(10), e0140230.
- Maiello, G., Harrison, W., Vera-Díaz, F., & Bex, P. (2015). Perceptual consequences of elongated eyes. *Journal of Vision*, 15(12):111, doi:10.1167/15.12.111. [Abstract]
- Mather, G. (1997). The use of image blur as a depth cue. *Perception*, 26(9), 1147–1158.
- Mather, G., & Smith, D. R. (2002). Blur discrimination and its relation to blur-mediated depth perception. *Perception*, 31(10), 1211–1219.
- McFadden, S. A., Tse, D. Y., Bowrey, H. E., Leotta, A. J., Lam, C. S., Wildsoet, C. F., To, C. H. (2014). Integration of defocus by dual power Fresnel lenses inhibits myopia in the mammalian EyeDefocus integration by dual power fresnel lenses. *Investigative Ophthalmology & Visual Science*, 55(2), 908–917. [PubMed] [Article]
- Morgan, M., Chubb, C., & Solomon, J. A. (2008). A ‘dipper’ function for texture discrimination based on orientation variance. *Journal of Vision*, 8(11):9, 1–8, doi:10.1167/8.11.9. [PubMed] [Article]
- Murray, S., & Bex, P. J. (2010). Perceived blur in naturally contoured images depends on phase. *Frontiers in Psychology*, 1, 185.
- Norton, T. T., Siegwart, J. T., & Amedo, A. O. (2006). Effectiveness of hyperopic defocus, minimal defocus, or myopic defocus in competition with a myopiagenic stimulus in tree shrew eyes. *Investigative Ophthalmology & Visual Science*, 47(11), 4687–4699. [PubMed] [Article]
- Oshima, S. (1958). Studies on the depth-of-focus of the eye. *Japanese Journal of Ophthalmology*, 2, 63–72.
- Päakkönen, A. K., & Morgan, M. J. (1994). Effects of motion on blur discrimination. *Journal of the Optical Society of America A*, 11(3), 992–1002.
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 10(4), 437–442.
- Plainis, S., Petratos, D., Giannakopoulou, T., Atchison, D. A., & Tsilimbaris, M. K. (2011). Binocular summation improves performance to defocus-induced blur. *Investigative Ophthalmology & Visual Science*, 52(5), 2784–2789. [PubMed] [Article]
- Poulere, E., Moschandreass, J., Kontadakis, G. A., Pallikaris, I. G., & Plainis, S. (2013). Effect of blur and subsequent adaptation on visual acuity using letter and Landolt C charts: Differences between emmetropes and myopes. *Ophthalmic and Physiological Optics*, 33(2), 130–137.
- Ronchi, L., & Molesini, G. (1975). Depth of focus in peripheral vision. *Ophthalmic Research*, 7(3), 152–157.
- Rosén, R., Lundström, L., & Unsbo, P. (2011). Influence of optical defocus on peripheral vision. *Investigative Ophthalmology & Visual Science*, 52(1), 318–323. [PubMed] [Article]
- Rosenfield, M., & Abraham-Cohen, J. A. (1999). Blur sensitivity in myopes. *Optometry & Vision Science*, 76(5), 303–307.
- Schmid, K. L., Iskander, D. R., Li, R. W., Edwards, M. H., & Lew, J. K. (2002). Blur detection thresholds in childhood myopia: Single and dual target presentation. *Vision Research*, 42(2), 239–247.
- Schor, C. (1999). The influence of interactions between accommodation and convergence on the lag of

- accommodation. *Ophthalmic and Physiological Optics*, 19(2), 134–150.
- Sebastian, S., Burge, J., & Geisler, W. S. (2015). Defocus blur discrimination in natural images with natural optics. *Journal of Vision*, 15(5):16, 1–17, doi:10.1167/15.5.16. [PubMed] [Article]
- Smith E. L., III, Campbell, M. C., & Irving, E. (2013). Does peripheral retinal input explain the promising myopia control effects of corneal reshaping therapy (CRT or ortho-K) & multifocal soft contact lenses? *Ophthalmic and Physiological Optics*, 33(3), 379–384.
- Smith E. L., III, & Li-Fang, H. (1999). The role of optical defocus in regulating refractive development in infant monkeys. *Vision Research*, 39(8), 1415–1435.
- Smith E. L., III, Li-Fang, H., & Harwerth, R. S. (1994). Effects of optically induced blur on the refractive status of young monkeys. *Vision Research*, 34(3), 293–301.
- Smith E. L., III, Ramamirtham, R., Qiao-Grider, Y., Hung, L.-F., Huang, J., Kee, C.-s., ... Paysse E. (2007). Effects of foveal ablation on emmetropization and form-deprivation myopia. *Investigative Ophthalmology & Visual Science*, 48(9), 3914–3922. [PubMed] [Article]
- Solomon, J. A. (2009). The history of dipper functions. *Attention, Perception, & Psychophysics*, 71(3), 435–443, doi:10.3758/app.71.3.435.
- Strang, N. C., Day, M., Gray, L. S., & Seidel, D. (2011). Accommodation steps, target spatial frequency and refractive error. *Ophthalmic and Physiological Optics*, 31(5), 444–455.
- Taylor, J., Charman, W. N., O'Donnell, C., & Radhakrishnan, H. (2009). Effect of target spatial frequency on accommodative response in myopes and emmetropes. *Journal of Vision*, 9(1):16, 1–14, doi:10.1167/9.1.16. [PubMed] [Article]
- Thibos, L. N., Walsh, D. J., & Cheney, F. E. (1987). Vision beyond the resolution limit: Aliasing in the periphery. *Vision Research*, 27(12), 2193–2197, doi:10.1016/0042-6989(87)90134-9.
- Vera-Diaz, F. A., Kerber, K. L., Thorn, F., & Bex, P. J. (2013). Peripheral awareness and attention in myopia. Presented at the 14th International Myopia Conference, Asilomar, CA, August 20, 2013.
- Vera-Diaz, F. A., Maiello, G., Kerber, K. L., Thorn, F., & Bex, P. (2015). Myopes' ability to discriminate and detect blur. *Investigative Ophthalmology & Visual Science*, 56(7), 537. [Abstract]
- Vishwanath, D. (2012). The utility of defocus blur in binocular depth perception. *i-Perception*, 3(8), 541–546.
- Vishwanath, D., & Blaser, E. (2010). Retinal blur and the perception of egocentric distance. *Journal of Vision*, 10(10):26, 1–16, doi:10.1167/10.10.26. [PubMed] [Article]
- Vul, E., Bergsma, J., & MacLeod, D. I. (2010). Functional adaptive sequential testing. *Seeing and Perceiving*, 23(5), 483–515.
- Wallis, T. S., & Bex, P. J. (2012). Image correlates of crowding in natural scenes. *Journal of Vision*, 12(7):6, 1–19, doi:10.1167/12.7.6. [PubMed] [Article]
- Wallman, J., & Winawer, J. (2004). Homeostasis of eye growth and the question of myopia. *Neuron*, 43(4), 447–468.
- Walsh, G., & Charman, W. (1988). Visual sensitivity to temporal change in focus and its relevance to the accommodation response. *Vision Research*, 28(11), 1207–1221.
- Wang, B., & Ciuffreda, K. J. (2004). Depth-of-focus of the human eye in the near retinal periphery. *Vision Research*, 44(11), 1115–1125.
- Wang, B., & Ciuffreda, K. J. (2005a). Blur discrimination of the human eye in the near retinal periphery. *Optometry & Vision Science*, 82(1), 52–58.
- Wang, B., & Ciuffreda, K. J. (2005b). Foveal blur discrimination of the human eye. *Ophthalmic and Physiological Optics*, 25(1), 45–51.
- Wang, B., & Ciuffreda, K. J. (2006). Depth-of-focus of the human eye: theory and clinical implications. *Survey of Ophthalmology*, 51(1), 75–85.
- Wang, B., Ciuffreda, K. J., & Irish, T. (2006). Equiblur zones at the fovea and near retinal periphery. *Vision Research*, 46(21), 3690–3698.
- Watson, A. B., & Ahumada, A. J. (2011). Blur clarified: A review and synthesis of blur discrimination. *Journal of Vision*, 11(5):10, 1–23, doi:10.1167/11.5.10. [PubMed] [Article]
- Watt, R. J., & Morgan, M. J. (1983). The recognition and representation of edge blur: evidence for spatial primitives in human vision. *Vision Research*, 23(12), 1465–1477.
- Watt, R. J., & Morgan, M. J. (1984). Spatial filters and the localization of luminance changes in human vision. *Vision Research*, 24(10), 1387–1397.
- Watt, R. J., & Morgan, M. J. (1985). A theory of the primitive spatial code in human vision. *Vision Research*, 25(11), 1661–1674, doi:10.1016/0042-6989(85)90138-5.
- Watt, S. J., Akeley, K., Ernst, M. O., & Banks, M. S. (2005). Focus cues affect perceived depth. *Journal*

- of Vision*, 5(10):7, 834–862, doi:10.1167/5.10.7. [PubMed] [Article]
- Wildsoet, C., & Wallman, J. (1995). Choroidal and scleral mechanisms of compensation for spectacle lenses in chicks. *Vision Research*, 35(9), 1175–1194.
- Williams, D. R., Artal, P., Navarro, R., McMahon, M. J., & Brainard, D. H. (1996). Off-axis optical quality and retinal sampling in the human eye. *Vision Research*, 36(8), 1103–1114, doi:10.1016/0042-6989(95)00182-4.
- Wilson, H. R. (1980). A transducer function for threshold and suprathreshold human vision. *Biological Cybernetics*, 38(3), 171–178, doi:10.1007/bf00337406.
- Wood, J. M., Collins, M. J., Chaparro, A., Marszalek, R., Carberry, T., Lacherez, P., & Chu, B. S. (2014). Differential effects of refractive blur on day and nighttime driving performance. *Investigative Ophthalmology & Visual Science*, 55(4), 2284–2289. [PubMed] [Article]
- Yamaguchi, T., Ohnuma, K., Konomi, K., Satake, Y., Shimazaki, J., & Negishi, K. (2013). Peripheral optical quality and myopia progression in children. *Graefe's Archive for Clinical and Experimental Ophthalmology*, 251(10), 2451–2461.

Supplementary Material to :

Blur Perception Throughout the Visual Field in Myopia and Emmetropia

Authors:

Guido Maiello^{a,b} PhD, Lenna Walker BSc^c, Peter J. Bex PhD^b, and Fuensanta A. Vera-Diaz, OD, PhD, FAAO^c

^a UCL Institute of Ophthalmology, University College London, London, UK

^b Northeastern University, 360 Huntington Avenue, Boston, Massachusetts 02115

^c New England College of Optometry, 424 Beacon Street, Boston, Massachusetts 02115

Corresponding author: Guido Maiello

Email: guido_maiello@yahoo.it

Present address: Department of Experimental Psychology, Justus-Liebig University Gießen, Otto-Behaghel-Str.10F, Gießen 35394, Germany

Appendix

Validation of the FAST Testing Procedure

The most common approach in psychophysics is to extensively test a small number of trained subjects. Given the number of conditions we set forth to test in the current study and the assessment of healthy young myopic subjects, typical psychophysical experimental sessions would have required several thousand trials and multiple hours of testing per subject. To limit testing time to a single hour per subject, we employed the FAST testing procedure (Vul, Bergsma, & MacLeod, 2010) to optimize the length of the experimental sessions with respect to the number of conditions tested. The FAST algorithm has not, to our knowledge, been previously employed to measure blur dipper functions. Thus, we ran the following control experiment to verify that the procedure would produce meaningful results throughout the range of conditions we tested. We measured binocular blur dipper functions at the fovea and at 12 degrees eccentricity both using the FAST algorithm and using a typical psychophysical approach.

Specifically, at each eccentricity we employed randomly interleaved three-down, one-up staircases (Wetherill & Levitt, 1965) to measure blur discrimination thresholds at five pedestal blur levels [0.125, 0.5, 2, 8, 32] arcmin. The raw data from 75 trials from each staircase were combined and fitted with a cumulative normal function by weighted least-squares regression (in which the data are weighted by their binomial standard deviation). Blur discrimination thresholds were estimated from the midpoint of the psychometric function. For both eccentricities tested these thresholds were then fitted to the dipper function presented in Equation 1. We also employed the FAST algorithm as described in the Methods section of the main text

to measure blur dipper functions at 0 and 12 degrees eccentricity. Staircase and FAST trials were randomly interleaved throughout the same experimental session.

The experiment was programmed with the Psychophysics Toolbox Version 3 (Brainard, 1997; Pelli, 1997) in Matlab. Five subjects were recruited for this experiment, which included authors GM and PJB as well as three naïve observers. Observers were placed 45 cm in front of a gamma corrected BenQ XL2720Z monitor (1920x1080 pixels resolution, 120 Hz, NVidia Quadro K420 GPU) with their head stabilized in a chinrest. Stimuli were the same dead leaves stimuli as those employed for the experiments described in the main text, scaled appropriately for the current viewing distance and monitor size. Because of the different setup, the full field stimuli spanned 41x41 degrees of visual angle. All other procedures were the same as those described in the main text.

Figure S1 presents the results of this experiment. Figure S1(a) shows individual and average thresholds (small and large circles) estimated using the staircase procedure at each pedestal blur level, as well as individual subject and average dipper functions estimated using the FAST testing procedure (thin and thick lines respectively). Data for the 0 deg condition are shown in blue, for the 12 deg condition in black.

As per the main experiment, the data from both the staircase and FAST procedures show that blur discrimination worsens in the visual periphery because intrinsic blur increases and blur sensitivity decreases. Furthermore, the average threshold functions estimated using the FAST procedure overlap the average threshold estimates from the staircase procedure.

To further verify the agreement between FAST and staircase procedures, Figures S1b and c show Bland & Altman (Bland & Altman, 1986) plots for Intrinsic Blur and Blur Sensitivity respectively. The bias between testing procedures was not significantly different from zero for either Intrinsic Blur ($p=0.92$, one sample t-test) nor for Blur Sensitivity ($p=0.43$, one sample t-test). The spread of the 95% limits of agreement, i.e. the range within which a difference value between tests is likely to fall for most participants, suggests that some of the between subjects variability observed in the results presented in Figures 5 and 6 is due to measurement noise. However, the fact that there is no bias suggests that both testing methods converge onto the true population averages given as few as five subjects. Hence, the FAST testing procedure provides unbiased estimates of blur discrimination functions with a five-fold reduction in testing time with respect to a more classic psychophysical approach.

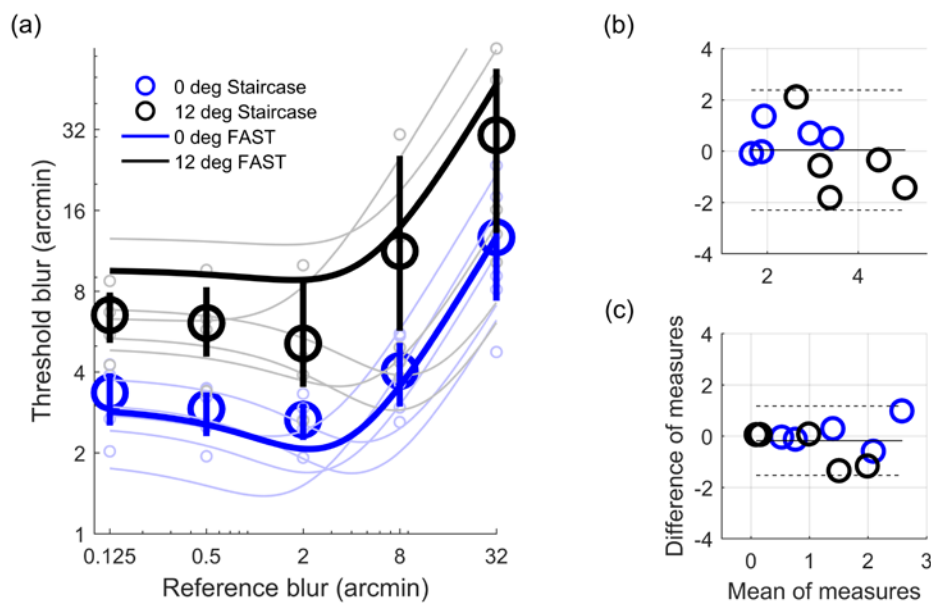


Figure S1. Comparison of the FAST procedure and a classical staircase procedure. (a) Threshold blur as a function of pedestal blur measured at 0 deg (blue) and 12 deg (black)

eccentricity. Thin circles are individual subject blur thresholds estimated using a staircase procedure (75 trials per pedestal level at each condition, 375 trials to estimate a full curve). Large circles are mean thresholds bounded by 95% confidence intervals. Thin lines are individual subject dipper blur threshold functions estimated using the FAST testing procedure (75 trials to estimate a full curve). Thick lines are mean dipper blur threshold functions. (b-c) Bland & Altman difference plots for (b) Intrinsic Blur and (c) Blur Sensitivity parameters estimated using FAST and by fitting Equation 1 to blur thresholds estimates obtained using the staircase procedure. The difference between the parameters estimated with the two testing procedures (i.e. staircase - FAST) are plotted as a function of mean values of the two (i.e., (staircase + FAST)/2) for each subject and each eccentricity condition (circles, blue for 0 deg, black for 12 deg). The black horizontal line is the bias between the two procedures, a value of zero on the y-axis indicates no difference between the two testing procedures. The dotted lines are the 95% limits of agreement, i.e. the range within which a difference value between tests is likely to fall for most participants.

Supplementary References

- Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet*, 327(8476), 307-310.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, 10, 433-436.
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 10(4), 437-442.
- Vul, E., Bergsma, J., & MacLeod, D. I. (2010). Functional adaptive sequential testing. *Seeing and Perceiving*, 23(5), 483-515.
- Wetherill, G., & Levitt, H. (1965). Sequential estimation of points on a psychometric function. *British Journal of Mathematical and Statistical Psychology*, 18(1), 1-10.