PERIPHERAL VISION, ACCOMMODATION AND BLUR PERCEPTION IN MYOPIA

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

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Thesis Committee in satisfaction of the
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New England College of Optometry, 2016

Disruption of the normal visual experience and changes in the normal interaction between central and peripheral vision may lead to failure of emmetropization and the development of myopia. Currently, there is no consensus as to what specific aspects of the visual environment are necessary for normal emmetropization. We studied various factors that may affect the risk for myopia, i.e., level of visual attention of tasks performed, ability to accommodate using different cues, and the ability to detect and discriminate blur.

In the first study we examined the effect of central vision attentional load on peripheral contrast sensitivity in order to evaluate the impact of every day tasks, which require greater attention to be deployed to central vision. Peripheral contrast detection thresholds were measured binocularly using vertical Gabor stimuli presented at three eccentricities (±8°, 17°, 30°) in a spatial 2AFC task. Contrast thresholds were measured in young (mean age 24.5±2.6 years) adult emmetropes (n=17; group SE: +0.19±0.32D) and myopes (n=25; group SE: -3.74±1.99D). Attention at central fixation was manipulated with: (1) a low attention task, requiring simple fixation; or (2) a high attention mathematical task at fixation. An interaction between eccentricity and attentional load, with a significantly higher contrast detection thresholds for the high attentional load task was found at 30° eccentricity for the overall subject group (linear mixed model, $p<0.01$). Attentional load did not cause a change in contrast thresholds at 8° or 17°. The high attention task induced a significant increase in detection thresholds at 30° for myopes (Wilcoxon Signed Rank, $p=0.016$), but not for emmetropes (Wilcoxon Signed Rank, $p=0.268$).

These data indicate that myopes experience a greater decrease in contrast sensitivity in the far periphery than emmetropes when attention is deployed centrally.

In the second study we assessed blur detection and discrimination thresholds in young adults emmetropes (n=13; group SE: +0.19 ± 0.25D), myopes (n=19; group SE: -4.14 ± 2.64D), and hyperopes (n=2; group SE: +2.50 ± 1.16D). Blur thresholds were measured using a spatial 4-alternative forced choice (4AFC) task with "dead leaves" stimuli presented at 40cm. Subjects were asked which quadrant appeared blurriest. Blur thresholds were fitted using dipper functions. There was no difference in intrinsic blur (Wilcoxon Rank-Sum, p=0.52), blur detection thresholds or blur discrimination thresholds (Wilcoxon Rank-Sum, p>0.05) between refractive groups. These data do not support a difference between myopes and emmetropes at detecting or discriminating central blur.

In the third study we used a PowerRefractor to measure accommodation responses to stimuli that mimicked natural images with different accommodative cues (None, Blur, Disparity [3D], Size, All cues). Stimuli were presented on a 3D display at 40cm while subjects wore 3D shutter glasses. Accommodation responses to 2D flat images with no accommodation cues were less stable in myopes (Wilcoxon Rank-Sum, p=0.01), but became as stable as in emmetropes when 3D or blur cues were added. Accommodation latencies and amplitude did not differ significantly among the refractive groups (Wilcoxon Rank-Sum, p>0.05).

The overall conclusion of these studies is that all factors investigated, central attention, peripheral vision, blur perception and accommodation responses, may be associated with myopia. Further studies are needed to evaluate whether this relationship is causal.

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1. General Introduction

It is accepted that disruption of the normal visual experience may lead to failure of emmetropization and development of refractive errors in susceptible individuals (McBrien and Adams, 1997; Saw, 2003; Wallman and Winawer, 2004; Siegwart and Norton, 2011). The failure of emmetropization arises from a multitude of factors that combine a predisposing genetic susceptibility with a major role for environmental factors, such as higher education level, likely related to an increased amount of near work (Saw, Chua, Hong, Wu, Chan, Chia, Stone, and Tan, 2002; Wang, Bao, Ou, Thorn, and Lu, 2013; Scheiman, Zhang, Gwiazda, Hyman, Harb, Weissberg, Weis, and Dias, 2014), and decreased time spent outdoors (Jones, Sinnott, Mutti, Mitchell, Moeschberger, and Zadnik, 2007; Rose, Morgan, Ip, Kifley, Huynh, Smith, and Mitchell, 2008a; Rose, Morgan, Smith, Burlutsky, Mitchell, and Saw, 2008b; Dirani, Tong, Gazzard, Zhang, Chia, Young, Rose, Mitchell, and Saw, 2009; Deng, Gwiazda, and Thorn, 2010). These factors are not necessarily dependent on each other (Rose et al., 2008a). Which aspects of nearwork may constitute a risk for myopia and which aspects of outdoors may be protective of myopia are yet to be determined. To further evaluate properties of nearwork and outdoors, three experiments were devised to assess differences in peripheral vision, attention, accommodation, and blur between myopes and emmetropes.

Studies using animal models have shown that peripheral visual input is important in normal emmetropization (Wallman, Gottlieb, Rajaram, and Fugate-Wentzek, 1987; Smith, Ramamirtham, Oiao-Grider, Hung, Huang, Kee, Coats, and Paysse, 2007; Smith, Hung, and Huang, 2009; Huang, Hung, and Smith, 2011; Liu and Wildsoet 2011). One possible

hypothesis on the role of outdoors in protecting myopia is that less time outdoors may lead to an abnormal peripheral visual input, therefore affecting the emmetropization process (Jones et al., 2007; Rose et al., 2008; Dirani et al., 2009; Deng et al., 2010). It has been argued that the range of neural responses at various retinal eccentricities may constitute the signal for the sclera to control its growth and promote emmetropization (McBrien, Moghaddam, Cottriall, Leech, and Cornell, 1995; Guo, Frost, Siegwart, and Norton, 2014; Srinvasalu, McFadden, Medcalf, Philip, Riaz, and Baird, 2015; Wang, Chun, Zhou, Zuo, Li, & Liu, 2015). Overall, this evidence suggests that a delicate balance between central and peripheral vision stimulation is important and that normal blur perception is necessary to emmetropize normally.

Indoor and outdoor environments also differ in the level of stress and consequent ability of subjects to concentrate they induce (Ulrich, 1984). These findings have been attributed to differences in attention, with effortless involuntary attention dominant in outdoor environments and more demanding, capacity-limited directed attention required for tasks in indoor environments (Kaplan and Kaplan, 1989).

A demand on perceptual attention on central vision may affect the required balance between central and peripheral vision input. The level of perceptual load on central vision, foveally-fixated targets, decreases sensitivity of peripheral stimulus detection (Lavie, 2005; 2011; Plainis, Murray, and Chauhan, 2001; Carmel, Thorne, Rees, and Lavie, 2011). Indoor activities typically require high attentional load in central vision (e.g., computers, reading and similar tasks that are most common of indoor environments require increased attention) and may therefore decrease the likelihood of detecting, and perhaps processing, peripheral

stimuli. Mills et al. (2011) showed that fixation and eye movements are task-related (more centrally loaded tasks result in longer fixations and smaller eye movement amplitudes) and Harb et al. (2006) showed that myopes take fewer fixation breaks in near tasks. Their data provide preliminary evidence that fixation duration and eye movements may be related to the lack of peripheral vision stimulation and ultimately the development and/or progression of myopia.

Normal perception of blur and ability to see fine details are necessary for normal emmetropization (Smith, Hung, and Harwerth, 1994; Hess, Schmid, Dumoulin, and Field, Brinkworth, 2006; Rosén, Lundström, and Unsbo, 2012; Poulere, Moschandreas, Kontadakis, Pallikaris, and Plainis, 2013). Siedel et al. (2005) and Strang et al. (2011) demonstrated that myopes have increased difficulty in interpreting and responding to small changes in defocus. This reduced accommodative response has been linked to decreased blur sensitivity and failure to emmetropize (Rosenfield and Abraham-Cohen, 1999). However, there is no general consensus on myopes showing greater blur thresholds under normal (binocular) viewing (e.g., Schmid, Iskander, Li, Edwards, and Lew, 2002; Taylor et al., 2009) or if an abnormal sensitivity to blur is a causative factor for myopia development. We believe this may be due to the absence of near peripheral vision consideration in blur detection studies.

Indoor environments also provide dioptrically different visual stimuli than outdoor environments. The range of dioptric depths, distances and disparities present in outdoor scenes is far less than in indoor scenes (Howe and Purves, 2002; Liu, Bovik, and Cormack, 2008; Flitcroft, 2012) and therefore require accommodation and convergence over a much smaller dioptric range of distances than indoor scenes.

Guido et al. (2014, 2015) recently demonstrated that disparity and peripheral blur interact to modify eye-movement behavior and facilitate binocular fusion, but only geometric and stereoscopic disparity (not blur) cues improve depth perception sensitivity.

It has been suggested that both myopic children (Gwiazda, Thorn, Bauer, and Held, 1993) and myopic adults (Bullimore, Gilmartin, and Royston, 1992; Abbott, Schmid, and Strang, 1999) have less accurate accommodative responses compared to emmetropes (Harb, Thorn, and Troilo, 2006; Pandian, Sankaridurg, Naduvilath, O'Leary, Sweeney, Rose, and Mitchell, 2006; Langaas, Riddell, Svarverud, Ystenaes, Langeggen, and Bruenech, 2008; Price, Allen, Radhakrishnan, Calver, Rae, Theagarayan, Sailoganathan, and O'Leary, 2013). It is thought that such inaccuracies may lead to blur on the retina and therefore prevent normal emmetropization. Other studies, however, have not found an association between myopia and accommodative inaccuracies (Rosenfield, Desai, and Portello, 2002; Seidel, Gray, and Heron, 2005; Mutti, Mitchell, Hayes, Jones, Moeschberger, Cotter, Kleinstein, Manny, Twelker, and Zadnik, 2006; Taylor, Charmna, O'Donnell, and Radhakrishnan, 2009; Berntsen, Sinnott, Mutti, and Zadnik, 2011). Animal studies have also shown an association between inaccurate accommodation and myopia (Troilo, Quinn, and Baker, 2007).

There are numerous factors that influence the accommodation response, mainly the spatial content of the image, the level of blur on the retina, the amount of retinal disparity between the two eyes (stimulus to convergence and therefore accommodation) and the proximity of the attended object. In previous studies, some have found differences in myopes' accommodation (Gwiazda et al., 1993), but others have not (Schmid, Hilmer, Lawrence, Loh, Morrish, and Brown, 2005). This may be due to differences in the types of

stimuli used and whether they used various factors affecting accommodation or only using flat stimuli. It's possible that myopes may be only be able to accurately accommodate when multiple cues for accommodation, e.g., adequate spatial image content, proximity, disparity, or an adequate balance between central and peripheral retinal blur, are present.

The following three research studies 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. The three studies were approved by the New England College of Optometry's Institutional Review Board.

2. Study One: Peripheral Contrast Sensitivity and Attention in Myopia

The results in this study were submitted to Vision Research, the manuscript is under review at the time of the submission of this thesis.

2.1. Background and Hypothesis

This experiment sought to explore the role of central attentional load on peripheral contrast thresholds. We hypothesized that increased central attentional load results in decreased peripheral contrast thresholds, and may therefore affect the normal balance between central and peripheral vision and the normal process of emmetropization. More specifically, we expected to see a more significant decrease in peripheral sensitivity when subjects performed tasks that required higher central attention in progressing myopes compared to stable myopes and emmetropes.

2.2. Methods

2.2.1. Subjects

Criteria for subjects' inclusion were: (1) no history of surgery or eye disease that may have resulted in visual consequences, (2) within 18-32 years of age, (3) best corrected VA=20/20 (logMAR 0.0) or better in each eye, (4) not using drugs that may affect their vision, (5) no current binocular vision or accommodative dysfunction, (6) contact lens wear if refractive correction is more myopic than -4.00DS, (7) refractive error (spherical equivalent, SE, in the least myopic eye) between +0.75 and -14.00DS with less than 1.50DC of astigmatism or 1.00D of anisometropia.

Refractive status was determined by refractive history and open-field autorefraction at the time of study. Refractive status was re-evaluated at a 6-month follow-up. Subjects were classified into two refractive groups: emmetropes, defined as SE in each eye between +0.75 to -0.25DS; and myopes, defined as SE in each eye between -0.50 to -14.00DS.

A total of 45 young adult subjects (Mean: 24.5 ± 2.6 years) were recruited and tested in this study. For 2 myopic and 1 emmetropic subjects, psychometric functions could not be fit and their data were not used, therefore data for a total of 42 subjects is included in the analyses. The refractive error of these 42 subjects ranged from SE in the least myopic eye between +0.75D to -8.50DS (Mean: -2.13 ± 2.48DS). Of these, 25 subjects were myopes (Mean: -3.74 ± 1.99DS) and 17 emmetropes (Mean: +0.19 ± 0.32DS).

2.2.2. Procedures

A vision screening was used to determine eligibility and refractive group category. The vision screening included an ocular history questionnaire, open-field autorefraction (Grand Seiko WR-5100K), axial length measurements (Zeiss IOL Master), distance VA, and ocular health evaluation.

Subjects who were eligible continued with the experimental testing. All myopes were corrected with contact lenses if they required refractive correction for the 100cm viewing distance of the task. Subjects viewed the targets on a 60-inch 8-bit LCD display presented with a uniform grey background (50 cd/m^2 mean luminance) (Figure 1) under mesopic room lighting conditions.

Following instructions and a period of training, subjects performed two psychophysical visual tasks assigned in a random order. Both tasks were identical in that they measured peripheral contrast sensitivity thresholds binocularly.

Subjects were asked to determine whether a peripheral stimulus was presented to the right or to the left of their central fixation by pressing left or right arrow keys, respectively, on a keyboard. Stimuli were Gabor patches with vertical gratings of spatial frequency (ω) and a standard deviation (σ) for the overall patch width (Figure 1) that were m-scaled for retinal eccentricity (Rovamo and Virsu, 1979). Gabor stimuli were presented within a Gaussian temporal window (σt=133ms) at one of three eccentricities randomly interleaved in a single run of 150 trials: 8 degrees (σ=0.25°, ω=3.08 c/deg), 17 degrees (σ=0.5°, ω=1.63 c/deg), and 30 degrees (σ=0.5°, ω=1.03 c/deg). Stimuli were briefly (133ms) presented at the required eccentricity on either the right or left side (at random) of the subject's central fixation. The contrast of the Gabor stimulus was under the control of a 3 down, 1 up adaptive staircase (Wetherill and Levitt, 1965) designed to converge on a contrast that produced 79.4% correct target detection. The detection task was performed two times under low and two times under high attention load conditions in a random order.

For the "low" attentional load condition, subjects were asked to look straight ahead at a fixation target in the center of the screen while performing the peripheral detection task (Figure 1).

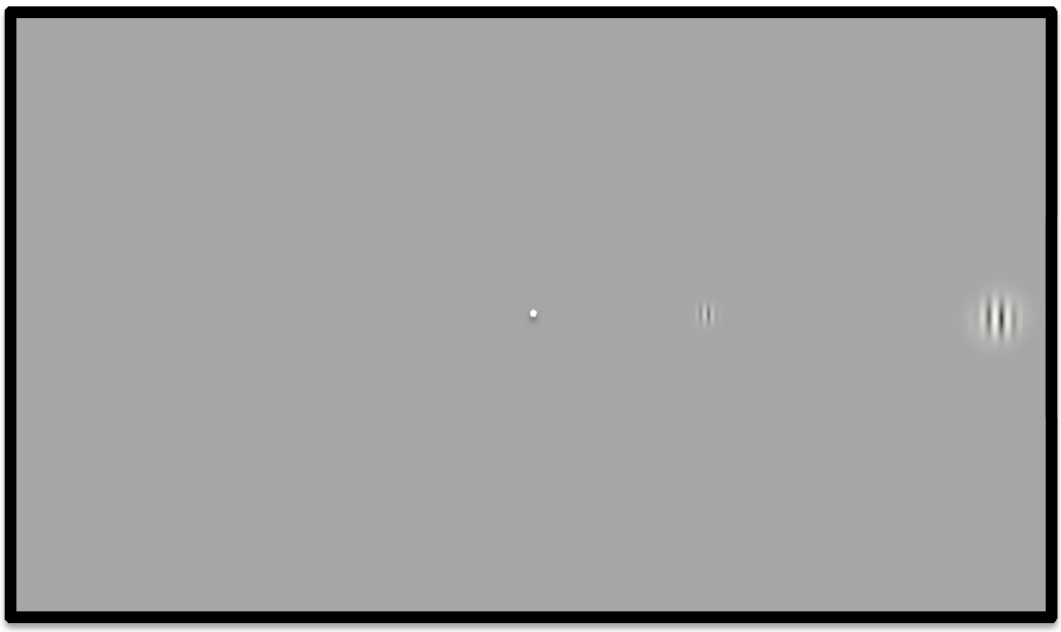


Figure 1. Representation of the low attentional load task: display and peripheral stimuli at the three set eccentricities (8, 17, and 30 degrees), only one presented at a time, at a random location (left or right), and random eccentricity.

For the "high" attentional load condition, subjects performed the same peripheral detection task while simultaneously performing an additional mathematical task at fixation (Figure 2). The mathematical task was a simple equation in the form 'A#B=C'; where A and B were integers randomly drawn from the interval [1, 9], # was a mathematical operator (+, -, *, / at random across trials) and the result, C, was an integer that was correct on 50% of the trials. On incorrect trials, a random error between -4 and +4, excluding 0, was added to the correct result. Each of the 5 symbols ('A', '#', 'B', '=', 'C') was presented sequentially at fixation in black (0.1 cd/m^2) 16pt Arial font for 80msec, for a total of 400msec, centered on the mid-time point of the Gabor stimulus. Subjects answered the mathematical task using the up and down arrow keys for correct or incorrect, respectively. Subjects could answer the peripheral stimulus task and the central mathematical task in any order.

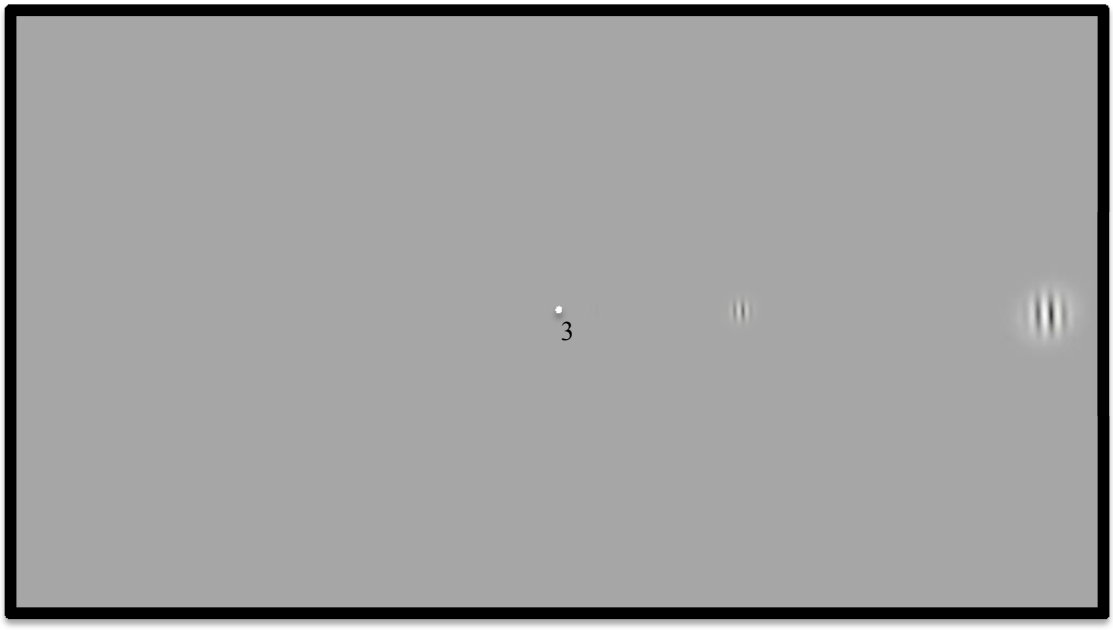


Figure 2. High attentional load task: display and peripheral stimuli at the three set eccentricities (8, 17, and 30 degrees) with number right below the fixation target.

2.2.3. Data Analyses

For data analyses, contrast detection thresholds and 95% confidence intervals were calculated from the 75% correct estimate of the cumulative Normal psychometric function fit by nonlinear least squares, using Matlab's fit function. Statistics were calculated using linear mixed model analyses in the Statistical Analysis System, and Pearson correlations and Wilcoxon Signed Rank Tests in JMP by SAS (SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513, USA).

Raw data from each run were fit separately. Threshold measurements were found to be repeatable per Bland Altman analysis (Table 1), demonstrating that subjects did not show

an effect of learning between the first and second run of each task at any eccentricity. Therefore, the two runs were combined and the fit used in comparative analyses.

	Mean Test-Retest Bias (SE)	**Test-retest CI (95%) of Bias**
8° low	-0.007 (0.031)	[-0.069,0.055]
17° low	-0.003 (0.013)	[-0.028,0.023]
30° low	-0.011 (0.049)	[-0.108,0.085]
8° high	-0.005 (0.012)	[-0.027,0.018]
17° high	-0.006 (0.015)	[-0.035,0.023]
30° high	-0.061 (0.136)	[-0.327,0.205]

Table 1. Bland Altman Analysis for Trials 1 and 2 that demonstrates repeatability. First column presents mean test-retest bias (with SE - standard error) for each experimental condition. Second column presents test-retest CI (confidence intervals) of the bias.

2.3. Results

As expected, axial length and refractive error were highly correlated (Pearson, r=0.821, $p<0.01$); therefore, refractive error was used in subsequent analyses. Note that only data for those subjects whose thresholds could be computed for both the high and low attentional load tasks were included in these analyses (n=42; with n=25 myopes).

Mean group data showed a significant interaction between eccentricity and attentional load, as a significant difference between low and high attentional load tasks was found at the 30° eccentricity for the total group of subjects (Linear mixed model, $p<0.01$). Although a trend was apparent, there were no significant differences between the low and high attention tasks group data at the 8° (Wilcoxon Signed Rank, $p=0.510$) or 17° (Wilcoxon Signed Rank, $p=0.237$) peripheral eccentricities.

Myopic subjects showed a significant increase in peripheral contrast thresholds when high attention was added to the task (Wilcoxon Signed Rank, $p<0.01$), whereas emmetropes did not show a significant change in peripheral contrast thresholds when high attention was added to the task (Wilcoxon Signed Rank, $p=0.10$) (Figure 3). The effect of a high attention central task was not significantly different between emmetropes and myopes at 30 degrees eccentricity (Wilcoxon Signed Rank, $p=0.27$).

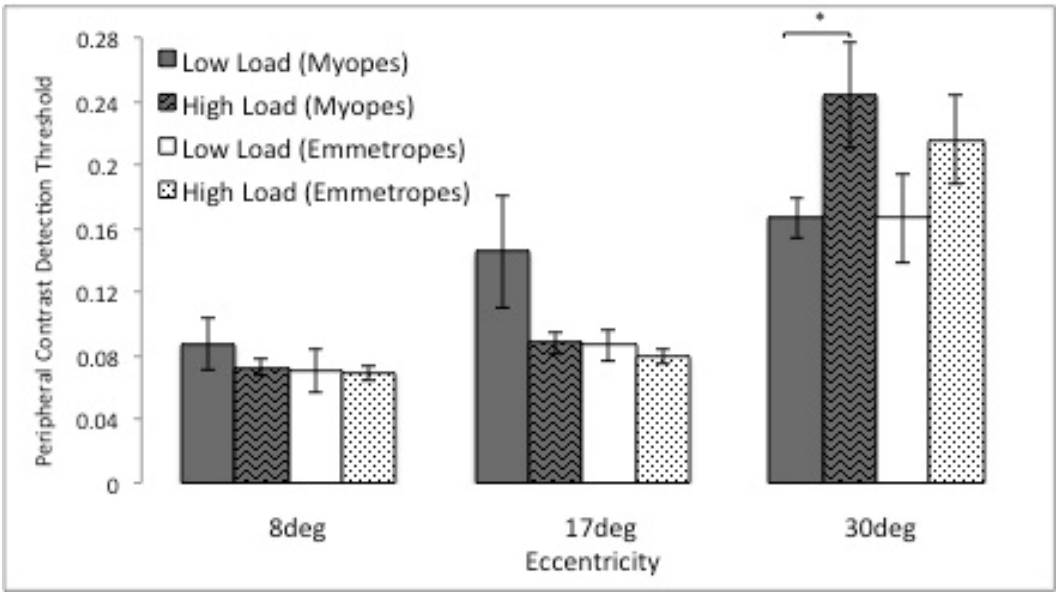


Figure 3. Peripheral contrast detection thresholds for "low" and "high" attention tasks at each eccentricity. Error bars represent standard error. The asterisk represents a significant difference (Wilcoxon Signed Rank, $p<0.01$).

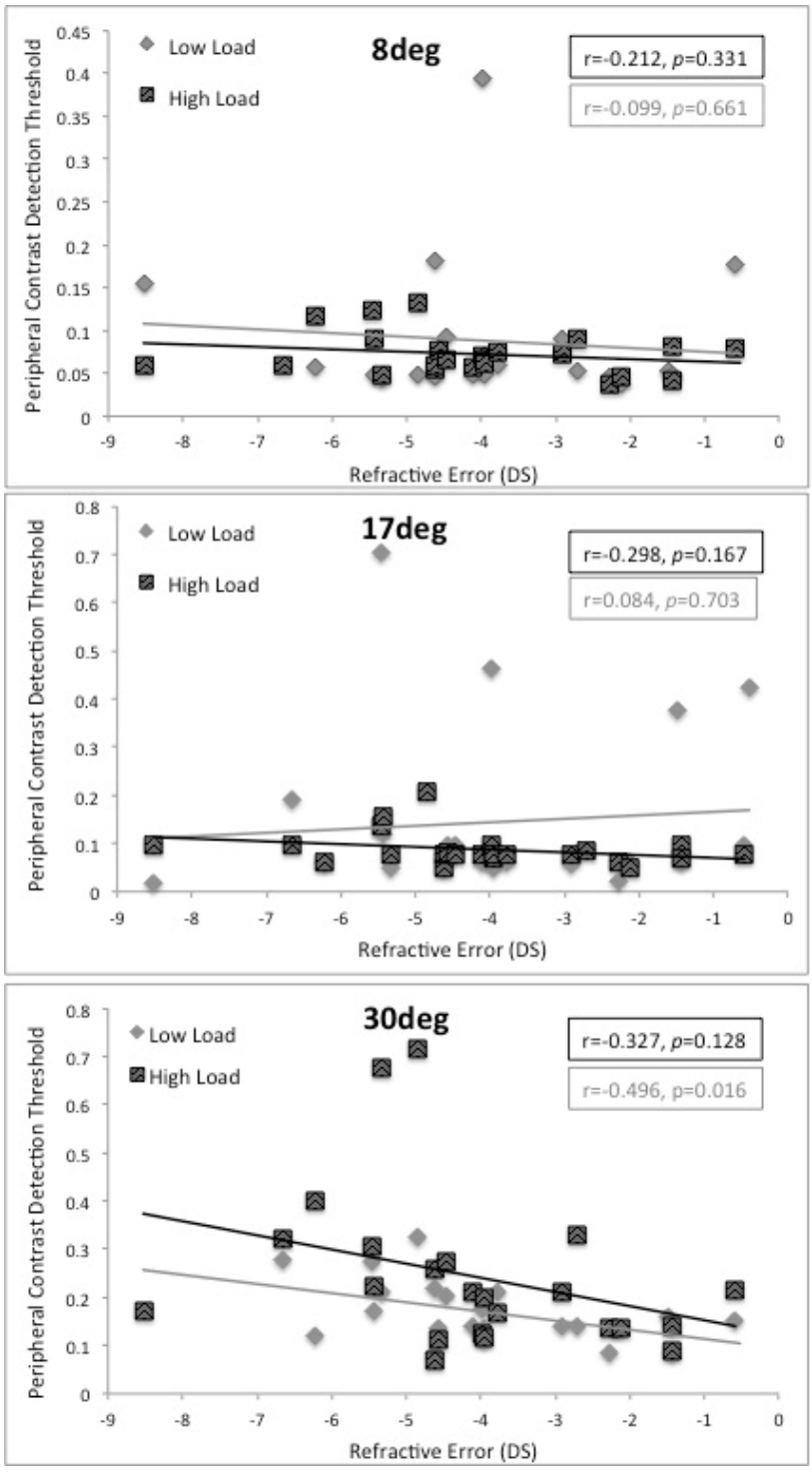


Figure 4. Individual peripheral contrast detection thresholds as a function of amount of myopia (SE in Diopters).

Contrast detection thresholds increased slightly with greater amounts of myopia in five of the six test conditions but this trend was significant for only the low load attention task at 30° eccentricity (Pearson r=-0.496, p=0.016) (Figure 4).

Importantly, there were no differences between myopes and emmetropes in performance (# of correct answers) on the mathematical task presented in their central vision (Wilcoxon Signed Rank, p>0.05 for all eccentricities). Both groups answered between 88-91% of the mathematical operations correct at each eccentricity. This suggests that there were no differences in the cognitive demand level of the task between refractive groups or eccentricities.

2.4. Discussion

This study shows that contrast detection thresholds for targets presented in the far peripheral visual field (30deg eccentricity) are impaired by the addition of an attention-demanding task in central vision. This finding is in agreement with previous studies on the effect of attentional load on sensory thresholds (Plainis et al., 2001; Carmel et al., 2011). Attending to a region of space can improve the signal to noise ratio for that region in space by increasing contrast sensitivity and spatial resolution and in turn weakens the signal to noise ratio in other regions (Carrasco, 2011).

No effect of central attentional load was found in the near periphery (8° and 17°) contrast detection thresholds task. A possible explanation for this result is that higher attentional load in central vision caused increased fixation stability and improved performance for these near-peripheral vision tasks (Martinez-Conde, Macknik, and Hubel,

2004). Alternatively, the task chosen in this study, contrast detection using a Gabor patch of vertical orientation, may not have been an optimal task to bring out the effect of central attention. It has been shown that it is orientation discrimination, not blur sensitivity, which shows a significant decrement in the periphery with central cognitive load (Loschky, Sethi, Simons, Pydimarri, Ochs, and Corbeille, 2007; Ringer, Throneburg, Walton, Erickson, Coy, amd DeHart, 2015). This suggests that the central cognitive load has its affect on a cortical process rather than a primarily retinal task. A third explanation for these results may be that subjects did not maintain central fixation during the low attention task and performed eye movements to the near periphery stimuli (eye movements were not recorded) for the low attention condition. However, the short duration of the peripheral stimuli presentations (133ms), together with the randomly assigned onset of the task and target location reject this possibility. For the high attention task, the high performance obtained for the mathematical operations presented at the fovea also suggest that subjects maintained accurate central fixation. Lastly, the binocular condition used in this study and consequent extend of the peripheral field may have prevented a significant effect for the near periphery conditions.

Animal studies of myopia development suggest that the main mechanisms of emmetropization and myopia development occur within the eye and are triggered by retinal blur signals (Wallman et al., 1987; Wildsoet and Wallman, 1995; Wallman and Winawer, 2004; Smith et al., 2007; Smith et al., 2009; Huang et al., 2011; Liu and Wildsoet, 2011). Decreased contrast sensitivity in the periphery caused by central attention could be associated with reduced peripheral retinal blur sensitivity (Lavie, 2011) and lead to an abnormal interaction between central and peripheral visual information processing. We hypothesize

that if such an abnormal interaction occurred during a time when the visual system is susceptible to developing refractive errors, the consequences could be errors in the emmetropization signaling process that may result in myopia.

Additionally, our results support previous understanding that peripheral contrast sensitivity is correlated with myopia and generally decreased in higher myopes in the peripheral field due to the prolate stretching of the globe in longer myopic eyes and the consequent visual field expansion (Vera-Diaz, McGraw, Strang, and Whitaker, 2005). Our findings show a correlation between amount of myopia and reduced peripheral contrast detection thresholds at further retinal eccentricities. It is important to note that the absolute peripheral contrast thresholds of emmetropes and myopes were not the main data outcome of this study, the goal of the study was rather to compare the within subject effect of central attention in their peripheral contrast sensitivity. Therefore, no consideration was made to effects such as the retinal stretching profile of each myopic subject and differences in receptive fields between myopes and emmetropes, or the effect of contact lens wear in myopes.

In conclusion, our results suggest that the magnitude of the effect of central attention is greater in myopic compared to emmetropic subjects at the more peripheral eccentricities, as contrast detection thresholds for the high attention task were higher in the group of adult myopes tested in this study compared to emmetropes for the 30 degrees eccentricity.

3. Study Two: Myopes ability to detect and discriminate blur

3.1. Background and Hypothesis

This study explored sensitivity to blur in myopes and emmetropes. We hypothesized that an impaired ability to discriminate blur (difficulty interpreting small changes in blur) and greater variability in sensitivity to blur would be found in subjects with myopia.

3.2. Methods

3.2.1. Subjects

Criteria for inclusion were: (1) no history of surgery or eye disease that may have resulted in visual consequences, (2) within 18-32 years of age, (3) best corrected VA=20/20 (logMAR 0.0) or better in each eye, (4) not using drugs that may affect their vision, (5) no current binocular vision or accommodative dysfunction, (6) contact lens wearers if correction for intermediate distance (1m) was necessary, (7) refractive error (spherical equivalent, SE, in the least myopic eye) between +6.00 and -14.00DS with less than 1.50DC of astigmatism or 1.00D of anisometropia.

Refractive status was determined by dry subjective refraction. Subjects were classified into three refractive groups: emmetropes, defined as SE in each eye between +0.50 to -0.25DS; myopes, defined as SE in each eye between -0.50 to -14.00DS; and hyperopes, defined as SE in each eye between +0.75 to +6.00DS.

3.2.2. Procedures

A total of 36 young adult subjects (22-31 years old) were recruited and tested in this study. Subjects' refractive error ranged from SE in the least myopic eye between +3.875 to -9.625DS. Of these, 16 subjects were myopes (Mean: -4.14 ± 2.64DS), 18 emmetropes (Mean: +0.19 ± 0.25DS), and 2 hyperopes (Mean: +2.50 ± 1.16DS). Due to a small n for hyperopes, they were excluded from analyses.

A vision screening was used to determine eligibility and refractive group category. The vision screening included an ocular history questionnaire, open-field autorefraction (Grand Seiko WR-5100K), subjective refraction (Snellen VA), axial length measurements (Haag-Streit Lenstar LS 900®), and an ocular health evaluation. Subjects who were eligible continued with the experimental testing. All myopes were corrected with contact lenses if correction for intermediate distance (1m) was necessary

Although naturalistic images would be ideal for assessment, we used "dead leaves" stimuli (Wallis and Bex, 2012) due to the complexity of natural images. Dead leaves are opaque elementary shapes (ellipses of pseudo-random aspect ratio) that are laid over the original natural image. The ellipses form naturalistic edges where some objects occlude others, a property that mimics the provenance of local image structure in natural scenes. The dead leaves patches have the same space-averaged luminance and contrast as the image segments they replace and differ from the background image only in structure such as texture and contours.

Blur sensitivity and blur discrimination thresholds were measured using a psychophysical task using 4-alternative forced choice (4AFC) with a spatial adaptive 3-

down-1-up staircase converging at 79.4% correct responses. Staircases initialized with random start values within 20% of estimated threshold in pilot runs. Step size was initially 2 dB and was reduced to 1 dB after two reversals. In order to binocularly detect and discriminate blur, continuous images of dead leaves stimuli are presented (for approximately 500ms) at a 16deg diameter in which there are four separate quadrants (top left, top right, bottom left, bottom right). Mean luminance of the dead leaves was the same as the screen background luminance. Each quadrant contains a different level of Gaussian blur (Figure 5) – each ellipse independently blurred with a Gaussian low pass filter– with 6 reference blur levels (0.4, 0.8, 1.6, 3.2, 6.4, and 12.8 arc min).

Subjects were asked to answer using a keypad to show which of the four quadrants was the *blurriest*. Subjects are free to take a break between image presentations, since the program requires an answer to move on to the next image. Depending on number and duration of breaks, this task took approximately 15 minutes.

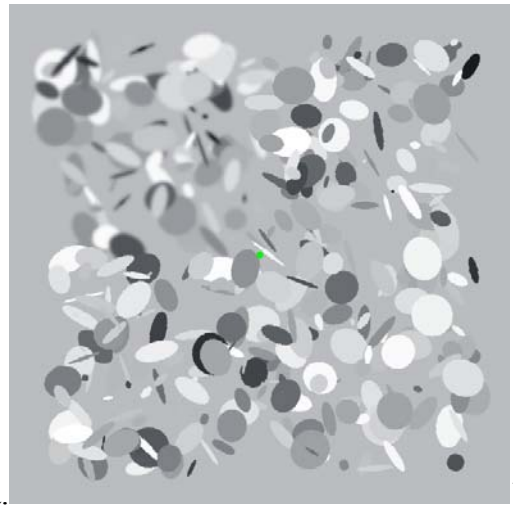
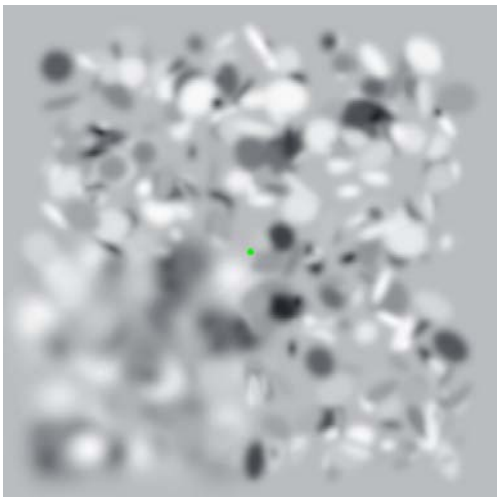
a.  b. 

Figure 5. Sample images used for blur detection (a.) and blur discrimination (b.).

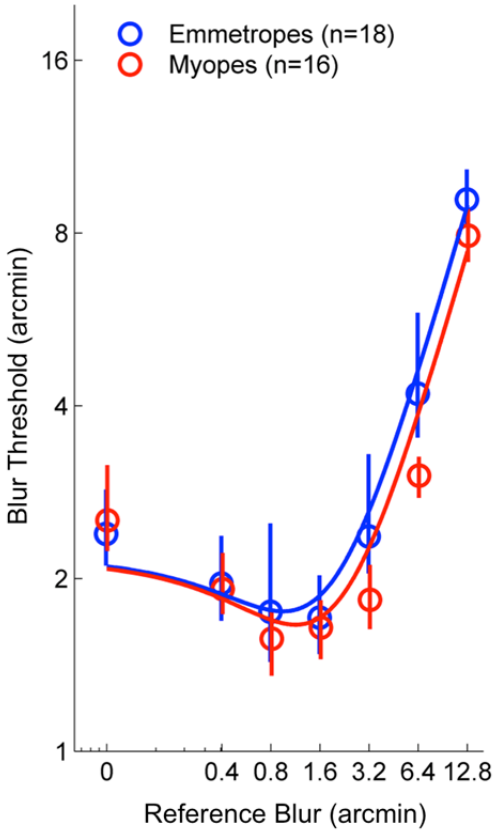
3.2.3. Data Analyses

Statistics were calculated using Pearson correlations and Wilcoxon Signed Rank Tests in JMP by SAS (SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513, USA).

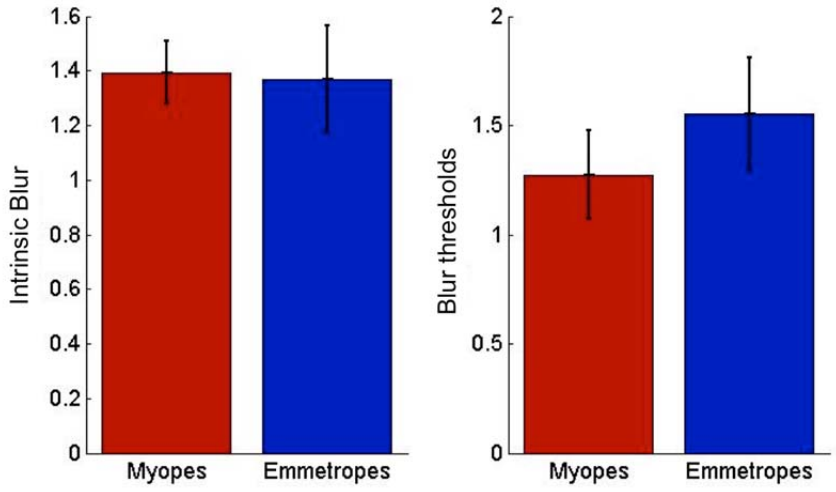
Raw data for each blur detection and discrimination condition was fitted with cumulative normal psychometric functions by a least squares analysis fit. Thresholds data for each reference blur level were fitted with a dipper function $\Delta\sigma = \Psi\sqrt{\sigma_i^2 + \sigma_e^2} - \sigma_e$, where σ_i is the subject's intrinsic blur, σ_e is the level of reference external blur (for detection task σ_e=0), Ψ is a measure of the increase in blur (with respect to the reference level of blur) necessary for reliable discrimination. Blur detection threshold = value of the dipper function where $\sigma e = 0$.

3.3. Results

Individual dipper blur functions revealed no differences in intrinsic blur (σ_i) levels between refractive groups (Wilcoxon Rank-Sum, *p*=0.52) (Figure 6). No differences in blur detection thresholds ($\Delta\sigma$ for σ_e=0) between refractive groups were observed (Wilcoxon Rank-Sum, *p*=0.61). Blur discrimination thresholds were also not significantly different between myopes and emmetropes (Wilcoxon Rank-Sum, *p*=0.07).



a.



b.

Figure 6. Dipper function (a.) showing blur detection and discrimination thresholds relative to the amount of pedestal (reference) blur for emmetropes and myopes. Graphical representation (b.) showing no significant difference of intrinsic blur levels and blur thresholds between emmetropes and myopes.

There was a significant correlation between blur discrimination thresholds and amount of refractive error for higher levels of reference blur (Spearman σ_e=12.8 arcmin, r^2= 0.39, p=0.02, σ_e=6.4 arcmin, r^2=0.34, p=0.04, σ_e=3.2 arcmin, r^2=0.26, p=0.12) (Figure 7). Myopes showed lower blur discrimination thresholds than emmetropes at these reference blur levels. No correlation was found between amount of refractive error and blur detection thresholds ($\Delta\sigma$ for $\sigma_e = 0$) (R^2=0.09, *p*=0.61).

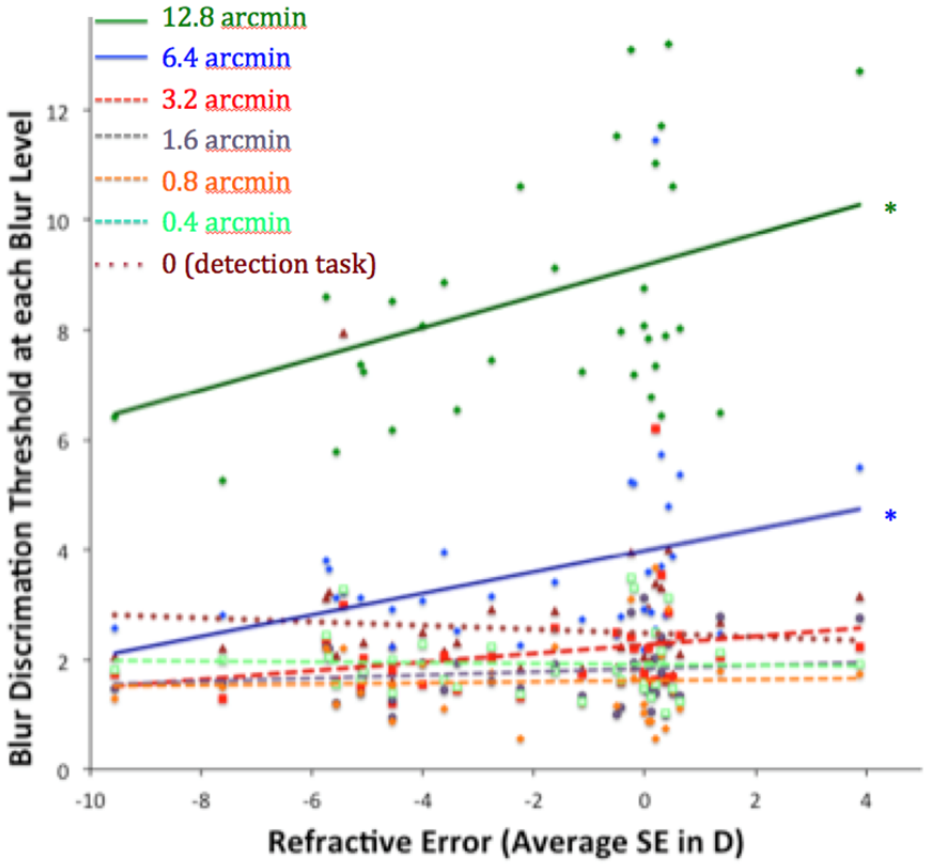


Figure 7. Individual raw data for all subjects. Blur discrimination thresholds (Δσ) presented in different colors for each reference blur level.

3.4. Discussion

These results indicate that emmetropes and best-corrected myopes are equally able to detect and discriminate Gaussian blur when images are blurred from the center to the periphery. Discrepancies among previous studies as to whether myopes are less sensitive to blur or not may be due to differences in experimental conditions, particularly the use of different stimuli (high contrast letters/symbols blurred with ophthalmic lenses or varying viewing distance), the use of cyclopegia, monocular measurements, use of cyclopegia, and

use of indirect measures (effect of blur on accommodation or VA rather than direct measures of blur sensitivity).

Adequate binocular vision and near peripheral vision may be important for myopes to correctly perceive blur. Further investigations are necessary to evaluate the effect of binocular vision, near peripheral vision and other types of blur in blur sensitivity in myopes. Investigations with children are also needed to evaluate a possible causative effect in emmetropization.

4. Study Three: Myopes ability to accommodate to virtual 3D images

4.1. Background and Hypothesis

This study explored the ability of a group of emmetropes and myopes to accommodate when available accommodation cues are manipulated. We hypothesized that when using binocular 3D viewing, myopes will have a decreased ability to accurately accommodate when certain cues are removed due to their decreased sensitivity and discrimination to blur.

4.2. Methods

4.2.1. Subjects

Criteria for inclusion were: (1) no history of surgery or eye disease that may have resulted in visual consequences, (2) within 18-32 years of age, (3) best corrected VA=20/20 (logMAR 0.0) or better in each eye, (4) not using drugs that may affect their vision, (5) no current binocular vision or accommodative dysfunction, (6) contact lens wearers if correction for intermediate distance (1m) was necessary, (7) refractive error (spherical equivalent, SE, in the least myopic eye) between +6.00 and -14.00DS with less than 1.50DC of astigmatism or 1.00D of anisometropia.

Refractive status was determined by dry subjective refraction. Subjects were classified into three refractive groups: emmetropes, defined as SE in each eye between +0.50 to -0.25DS; myopes, defined as SE in each eye between -0.50 to -14.00DS; and hyperopes, defined as SE in each eye between +0.75 to +6.00DS.

4.2.2. Procedures

A total of 36 young adult subjects (22-31 years old) were recruited and tested in this study. Subjects' refractive error ranged from SE in the least myopic eye between +3.875 to -9.625DS. Of these, 16 subjects were myopes (Mean: -4.14 ± 2.64DS), 18 emmetropes (Mean: +0.19 ± 0.25DS), and 2 hyperopes (Mean: +2.50 ± 1.16DS). Due to a small n for hyperopes, they were excluded from analyses.

Accommodation responses under various conditions were measured using a PowerRefractor (Figure 8).

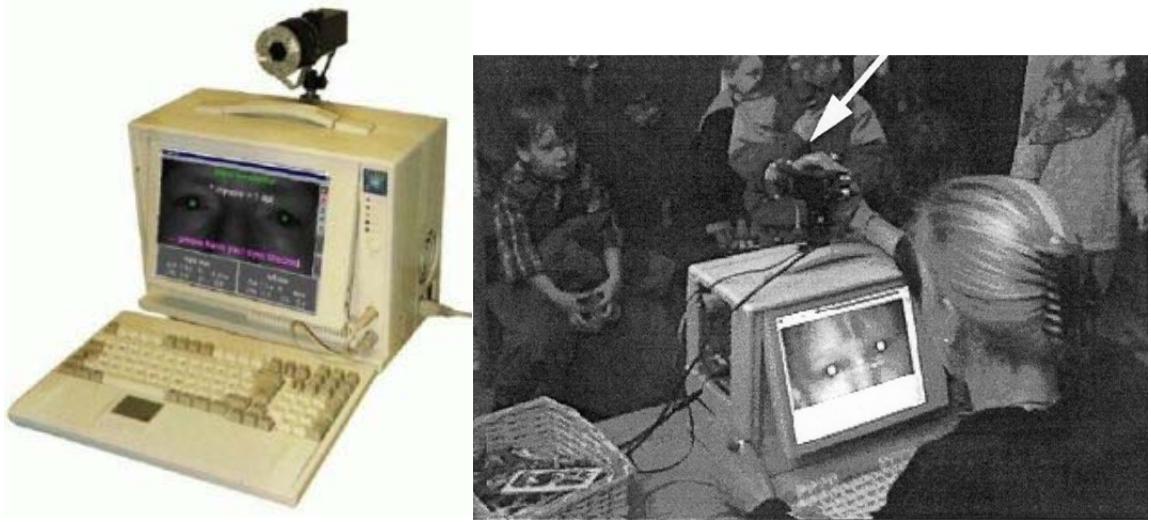


Figure 8. The PowerRefractor (http://www.plusoptix.com/)

Subjects viewed dead leaves stimuli binocularly since it has been shown that accommodative responses are less accurate under monocular conditions in both infants and children (Bharadwaj and Candy, 2008). During the fist task, subjects viewed dead leaves

stimuli, which were presented randomly in a 3D computer display 40cm away. There are 5 different types of images (Figure 9) each presented for 5 seconds at a time, 5 times in random order (total 25 images):

a. Geometric: “flat image”- entire image is in focus in the plane of the display
b. Blur Gradient: flat image with blur outside central fixation
c. Disparity Gradient: varying disparity cues outside central fixation
    - Positive disparity- images closer than fixation
    - No disparity- images in plane of fixation
    - Negative disparity- images further than fixation
d. Size Gradient: increasing size away from fixation
e. All cues present: Disparity, Size, and Blur

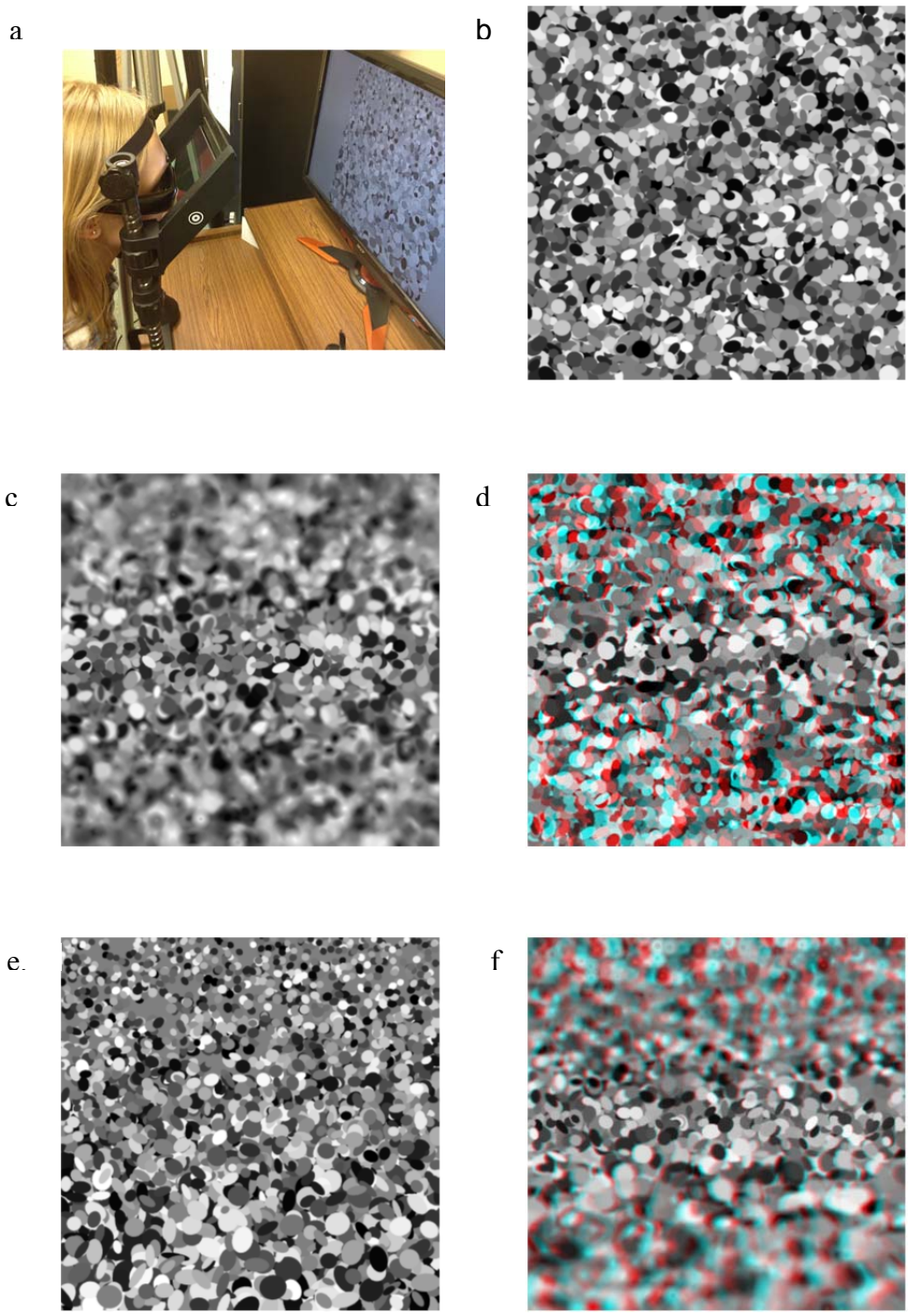


Figure 9. Stimuli used in this study **A.** 3D viewing apparatus with shutter glasses. **B.** Flat. **C.** Blur. **D.** Disparity. **E.** Size. **F.** All cues present: Disparity, Size, & Blur.

Prior to, and in between each of test images, a gray screen was presented with a central, green fixation dot, which had a negative disparity in order to relax accommodation between stimuli. This is used to control subjects' fixation, record accommodation at rest, and obtain a time stamp to differentiate data between the eight conditions. Each condition was presented for 5 seconds, and the gray screen was on for a minimum of 3 seconds, after which the subject could control when the next image was presented by pushing any key on the keyboard. Accommodation and pupil size were constantly recorded during the experiment by the PowerRefractor. Subjects were free to take a break between images by refraining from pressing a key until they were ready. Depending on the amount and duration of breaks, this portion took about 7-14 minutes.

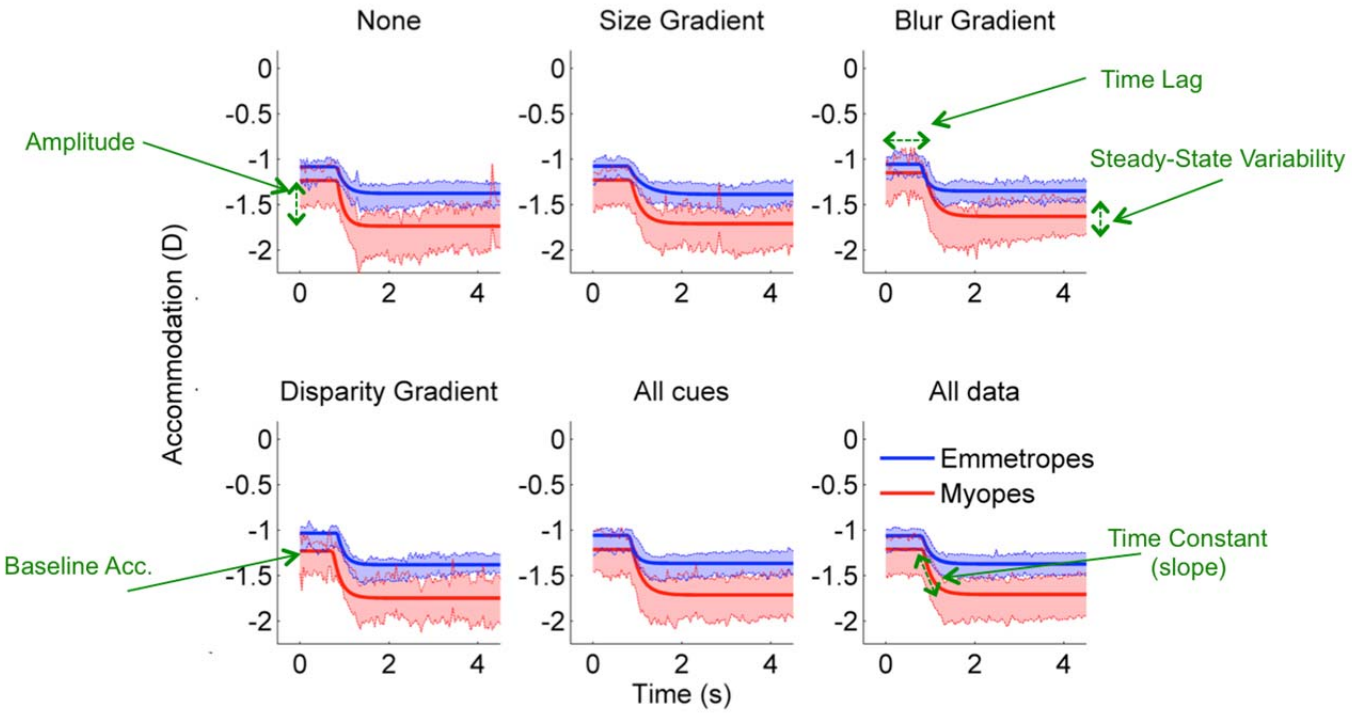


Figure 10. Raw accommodation data output from the PowerRefractor. Raw data were fitted to obtain the following parameters: accommodative amplitude (D), accommodation time

constant (sec), accommodative time lag (sec), initial accommodation state (D), and steady state variability (D) for each subject.

4.2.1. Data Analyses

Raw accommodation data output from the PowerRefractor was fitted using the formula $D = y_0 - a\left(1 - e^{-(t-t_0)/\tau}\right)$ in order to analyze accommodative amplitude (*a* in D), accommodation time constant (τ in sec), accommodative time lag (t_0 in sec), initial accommodation state (y_0 in D), and steady state variability (D) (Figure. 10).

4.3. Results

Myopes showed less stable accommodation responses compared to emmetropes when viewing 2D flat images (Wilcoxon Rank-Sum, p=0.01), without size, blur, disparity or a combination of these cues. However, the accommodation responses for myopes and emmetropes were not different when 3D cues, blur, or size cues (Wilcoxon Rank-Sum, p>0.05) were added to the scene (Figure 11).

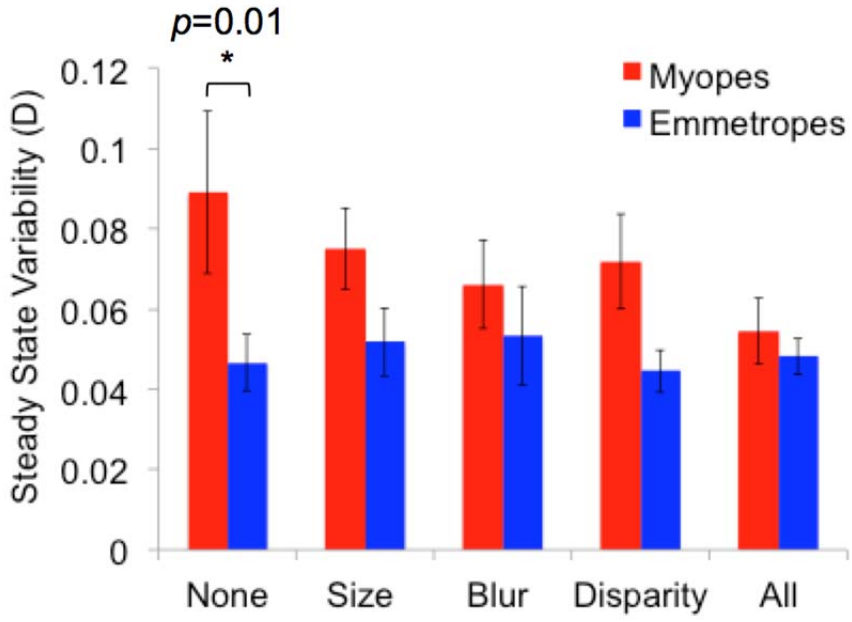


Figure 11. Variability of accommodation responses for myopes and emmetropes over a period of 5 seconds when viewing images with different accommodative cues.

Accommodation response latencies appeared greater in myopes for all conditions, particularly for the "flat", "size", and "blur" conditions, and appeared to improve when disparity cues were added (Figure 12). However, no significant differences were found between the groups of subjects used in this study (Wilcoxon Rank-Sum, $p>0.05$).

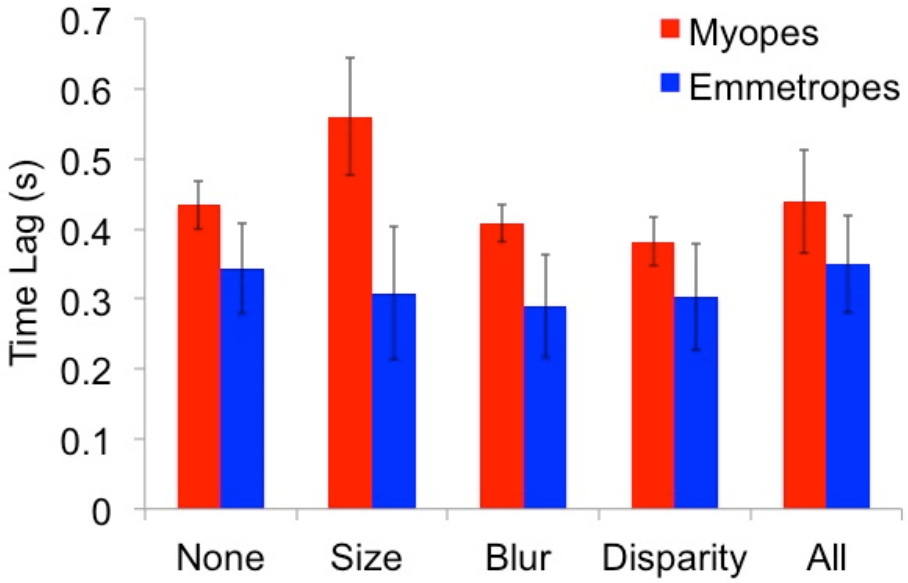


Figure 12. Accommodation response latencies of myopes and emmetropes with varying accommodative cues.

The amplitude of the accommodation response was also not significantly different (Wilcoxon Rank-Sum, $p>0.05$) between myopes and emmetropes for any condition tested, although myopes again appeared to accommodate more (smaller lags) for all conditions (Figure 13).

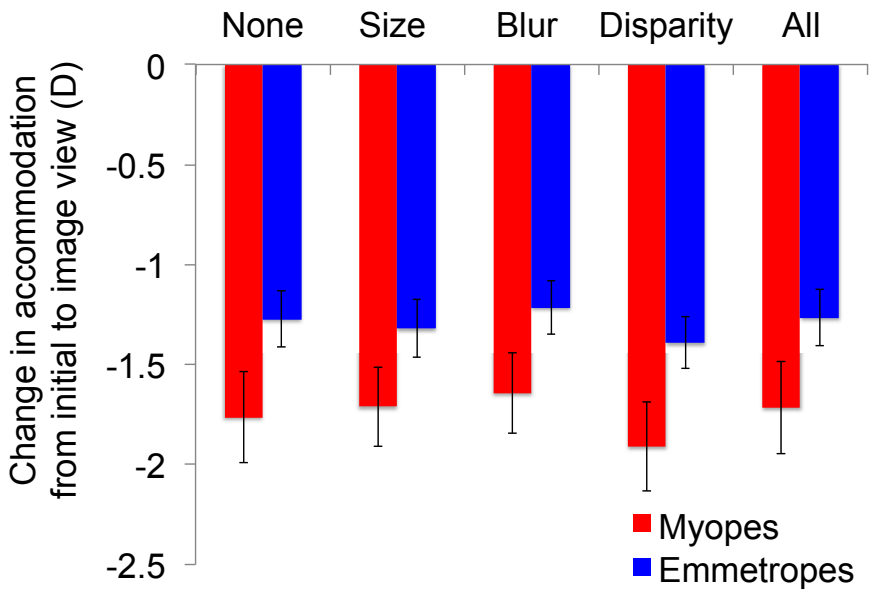


Figure 13. Amplitude of accommodative responses for myopes and emmetropes with varying accommodative cues.

4.4. Discussion

Our results indicate a larger variability (less stable) in accommodation responses in myopes when viewing flat images, but when additional cues to accommodation are added (i.e., blur or disparity, 3D, cues), myopes' accommodation responses stabilize. The time lag to achieve adequate accommodation is also larger for myopes when viewing flat images but improve when disparity (3D) cues are available. These results indicate that myopes may need more cues in order to accommodate appropriately.

Discrepancies among previous studies as to whether myopes are able to accurate accommodate or not may be due to differences in experimental conditions, particularly the use of different stimuli (contrast, spatial frequency, 2D).

Inaccuracies of accommodation when viewing 2D images (typical of most indoor activities such as reading or computer use) may cause long-term blur on the retina, which may impede precise emmetropization.

The results from this study support the hypothesis that adult myopes may have less stable accommodation responses than emmetropes, and their responses are significantly more variable when using 2D flat images compared to using 3D images or images that have other blur cues. Children with myopia may show significant differences in their ability to perceive blur and adequately accommodate compared to children without myopia. The consequence for these myopic children could result in long-term blur, preventing their eyes from receiving signals necessary for normal emmetropization, resulting in excessive eye growth.

Further investigations with a larger number of subjects are necessary to reveal if these inaccuracies are consistent. Investigations with children are also needed to evaluate a possible causative effect of these inaccuracies of accommodation in emmetropization.

5. General Conclusions and Summary

The overall conclusion of these studies is that central attention, peripheral vision and accommodation are associated with myopia. A larger detrimental effect of central attention in peripheral vision was found in adult myopes compared to emmetropes, which may affect normal signals for emmetropization. Adult myopes have less stable accommodation responses and larger accommodation time lags than emmetropes when not all accommodation cues are available. These results indicate that myopes may need more cues in order to accommodate appropriately.

Children at risk for myopia may also show significant differences in their ability to perceive blur and adequately accommodate compared to children who will not develop myopia. The consequence for these children could result in long-term blur, prevention of signals necessary for normal emmetropization, with a resultant excessive eye growth and myopia.

Although no differences were found in Gaussian blur detection or discrimination between adults with emmetropia and myopia, our results suggest that adequate binocular vision and near peripheral vision may be important for myopes to correctly perceive blur. Further investigations are necessary to evaluate the effect of binocular vision, near peripheral vision and other types of blur in blur sensitivity and accommodation in myopes. Investigations with children are also needed to evaluate a possible causative effect in emmetropization.

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7. Appendix – Vision Research Manuscript

TITLE:

Peripheral Contrast Sensitivity and Attention in Myopia

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ABSTRACT

Disruption of normal visual experience or changes in the normal interaction between central and peripheral retinal input may lead to the development of myopia. In order to examine the relationship between peripheral contrast sensitivity and myopia, we manipulated attentional load for foveal vision while observers detected targets with peripheral vision. Peripheral contrast detection thresholds were measured binocularly using vertical Gabor stimuli presented at three eccentricities (±8°, 17°, 30°) in a spatial 2 alternative forced choice task. Contrast thresholds were measured in young adult (mean age 24.5±2.6 years) emmetropes (n=17; group SE: +0.19±0.32D) and myopes (n=25; group SE: -3.74±1.99D). Attention at central fixation was manipulated with: (1) a low attention task, requiring simple fixation; or (2) a high attention task, which required subjects to perform a mathematical task. We found an interaction between eccentricity and attentional load, with significantly higher contrast detection thresholds for the high attentional load task compared to low attentional load task at 30° eccentricity for the overall subject group (linear mixed model, $p<0.01$). The high attention task induced an increase in detection thresholds (decreased sensitivity) at 30° that reached significance for myopes (Wilcoxon, $p<0.01$) but not for emmetropes (Wilcoxon, $p=0.1$). The attention dependent threshold increase for myopes was not significantly greater than for emmetropes (Wilcoxon, p=0.27). Attentional load did not increase thresholds at 8° or 17° for either refractive group. These data indicate that myopes experience a greater decrease in contrast sensitivity in the far periphery than emmetropes when attention is deployed in central vision.

Keywords: myopia, emmetropization, periphery, attention, contrast, sensitivity.

1. INTRODUCTION

It is known that disruption of normal visual experience may lead to the development of refractive errors[1–4]. The failure of emmetropization in certain individuals seems to arise from a multitude of factors combining a predisposing genetic susceptibility with a major role for environmental factors, such as a high education level, an increased amount of near work, near work posture[5–7], and decreased time spent outdoors[8–12].

Several groups have argued that a normal ability of the retina to detect and respond to blur and the directional sign of defocus are necessary for normal emmetropization and protection against myopia[13–15] and that myopes show decreased sensitivity to blur[16,17]. However, there is no general consensus that myopes show greater blur thresholds under normal (binocular) viewing[18,19]. It is also undetermined whether an abnormal sensitivity to blur is related to the retina's ability to derive blur signals which are known to regulate eye growth and therefore myopia development. We propose this lack of a consensus may be partially due to a lack of consideration of the influence of peripheral vision in blur detection studies.

There is evidence for the importance of peripheral visual input in normal emmetropization and eye growth[13–15,20–23]. It has been argued that the range of neuronal responses at various retinal eccentricities may constitute the signal for the sclera to control its growth and promote emmetropization[24–27]. Several current models emphasize that retinal cells respond more vigorously to in-focus targets as they move across the retina than when the focus is reduced due to dioptric blur at the fovea[26,28,29]. The prolate retinal profile in myopic eyes[30] causes a peripheral retinal defocus when the central retina is in focus. Hyperopic defocus is known to induce myopia in animal studies. This peripheral defocus may cause reduced responsiveness to patterns moving across peripheral retinal regions and induce further eye growth and myopia[31,32].

Additional evidence supporting the influence of peripheral vision are studies indicating that time outdoors is an environmental factor known to decrease the risk for myopia[33,34]. It is possible that indoor settings provide dioptrically different visual targets and that an abnormal peripheral visual input may disrupt a child's ability to maintain emmetropia. The range of

dioptric depths, distances and disparities present in outdoor scenes is far less than in indoor scenes[35–37] and therefore require accommodation and convergence over a much smaller dioptric range of distances than indoor scenes. Additionally, a number of studies have observed differences in stress levels and the ability to concentrate in indoor and outdoor scenes[38]. These findings have been attributed to differences in attentional load, with effortless involuntary attention dominant in outdoor environments and more demanding, capacity-limited directed attention required for tasks in indoor environments[39].

An increased demand on perceptual attention in central vision can affect the balance between central and peripheral visual input. Indeed, increasing the level of perceptual attentional load on central vision while foveally-fixating targets, decreases sensitivity (increases detection thresholds) of peripheral stimulus detection[40–43] and increases detection reaction time[44]. The simplest example of this is the Troxler effect in which careful foveal fixation causes patterns in the periphery to fade from view because normal fixation tremors provide too small a movement to allow a steady pattern to repeatedly excite the large retina receptive fields in the periphery.

Collectively, these findings suggest that normal perception of blur is necessary to adequately control the level of blur signals at the retinal level, and that a delicate balance between central and peripheral retinal stimulation may be important in the retina's ability to derive blur signals for normal emmetropization[45]. In order to examine the effect of attention on peripheral retinal control in myopia we explored the role of central attentional load on sensitivity to signals in temporal and nasal of peripheral vision.

2. METHODS

2.1. Subjects

A total of 45 young adult subjects (24.5 ± 2.6 years) participated in this study. Subjects' refractive error (spherical equivalent, SE) ranged from +0.75D to -8.50D (Mean SE: -2.13 ± 2.48D). Of these, 25 subjects were myopes (Mean SE: -3.74 ± 1.99D) and 17 emmetropes (Mean SE: +0.19 ± 0.32D). Criteria for subjects' inclusion were: (1) no history of surgery or

eye disease that may have resulted in visual consequences, (2) within 18-32 years of age, (3) best corrected visual acuity (BCVA) 20/20 or better in each eye, (4) not using drugs that may affect their vision, (5) no current binocular vision or accommodative dysfunction, (6) contact lens wearer if myopic refractive correction was greater than -4.00DS, (7) refractive error between +0.75 hyperopia and -14.00DS myopia with ≤1.50DC of astigmatism or ≤1.00D anisometropia.

Refractive status was determined by open-field autorefraction. Subjects were classified into two refractive groups: emmetropes, defined as having a refractive error- spherical equivalent (SE)- between +0.75 to -0.25D (SE); and myopes, those subjects with refractive error between -0.50 to -14.00D (SE).

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.

2.2. Procedure

Following a vision screening that included an ocular history questionnaire, autorefraction (Grand Seiko WR-5100K), axial length (AL) (Zeiss IOL Master) measurements, Snellen VA, and an ocular health evaluation, subjects were asked to perform the psychophysical tasks.

All myopes were corrected with soft contact lenses. Subjects were tested binocularly as this is the normal condition during myopia development. Subjects viewed the target in a 152.4cm 8-bit LCD display viewed at 100 cm presented on a uniform grey background (50 cd/m^2 mean luminance) under mesopic room lighting conditions. Subjects performed two different peripheral contrast detection threshold tasks in a random order.

Each task was identical in that subjects were asked to determine whether a peripheral stimulus was presented to the right or to the left of their central fixation by pressing the left or right arrow keys, respectively, on a keyboard. Stimuli were Gabor patches with vertical

gratings of spatial frequency (ω) and a standard deviation (σ) for the overall patch width that were m-scaled for eccentricity[46]. Gabor stimuli were presented within a Gaussian temporal window (σ_t=133ms) at one of three eccentricities randomly interleaved in a single run of 150 trials: 8 degrees (σ=0.25°, ω=3.08 c/deg), 17 degrees (σ=0.5°, ω=1.63 c/deg), and 30 degrees (σ=0.5°, ω=1.03 c/deg). Stimuli were briefly (σ_t=133ms) presented at the required eccentricity on either the right or left side (at random) of the subject's central fixation. The contrast of the Gabor stimulus was under the control of a 3 down, 1 up adaptive staircase[47] designed to converge on a contrast that produced 79.4% correct target detection. The detection task was performed two times under low and two times under high attention load conditions in a random order.

For the "low" attentional load condition, subjects were asked to look straight ahead at a fixation target in the center of the screen while performing the detection task. For the "high" attentional load condition, subjects performed the same peripheral detection task while simultaneously performing an additional mathematical task at fixation. The math task was a simple equation in the form 'A#B=C'; where *A* and *B* were integers randomly drawn from the interval [1, 9], # was a mathematical operator (+, -, *, / at random across trials) and the result, C, was an integer that was correct on 50% of the trials. On incorrect trials, a random error between -4 and +4, excluding 0, was added to the correct result. Each of the 5 symbols ('A', '#', 'B', '=', 'C') was presented sequentially at fixation in black (0.1 cd/m^2) 16pt Arial font for 80msec, for a total of 400msec, centered on the mid-time point of the Gabor stimulus. Subjects answered the mathematical task using the up and down arrow keys for correct or incorrect, respectively. Subjects could answer the peripheral stimulus task and the central mathematical task in either order.

2.3. Statistical Analyses

Contrast detection thresholds and 95% confidence intervals were calculated from the 75% correct estimate of the cumulative Normal psychometric function fit by nonlinear least squares, using Matlab's fit function. Statistics were calculated using linear mixed model analyses in the Statistical Analysis System, and Pearson correlations and Wilcoxon Signed

Rank Tests in JMP by SAS (SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513, USA).

3. RESULTS

Raw data from each run were first fit separately. Threshold measurements were repeatable per Bland Altman analysis (Table 1), demonstrating that subjects did not show an effect of learning between the first and second run of each task at any eccentricity. Therefore, the two runs were combined and the fit used in comparative analyses.

As expected, axial length and refractive error were highly correlated (Pearson, r=0.821, p<0.01); therefore, refractive error was used in subsequent analyses. Note that only data for those subjects whose thresholds could be computed for both the high and low attentional load tasks were included in these analyses (final n=42; with n=25 myopes). For 2 myopic and 1 emmetropic subjects, psychometric functions were not adequately fit and their data were not used.

	Mean Test-Retest Bias (SE)	**Test-retest CI (95%) of Bias**
8° low	-0.007 (0.031)	[-0.069,0.055]
17° low	-0.003 (0.013)	[-0.028,0.023]
30° low	-0.011 (0.049)	[-0.108,0.085]
8° high	-0.005 (0.012)	[-0.027,0.018]
17° high	-0.006 (0.015)	[-0.035,0.023]
30° high	-0.061 (0.136)	[-0.327,0.205]

Table 1. Bland Altman Analysis for Trials 1 and 2 that demonstrates repeatability. First column presents mean test-retest bias (with SE - standard error) for each experimental condition. Second column presents test-retest CI (confidence intervals) of the bias.

Mean group data showed a significant interaction between eccentricity and attentional load, as a significant difference between low and high attentional load tasks was found at the 30° eccentricity for the total group of subjects (Linear mixed model, $p<0.01$). Although a trend was apparent, there were no significant differences between the low and high attention tasks group data at the 8° (Wilcoxon Signed Rank, $p=0.510$) or 17° (Wilcoxon Signed Rank, $p=0.237$) peripheral eccentricities.

Myopic subjects showed a significant increase in peripheral contrast thresholds when high attention was added to the task (Wilcoxon Signed Rank, $p<0.01$), whereas emmetropes did not show a significant change in peripheral contrast thresholds when high attention was added to the task (Wilcoxon Signed Rank, p=0.10) (Fig 1). The effect of a high attention central task was not significantly different between emmetropes and myopes at 30 degrees eccentricity (Wilcoxon Signed Rank, p=0.27).

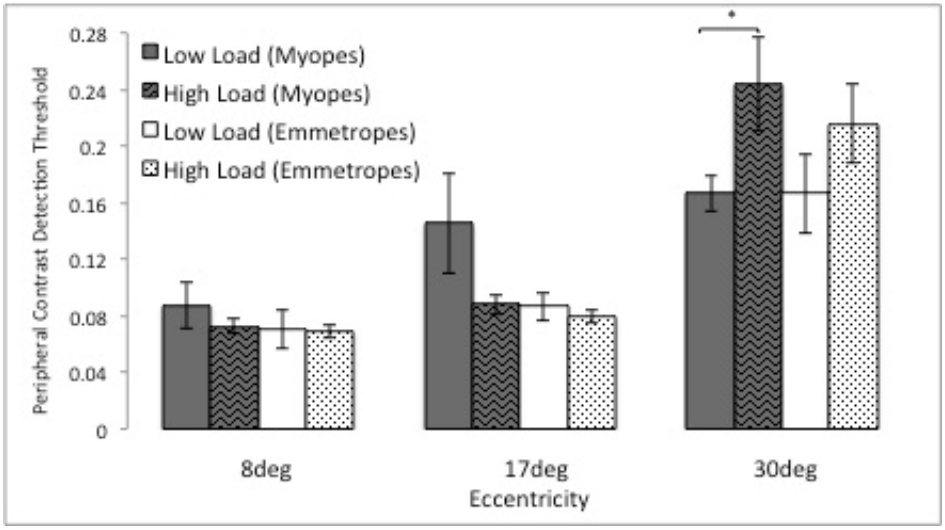


Figure 1. Peripheral contrast detection thresholds for "low" and "high" attention tasks at each eccentricity. Error bars represent standard error. The asterisk represents a significant difference (Wilcoxon Signed Rank, $p<0.01$).

Contrast detection thresholds increased slightly with greater amounts of myopia in five of the six test conditions but this trend was significant for only the low load attention task at 30° eccentricity (Pearson, r=-0.496, p=0.016) (Fig. 2).

Importantly, there were no differences between myopes and emmetropes in performance (# of correct answers) on the mathematical task presented in their central vision (Wilcoxon, p>0.05 for all eccentricities). Both groups answered between 88-91% correct at each eccentricity. This suggests that there were no differences in the cognitive demand level of the task between refractive groups or eccentricities.

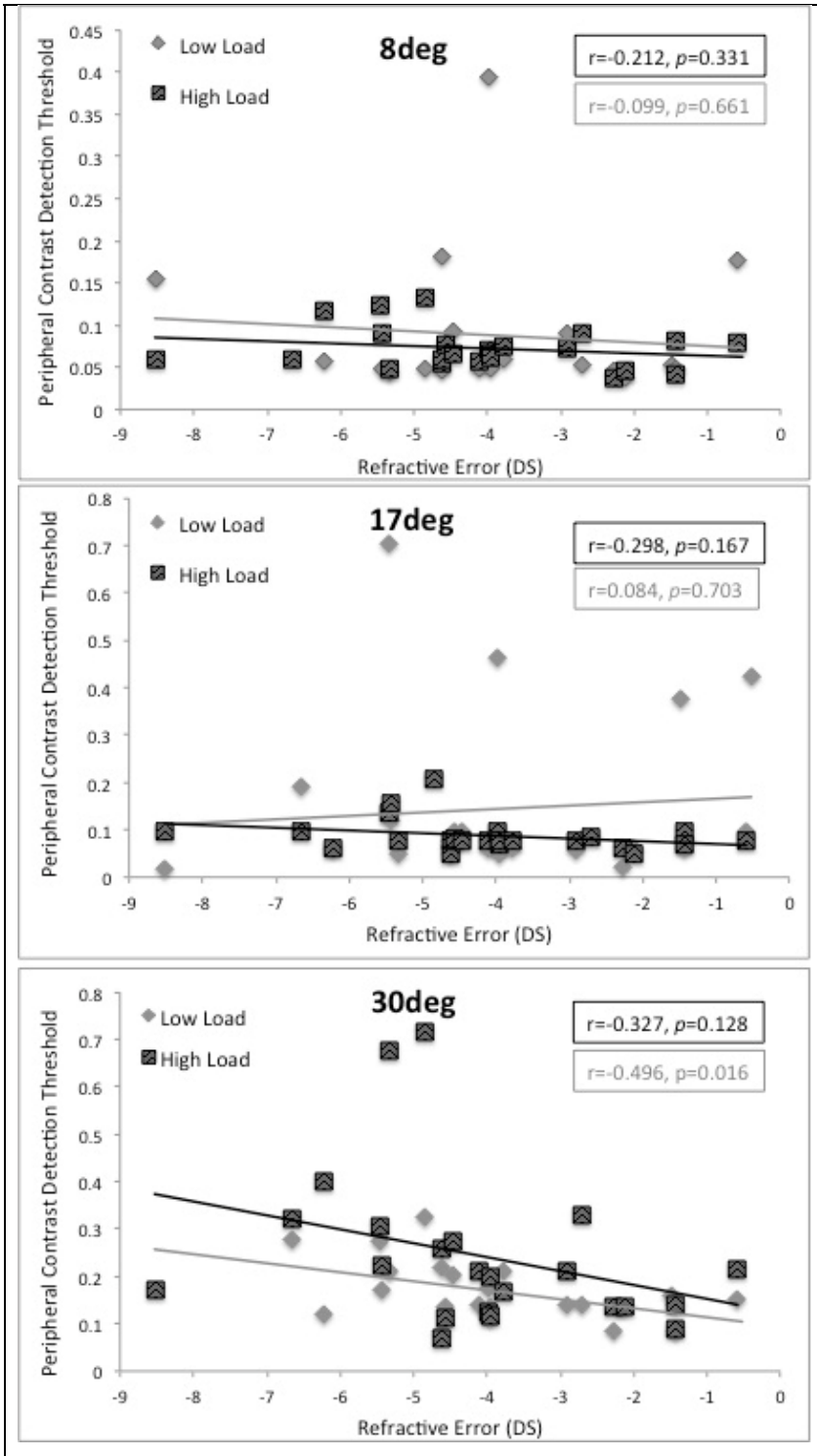


Figure 2. Individual peripheral contrast detection thresholds as a function of amount of myopia (SE in Diopters). There was a significant positive (higher thresholds for larger myopia) correlation between

amount of myopia and the peripheral contrast detection thresholds at 30deg eccentricity, but not at 8deg or 17deg eccentricity.

4. DISCUSSION

This study shows that contrast detection thresholds for targets presented in the far peripheral visual field (30deg eccentricity) are impaired by the addition of an attention-demanding task in central vision. This finding is in agreement with previous studies on the effect of attentional load on sensory thresholds[42,43]. Attending to a region of space can improve the signal to noise ratio for that region in space by increasing contrast sensitivity and spatial resolution and in turn weakens the signal to noise ratio in other regions[48].

A significant effect of central attentional load was not found in the near periphery (8° and 17°) contrast detection thresholds task. A possible explanation for this result is that higher attentional load in central vision caused increased fixation stability and improved performance for these near-peripheral vision tasks[49]. Alternatively, the task chosen in this study, contrast detection using a Gabor patch of vertical orientation, may not have been an optimal task to bring out the effect of central attention. It has been shown that it is orientation discrimination, not blur sensitivity, which shows a significant decrement in the periphery with central cognitive load[50,51]. This suggests that the central cognitive load has its affect on a cortical process rather than a primarily retinal task. A third explanation for these results may be that subjects did not maintain central fixation during the low attention task and performed eye movements to the near periphery stimuli (eye movements were not recorded) for the low attention condition. However, the short duration of the peripheral stimuli presentations (133ms), together with the randomly assigned onset of the task and target location reject this possibility. For the high attention task, the high performance obtained for the mathematical operations presented at the fovea also suggest that subjects maintained accurate central fixation. Lastly, the binocular condition used in this study and consequent extent of the peripheral field may have prevented a significant effect for the near periphery conditions.

Animal studies of myopia development suggest that the main mechanisms of emmetropization and myopia development occur within the eye and are triggered by retinal blur signals[3,20–22,32,52,53]. Decreased contrast sensitivity in the periphery caused by central attention could be associated with reduced peripheral retinal blur sensitivity[40] and lead to an abnormal interaction between central and peripheral visual information processing. We hypothesize that if such an abnormal interaction occurred during a time when the visual system is susceptible to developing refractive errors, the consequences could be errors in the emmetropization signaling process that may result in myopia.

Additionally, our results support previous understanding that peripheral contrast sensitivity is correlated with myopia and generally decreased in higher myopes in the peripheral field due to the prolate stretching of the globe in longer myopic eyes and the consequent visual field expansion[30]. Our findings show a correlation between amount of myopia and reduced peripheral contrast detection thresholds at further retinal eccentricities. It is important to note that the absolute of peripheral contrast thresholds between emmetropes and myopes were not the main data outcome of this study, the goal of the study was rather to compare the within subject effect of central attention in their peripheral contrast sensitivity. Therefore, no consideration was made to effects such as the retinal stretching profile of each myopic subject and differences in receptive fields between myopes and emmetropes, or the effect of contact lens wear in myopes.

In conclusion, our results suggest that the magnitude of the effect of central attention is greater in myopic compared to emmetropic subjects at the more peripheral eccentricities, as contrast detection thresholds for the high attention task were higher in the group of adult myopes tested in this study compared to emmetropes for the 30 degrees eccentricity. These data may support a correlation between abnormalities in peripheral retinal sensitivity and the deployment of attention in central vision in myopia.

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