EXPLORATION OF FACTORS TO MAXIMIZE VISUAL FUNCTION IN BILATERAL CENTRAL VISION LOSS

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

Brittany A. Bowman

April, 2022

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Abstract

EXPLORATION OF FACTORS TO MAXIMIZE VISUAL FUNCTION IN BILATERAL CENTRAL VISION LOSS

Brittany A. Bowman
New England College of Optometry, 2022

Purpose

Central vision loss (CVL) is a common cause of low vision (LV). Bilateral loss of foveal function results in the use of an alternate peripheral retina location for fixation instead of the damaged foveae. This new "pseudofovea" is called the preferred retinal locus (PRL). Due to the poor resolution of the peripheral retina, CVL patients using a PRL still report difficulties in many aspects of vision including reading. Therefore, the purpose of this thesis is to explore alternate ways to improve visual function in the CVL population through 1) changing parameters of text presentation to possibly facilitate reading, 2) training patients through a variety of different feedback approaches to use an alternate peripheral retinal location that may lead to better visual function, and 3) understanding blur discrimination in LV patients in order to optimize remaining vision through refraction.

Methods

First, the influence of text presentation and font size on reading rate was explored in two groups of observers: (1) patients with CVL and (2) normally sighted participants with simulated central vision loss. There were 9 CVL patients and 12 simulated-CVL, who used 4-degree inferior eccentric viewing, achieved by constant fixation 4-degrees above the reading task. Both groups of observers read aloud 4-word phrases presented at 60 cm

viewing distance. Six font sizes (0.8-1.3 logMAR) were tested with the better acuity eye and both eyes of CVL patients. Three font sizes (0.5-1.0 logMAR) were tested binocularly in simulated-CVL. Two text presentations were tested: rapid serial visual presentation (RSVP) and horizontal scrolling.

Second, we explored what feedback mechanisms enhance fixation stability and perceptual performance in eccentric viewing training. A PRL in the inferior visual field was trained with each of the following feedback types in random order: audio, contracting ring, gaze-contingent ring, image of a hand, and tactile feedback. Fixation stability and performance with the feedback types were compared to free viewing. Bivariate contour ellipse areas (BCEA), area under-the contrast (AUC) sensitivity function (CSF) and CSF acuities were calculated.

Lastly, to explore how LV patients perceive blur, we recruited CVL (n=6), peripheral vision loss (PVL) (n=9), albinism (n=5) and normally-sighted controls (n=5). Subjects gave estimates of the change in blurriness of vision using a scale (0-6) as a series of 26 lenses (range of +/- 10D) were individually introduced over the subject's refractive correction. We derived the slopes of the relationships between dioptric blur magnitude and plus- and minus-lens defocus which represented sensitivity to dioptric blur.

Results

CVL patients demonstrated no significant differences in reading rate between font sizes, p=0.28, text presentation, p=0.47 or interaction between font size and text presentation, p=0.60. Reading acuity significantly worsened with increasing PRL eccentricity, $p=0.018$.

For the eccentric viewing training experiment, we found there was no significant differences in BCEA, CSF acuity or AUC across feedback mechanisms in both the remote and in-lab experimental protocols.

Lastly, results from the blur tolerance showed that LV subjects demonstrated more variability in perceived dioptric blur than controls ($p<0.001$) but blur sensitivity did not significantly differ. There was minimal correlation between slopes of blur ratings with contrast sensitivity, visual acuity and visual field scores.

Conclusions

In exploring different approaches to help CVL patients use their remaining vision, we found changing text presentation methods (RSVP versus scrolling text) did not produce a difference in reading speed. We were able to develop a novel in-lab and also remote training systems, which were comparable. However, in exploring five eccentric viewing training feedback techniques, we found no significant differences. Additionally, we find that dioptric blur sensitivity in LV participants is not well correlated with clinical measures such as visual acuity, contrast sensitivity and visual field.

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Chapter 1: General Introduction

Approximately 217 million people worldwide are affected by moderate to severe permanent visual impairment, or low vision, defined as acuity worse than Snellen visual acuity of 20/60 by Bourne et al. (2017). The majority of patients with vision impairment are over 50 years of age (World Health Organization, 2021), and with the aging population demographics in the USA, the prevalence and incidence of low vision is rapidly increasing. The estimated prevalence of low vision cases in the United States is expected to increase from 1.5 million persons in 2017 to 7.6 million by 2050 (Chan et al., 2018). Of the low vision patients presenting to low vision rehabilitation clinic, 55% have a form of macular disease, the most common being age-related macular degeneration (AMD) (Goldstein et al., 2012). Common complaints of central vision loss patients include difficulty with reading, driving, use of visual assistive equipment, mobility, performance of in-home activities, facial recognition and social interactions (Brown et al., 2014). The aim of this thesis is to explore how patients of central vision loss use their remaining vision and how this can be further maximized to improve visual function, in order to inform future directions for clinical and rehabilitation methods. To explore these ideas, this thesis will explore the following three main areas:

1) Understand the role of text presentation on the ability of central vision loss patients to read (Chapter 2).

2) Understand the role of eccentric viewing training and its potential impact on reading and visual function enhancement (Chapter 3).
3) Understand how patient's perception of blur may be affected by acuity loss, contrast loss, visual field loss, and how this might affect the clinician's approach to refraction (Chapter 4).

1.1. Central Vision Loss: Preferred Retinal Locus

The disease progression of central vision loss, most commonly age-related macular degeneration, is usually, but not always, progressive. In the early stages of age-related macular degeneration, the para-foveal areas are affected first (Owsley et al., 1999). The patient may experience distortion, decreased contrast, etc. but still have a visual acuity of 0.0 logMAR (20/20) vision. Once damage occurs to the fovea, the patient will experience a measurable decrease in visual acuity and noticeable central scotoma. At some point during this progression, the patient may achieve clearer vision when attending to an area of peripheral retina instead of the damaged fovea. This new peripheral retinal location the patient uses for fixation is called the preferred retinal locus (PRL) or pseudofovea.

The most common method which clinicians utilize to measure and explore the PRLs of patients with central vision loss is through microperimetry. With the use of a scanning laser ophthalmoscope, microperimetry will map monocular retinal sensitivity on a live fundus photo while tracking a retinal landmark while the patient is asked to fixate on a fixation stimulus (Figure 1.1). This real-time tracking provides details regarding the specific

peripheral retina areas the patient is using to attend to the fixation target throughout the duration of the test. In particular, a common microperimeter used is the Macular Integrity Assessment (MAIA). This was also the microperimeter used at all data collection visits in Chapters 2 and 3 of this thesis.

When exploring the characteristics of a PRL, there are several outcome measures commonly explored via microperimetry. First, fixation stability at the PRL is represented by the variability in retinal locations used for fixation at any given moment. Fixation stability is defined by the bivariate contour ellipse area, which represents the 95% confidence interval of all the specific retinal locations used for fixation. A larger BCEA area, suggests a wider distribution and variability of retinal areas used for fixation, and thus represents greater fixational instability. Therefore, a patient with an unstable PRL will utilize a large area of retina for fixation whereas a patient with a stable PRL will utilize a small, concise area of retina for fixation (see Figure 1.1). In addition to PRL fixation stability, other common PRL measures include PRL retinal eccentricity which is the distance (in degrees or millimeters) from the center of the fovea (damaged or partially-damaged) to the center of the PRL (if using microperimetry, then defined as the average of all PRL locations, within the BCEA, during the perimetry task). In addition to the PRL distance, orientation relative to the center of the fovea may also be measured. This may be defined categorically, for example, the PRL may be located in the inferior, temporal, superior or nasal retinal quadrant, or defined as a continuous variable with a specified orientation direction (in degrees) (see Figure 1.2).

To determine the visual function at the PRL, investigators commonly measure visual acuity (Rees et al., 2005; Crossland et al., 2004; Haris et al., 2005), contrast sensitivity (Rees

et al., 2005, Crossland et al., 2004), facial recognition (Haris et al., 2020), smooth pursuit (Barraza-Bernal, Rifai &Wahl, 2017), saccade characteristics (Van Der Stigchel et al., 2013; Bullimore & Bailey, 1995) or reading speed (Trauzettel-Klosinski, Dieling & Pietsch, 2003; Crossland et al., 2004). Chapter 2 outlines the *Exploration of Dynamic Text Presentations in Bilateral Central Vision Loss*, a research project which examines how PRLs impact reading accuracy and reading speed. In this research project, the primary outcome measures included reading speed, PRL eccentricity and reading acuity.

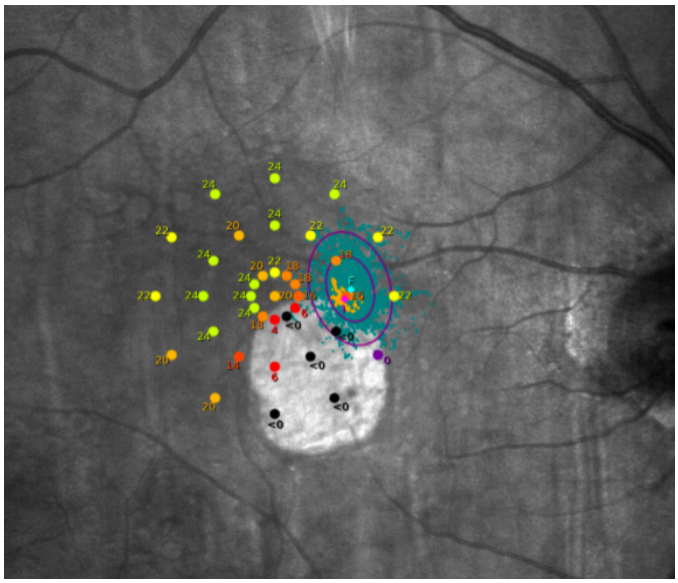


Figure 1.1. *Example of MAIA Microperimetry*. This patient was diagnosed with dry age-related macular degeneration and subsequently developed a distinct area of geographic atrophy (seen by the hyper-reflective region of the fundus image). The geographic atrophy is centered within the fovea and paramacular region. The MAIA microperimetry tested threshold sensitivity in 50 points directed in superior retina to the geographic atrophy. Each point tested shows the threshold value in dB. The blue points on the fundus image represent the areas of the retina which the patient used to fixate at a target while the microperimetry task was performed. The outer purple ring represents 95% of the fixation points and the inner purple ring represents 68% of the fixation points. The center light blue point labeled "F" represents the geometric center of all fixation points used by the patient. The "F" represents the estimated PRL and the purple ellipses represent the range of PRLs and represent stability. This patient used a superior retinal PRL or inferior visual field PRL.

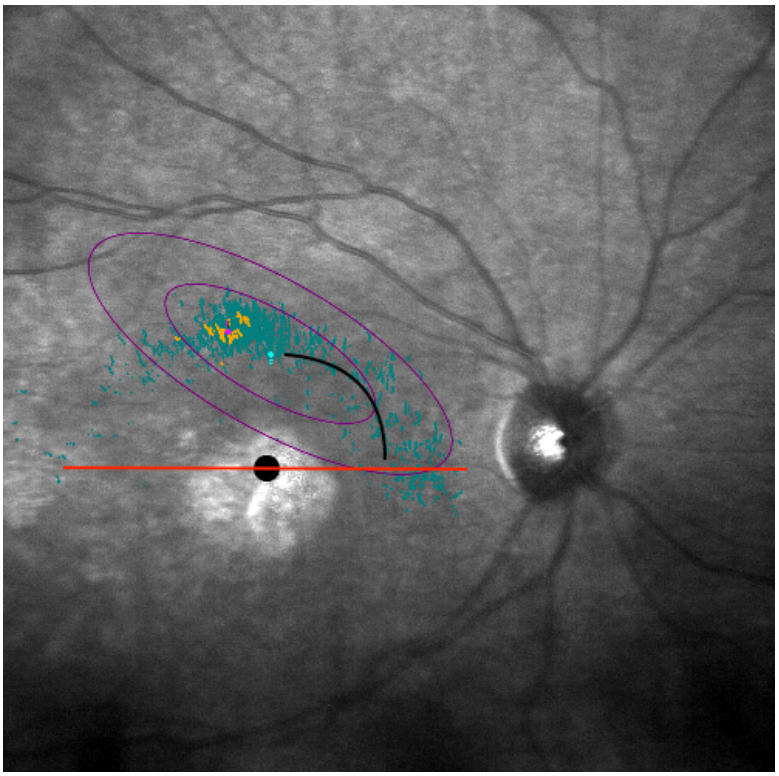


Figure 1.2. *Demonstration of PRL eccentricity*. In this MAIA image, the hyperfluorescent region of the retina is the geographic atrophy and the black dot is the damaged fovea of a patient's right eye. This participant had a PRL in superior retina (in relation to the damaged fovea). The light blue dot in the center of the 68% and 95% BCEA ellipses represents the average PRL location throughout the duration of the microperimetry. This PRL, has an orientation of 87.47 degrees (represented by the curved black line) in relation to the 0 degree meridian (represented by the red horizontal line through the damaged fovea).

Several past research studies have shown that central vision loss patients commonly adopt a PRL in inferior or right visual field space (Schoessow, Fletcher & Schuchard, 2012; Fletcher & Schuchard, 1997) although PRLs can be seen in any of the four quadrants (Crossland, Culham & Rubin, 2005). Fletcher & Schuchard (1997) examined the characteristics of the PRL in a group of central vision loss patients and found 39% of patients had a PRL inferior to their central scotoma, 33.7% had a left PRL, 19.9% had a right PRL

and 7.5% had a superior PRL, all within visual field space. The time which it takes for a PRL to be adopted varies but Crossland et al. (2005) determined that it takes less than six months for a patient with bilateral central vision loss to use a repeatable PRL after the onset of vision loss in the second affected eye. Even after the establishment of a PRL, patients with central vision loss may have a central scotoma which enlarges rapidly or slowly depending on the progression of the macular disease. However, little research has been performed to determine how the PRL changes as the scotoma changes but one study did examine such question in a group of simulated central vision loss individuals. This study reported that the PRL remained at the same orientation but at a larger eccentricity as the scotoma enlarged and fixation stability decreased (Costela, Reeves & Woods, 2020).

Additionally, the PRL that a patient may develop in the setting of central vision loss often does not correlate with the retinal area of highest sensitivity (Shima, Markowitz & Reyes, 2010) or best acuity (Bernard & Chung, 2018). Therefore, it is likely that multiple factors, which are not yet well understood, determine how or why a patient adopts a particular PRL location. A patient may also adopt multiple PRLs which may change depending on light level (Lei & Schuchard, 1997), target size and word length (Deruaz et al., 2002) or task (Duret, Issenhuth & Safran 1999; Timberlake et al., 2006). But the presence of multiple PRLs does not impact reading speed of MNRead style sentences (Crossland et al., 2005). It is evident that PRLs differ across patients, as there are a wide variety of individual characteristics.

Although use of a PRL may be more advantageous than use of a damaged fovea, many patients with central vision loss are unsatisfied with their vision due to the reduced

acuity and increased susceptibility to crowding in the peripheral retina. Even with mild visual acuity loss, many low vision patients rate their vision quality as poor or fair (Goldstein et al., 2012) and frequently seek low vision rehabilitation care. Since reading is the most common complaint of central vision loss patients (Brown et al., 2014), the research study outlined in Chapter 2 explores further characteristics of reading with PRLs and the research study in Chapter 3 explores possible eccentric viewing training methods which may improve visual performance within the central vision loss population.

1.2. Central Vision Loss and Reading: Background

1.2.1 General Background

Numerous outcome measures are utilized when exploring reading ability. First, text size can be explored in several ways including critical print size, defined as the smallest print size a patient can read at their maximum reading speed, and threshold print size, defined as the smallest print size a patient can read regardless of the reading speed, though often slower. Reading speed can be explored through measures such as maximum reading speed when not limited by print size and silent reading speed. Reading comprehension may also be measured. Visual span is another common measure and is defined by the number of characters clearly seen without any eye movements. Additionally, oculomotor measurements may be explored when researching reading ability. Saccades are rapid binocular eye movements from one fixation point to another and are continuously used while reading. When reading, patients will use multiple forward saccades from left to right when reading across a line and then use

a saccade from the end of one line to the start of the next line located below (return-sweeps). Less commonly, readers also use backward saccades (right to left) to re-read missed information. Research has shown that forward saccades and return-sweeps are guided by the size of the text (Vasilev et al., 2021). When examining saccades while reading, saccades are generally measured as characters per saccade. Saccade sizes are measured by numerous eye-tracking systems. These reading measures are well studied in normally-sighted individuals but are less commonly studied in individuals with central vision loss.

Reading is the most common complaint of central vision loss patients presenting to low vision clinic (Brown et al., 2014). Individuals with central vision loss read as slowly as 20-50 words per minute (wpm) and subsequently exhibit poor reading comprehension (Trauzettel-Klosinski, Dieling & Pietsch, 2003) whereas normally sighted individuals can read up to 250 wpm (Ziefle, 1998).

1.2.2. Characteristics of Reading with a PRL

There are numerous reading characteristics which central vision loss patients exhibit which helps explain why those who use a PRL read slower than normally sighted individuals. These characteristics include decreased size of forward saccades (Crossland et al., 2004), increased number of regressions (Crossland et al., 2004; Bullimore & Bailey, 1995), poor fixation stability (Altinbay, Idil & Sahli, 2021; Crossland et al., 2004), smaller visual span (Cheong et al., 2008), and additionally, the larger the PRL, the slower the reading speed (Ergun et al., 2003). Although previous research has shown that patients with central vision loss differ from normally-sighted, it is also probable that central vision loss individuals do

not behave the same way among themselves. See section *2.1.3. Reading with a PRL* for more information.

The relationship between reading and the PRL is poorly understood. To gain insight regarding how the use of PRL impacts reading ability, researchers commonly explore the behaviors of simulated-central vision loss. One question is how does the location of a PRL impact reading and what PRL location may be advantageous for reading. Studies have shown that use of an inferior visual field space PRL is advantageous for reading (Fine & Rubin, 1999; Petre et al., 2000) and associated with faster reading speed and fewer number of fixations (Fine & Rubin, 1999). An inferior PRL is advantageous because the scotoma will be superior and therefore not obstructing a line of words as the patient scans left to right and, additionally, not obstructing the next line of words. However, other research studies have shown that PRL location does not impact reading ability (Bowers, Woods & Peli, 2004; Fletcher & Rubin, 1999).

In addition to PRL location, researchers also question if a particular text presentation improves reading in central vision loss. When a patient has central vision loss, their visual acuity typically worsens and a patient must magnify the text they read. The conventional page format of reading material becomes more difficult and two text presentations, rapid serial visual presentation (RSVP) and horizontal scrolling (scrolling) are faster to read (Legge et al., 1989; Rubin & Turano, 1992). RSVP is an electronic text presentation where a single word appears one at a time at the same location. Scrolling is an electronic text presentation where a single line of words continuously moves from right to left. Both text presentations can be modified by speed and text size. RSVP is faster to read than standard

text presentation because it eliminates nearly all eye movements needed (Potter, 1984) and scrolling is faster because it eliminates the saccadic eye movement to the next line, which is beneficial because central vision loss patients are more likely to have inaccurate and slower saccades (Whittaker, Cummings & Swieson, 1991; McMahon, Hansen & Viana, 1991). Several studies have shown that central vision patients read RSVP faster than static text and, separately, read scrolling faster than static text (Legge et al., 1989; Rubin & Turano, 1992). However, fewer studies have directly compared RSVP versus scrolling. Although reading RSVP requires fewer eye movements than scrolling, one study comparing central vision loss patients' ability to read RSVP versus scrolling showed there is no difference in the reading rate between the two (Fine & Peli, 1995).

This concept can be further expanded to examine whether reading rates of certain text presentations depends on PRL location. The well-accepted hypothesis concerning scrolling is that if central vision loss patients use a vertical (either inferior or superior) PRL, then they will be able to read scrolling faster than patients using a lateral PRL. As stated earlier, research has not proved that such hypothesis is true and this concept needs to be studied further. The purpose of the first research experiment in this thesis (Chapter 2) is to explore if text presentation (RSVP and scrolling), text size and PRL eccentricity impact reading speed in both simulated central vision loss in normally-sighted controls and patients with central vision loss.

Based on the current literature, our hypotheses of this research experiment are as follows: 1) both simulated central vision loss and patients with central vision loss will read RSVP faster than scrolling 2) both simulated central vision loss and patients with central

vision loss will read larger text sizes (regardless if RSVP or scrolling) faster than smaller text sizes and 3) patients with central vision loss and a less eccentric PRL will read RSVP and scrolling faster than those with a more eccentric PRL location.

1.3. Eccentric Viewing Training: Background

1.3.1 General Background

Several rehabilitation techniques exist to help central vision loss patients read more comfortably. First, the print can be modified. Hand-held magnifiers, stand magnifiers and closed-circuit television (CCTV) systems can magnify reading material to help those with reduced acuity see better. Additionally, accessible yet simple tools such as magnification on tablets or smartphones can be used to magnify text. Besides modifying the reading text, the peripheral vision of patients with central vision loss can be maximized by low vision refraction or modifying patient behavior. Specifically, a technique called eccentric viewing training can be performed to train the patient to use a particular PRL for fixation while reading.

As described previously, patients with central vision loss have reduced acuity, reduced visual span and unstable fixation even with use of a developed PRL. Because of the poor visual function, the question as to whether eccentric viewing training may improve visual function and oculomotor control continues to be contentious. Therefore, we sought to explore what are the best and most effective eccentric viewing training techniques may be. Eccentric viewing training is typically performed for central vision loss patients and broadly

speaking, the goal of eccentric viewing training is to maximize a patient's remaining visual function. The goal of eccentric viewing training is not to regain vision.

In order to determine if a particular eccentric viewing technique is effective, there are several quantitative outcome measures which can be explored. Visual function measures such as visual acuity, contrast sensitivity or reading speed can be measured in addition to oculomotor behaviors such as fixation stability. Other valuable measures include saccade size, facial recognition, search task accuracy, and self-reported improvement in function via a survey tool such as Massof Activity Inventory, an adaptive visual function questionnaire which assesses the rehabilitation needs of visually impaired patients.

The two most common participant groups included in eccentric viewing training research are those with simulated central vision loss and patients with central vision loss. Often, eccentric viewing methods are explored with simulated central vision loss to predict if it will be effective in patients with central vision loss. This approach is common in the literature, as it is easier to recruit normally-sighted individuals than those with central vision loss.

Another component of eccentric viewing training research to consider is what part of the retina should be trained: an already established, habitual PRL or a new PRL? Although patients with central vision loss may habitually adopt a PRL anywhere within the retina (Crossland et al., 2005), some research has shown an inferior visual field PRL may be especially advantageous for reading (Fine & Rubin, 1999; Petre et al., 2000). These findings have prompted some research studies to train a vertically aligned PRL (Nilsson, 2003) instead of a horizontally aligned PRL. Other research studies have trained a PRL at the

retinal location of best acuity (Hassan et al., 2019) while other research studies have trained "better use" of a habitual, established PRL (Rubin, 2017) as there is clinical suspicion that central vision loss patients may tend to change a PRL to a more natural location despite a trainer-select PRL. Time spent performing eccentric viewing training varies as well. For example, a single training session could last ten minutes (Amore et al., 2013), 30 minutes (Daibert-Nido et al., 2019) or up to an hour (Deruaz et al., 2006).

1.3.2 Eccentric Viewing Training Techniques

A variety of eccentric viewing training techniques have been researched. The methods vary and can be as simple as describing what eccentric viewing is to a patient (Crossland et al., 2005). Additionally, monocular eccentric viewing training can be implemented with use of a scanning laser ophthalmoscopy (SLO) (Deruaz et al., 2006) and the MP-1S (MP-1 scotopic microperimeter) (Markowitz & Reyes, 2013). The MP-1S has embedded feedback including audio. The change of audio frequency indicates how accurate the patient is fixating. A flickering light feedback system would be implemented in the same manner. See section *3.1.2. Eccentric Viewing Techniques* for more information regarding eccentric viewing training methods and results on training efficacy.

In general, research studies show that eccentric viewing training is effective in the central vision loss population to a varying extent (Amore et al., 2013; Daibert-Nido et al, 2019). However, there are some studies with particular eccentric viewing training methods or outcomes measures which do not produce favorable results (Hassan et al., 2019; Rubin, 2017). Howe (2012) conducted a meta-analysis of 17 eccentric viewing training studies of

central vision loss patients. The meta-analysis results revealed nearly each of the studies showed a significantly faster reading rate after eccentric viewing training. Additionally, there was a positive correlation between hours spent training and reading speed. Eccentric viewing training programs which had a longer duration resulted in a faster reading speed post-training. Additionally, the younger the patient was, the faster the final reading speed and the worse the visual acuity, the greater the change in reading speed.

It is evident some benefits of eccentric viewing training exist for at least some central vision loss patients. Currently, there is no consensus with respect to the goals of eccentric viewing training (Stelmack, Massof & Stelmack, 2004). There is also no standardized method for eccentric viewing training or outcomes to assess the effectiveness of training (Stelmack et al., 2004) so more research needs to be conducted in order to determine: what are the most effective feedback techniques, what patient characteristics are most likely to benefit from training, what PRL location should be trained and are the training effects long-standing.

The purpose of the experiments described in Chapter 3, are to explore the efficacy of five feedback mechanisms for inferior PRL eccentric viewing in two populations: simulated central vision loss and central vision loss patients in a one-visit training session. Primary outcome measures included visual acuity and contrast sensitivity.

Based on previous literature, our hypothesis is that visual acuity and contrast sensitivity measures will be better post-training than pre-training in central vision loss patients.

1.4.Blur Perception in Low Vision Patients: Background

Although low vision patients tend to have reduced acuity, contrast sensitivity or visual field, it is imperative the clinician maximizes patients' vision through the process of refraction. The current protocol for low vision refraction utilizes the just noticeable difference rule (JND rule) (DeCarlo, Woo & Woo, 2006). The JND rule suggests that the selection of bracketing lenses shown to the patient during refraction should solely be based off of their visual acuity such that JND=MAR/100. The bracketing lenses become smaller during the refraction procedure as visual acuity improves. The assumption behind the JND rule is that patients with poorer visual acuity cannot discriminate dioptric blur as reliably as those with better visual acuity and therefore, larger bracketing lenses need to be used. Patients with reduced visual acuity have a larger depth of focus (Green, Powers & Banks, 1980) and increased tolerance to defocus (Legge et al., 1987). Although visual acuity does predict how a patient will perceive their vision, other factors play into a patient's vision such as visual field loss, scotomas, contrast sensitivity, nystagmus, and any ocular pathology and perhaps those factors may need to be considered during low vision refraction.

Anecdotally, low vision clinicians often express that patients can perceive smaller or larger differences in lens power than what the JND rule predicts and therefore need to deviate from the standard low vision trial frame refraction protocol in order to prescribe the most accurate refraction. Bailey (2017) has proposed a modified low vision technique involving large step bracketing to discourage assumptions based upon the patient's blur discrimination abilities. In Bailey's proposed low vision refraction method, to replace the JND rule, two

lenses of opposite sign and same power are presented to the patient in front of best estimated refractive correction. The clinician notes the emphasis of rejection to both lenses and determines if the patient suggested a preference for the more minus or more plus lens. The bracket size begins large and becomes smaller (+/- 8.00D, +/- 3.50D, +/- 1.25D).

Neither refraction method has been experimentally proven to be effective and it is unknown what factors impact a low vision patients' ability to perceive blur. The purpose of this study was to examine the validity of the JND rule and explore how other visual factors such as visual field loss, contrast sensitivity less and visual acuity impact low vision patients' perception of dioptric blur.

1.4.1. Blur Perception Literature

Blur perception studies in normally sighted subjects has shown that blur adaptation varies between people. Inter-subject blur adaptation variability exceeded test and re-test variability when normally sighted participants were asked about their perception of blur following a brief exposure to either a blurrier or sharper image (Vera-Diaz, Woods & Peli, 2010). Additionally, perception of blur in normally sighted may depend on personality (Woods et al., 2010) and normally-sighted myopic patients who experienced long term blur without refractive error correction demonstrated a shift in the blur adaptation function (Pesudovs & Brennan, 1993).

Minimal research studies have explored blur perception within the low vision population, but Vera-Diaz et al. (2017) found that short term blur adaptation can be measured in patients with central vision loss despite experiencing long term blur secondary to central

vision loss. Research thus far provides some insight on blur tolerance and adaptation of low vision patients but more studies are needed to fully understand what impacts a low vision patients' perception of blur.

Chapter 4 of this thesis explores blur perception in low vision patients. The purpose of this research experiment is to explore if common clinical measures such as visual acuity, contrast sensitivity or visual field impact low vision patients' and normally-sighted individuals' perception of blur. Specifically, three groups of the low vision population were considered: central vision loss (CVL), peripheral vision loss (PVL) and albinism. Central vision loss, peripheral vision loss and albinism patients all experience different visual perceptions. Patients with central vision loss have neural blur due to reduced spatial resolution secondary to a retinal etiology. Patients with peripheral vision loss have reduced field of view. Patients with albinism have neural blur due to increased retinal image motion secondary to nystagmus. The importance of this research question is because the first step in optimizing vision for low vision patients is refraction. Clinical observation reveals low vision patients perceive blur differently from normally-sighted so blur perception in the low vision population needs to be explored to improve refraction.

Based on previous literature, the hypotheses of this research project are that 1) all three clinical measures impact blur sensitivity where the worse the visual acuity and contrast sensitivity is and the smaller the visual field is, the less sensitive the patient is to blur normally-sighted and 2) low vision patients will have less sensitivity to blur and more variability in their perception of blur compared to normally-sighted controls.

Chapter 2: Exploration of Dynamic Text Presentation in Bilateral Central Vision Loss

2.1. Exploration of Dynamic Text Presentation in Bilateral Central Vision Loss: Introduction

2.1.1. Central Vision Loss: Details about Preferred Retinal Locus

One reason why visual function is poor in patients with central vision loss is because these patients have damaged or non-functional foveae from a myriad of etiologies depending on the ocular condition. In the progression of age-related macular degeneration, the para-foveal area may be affected first, but once the foveal region is damaged, the patient will experience a decrease in acuity and central scotomas. When a patient experiences significant central vision loss, at some point during disease progression, an area of the peripheral retina is used as a pseudofovea, in place of the damaged fovea. This location of the retina they subsequently attend with is called the preferred retinal locus (PRL).

The most common method which clinicians utilize to measure and explore the PRLs of patients with central vision loss is through microperimetry. See section *1.1. Central Vision Loss: Preferred Retinal Locus* including Figures 1.1. *Example of MAIA Microperimetry* and 1.2. *Demonstration of PRL eccentricity* for more details regarding microperimetry. With the use of a scanning laser ophthalmoscope, microperimetry will map monocular retinal sensitivity on a live fundus photo while performing eye tracking (Figure 1.1). The eye tracking ability helps the microperimetry assess what part of the peripheral retina, or fovea,

the patient is using to attend to the fixation target throughout the duration of the test. The MAIA microperimeter was used in the methods of this chapter.

Common measures derived from a microperimeter include the bivariate contour ellipse area (BCEA) which represents fixation stability, PRL retinal eccentricity or PRL distance. Oculomotor measures are typically acquired from microperimetry. To determine the visual function at the PRL, investigators commonly measure visual acuity, contrast sensitivity, facial recognition, smooth pursuit and saccade accuracy or reading speed. This chapter outlines the *Exploration of Dynamic Text Presentations*, a research project which examines how PRLs impact reading. In this research project, we use the PRL outcome measures of reading speed, PRL eccentricity and reading acuity.

Many research studies have been conducted to determine the characteristics of a PRL and how it develops. See section *1.1. Central Vision Loss: Preferred Retinal Locus Characteristics* for more details. Although use of a PRL may be more advantageous than use of a damaged fovea, many patients with central vision loss are unsatisfied with their vision due to the reduced acuity and increased susceptibility to crowding in the peripheral retina. Even with mild visual acuity loss, many low vision patients rate their vision quality as poor or fair (Goldstein et al., 2012) and frequently seek low vision rehabilitation care. Since reading is the most common complaint of central vision loss patients (Brown et al., 2014), the research study outlined in this chapter explores further characteristics of reading with PRLs and the research study in the next chapter, Chapter 3, explores possible eccentric viewing training methods which may improve reading within the central vision loss population.

2.1.2. Central Vision Loss and Reading Characteristics

Research studies which explore reading ability often use a variety of parameters in their methodology. First, reading speed is often explored. Reading speed can be measured in several ways such as maximum reading speed when not limited by print size, silent reading speed. Reading can also be measured based on reading comprehension. Other outcomes include: the critical print size – defined as the smallest print size a patient can read at their maximum speed and threshold print size – defined as the smallest print a patient can read regardless of the reading speed. Additionally, accuracy and size of reading saccadic eye movements are often explored. Saccades are rapid binocular eye movements from one fixation point to another. When reading, patients use multiple forward saccadic eye movements in the direction of left to right to read a line of words and then use a saccade from the end of a line to the start of the next line below (return-sweeps). Readers also use backward saccades from right to left to re-read missed information. Saccades are generally measured by characters per saccade and the size of a saccade varies depending upon the reader and difficulty of text. Numerous eye-tracking systems are now commercially available to monitor and measure saccades while patients read text. Visual span is another common measure and is represented by the number of characters seen reliably without any eye movements. These measures of reading are well studied in normally-sighted individuals but are less commonly studied in those with abnormal vision, such as central vision loss.

Of all complaints of central vision loss patients, reading is the most common (Brown et al., 2014). Normally sighted individuals can read up to 250 words per minute (wpm)

(Ziefle, 1998) whereas individuals with central vision loss read as slowly as 20-50 wpm which hinders their reading comprehension (Trauzettel-Klosinski, Dieling & Pietsch, 2003). As mentioned in Chapter 1, there are numerous reading characteristics which central vision loss patients exhibit which may explain why those who use a PRL for fixation read slower than normally sighted individuals. Central vision loss patients read with a decreased size of forward saccades and an increased number of regressions (Crossland et al., 2004). These abnormal oculomotor findings are correlated with a slower reading speed (Timberlake et al., 2006) and poor facial recognition (Seiple, Rosen & Garcia, 2013).

Additionally, previous studies have shown that the PRL diameter, defined as the bivariate contour ellipse area (BCEA) used to describe 63%, 68% or 95% of the retinal loci used for fixation, ranges from 1 to 9 degrees (Fletcher & Schuchard, 1997), where the larger the BCEA the greater the fixation instability. Fixation stability has also been correlated with reading speed (Altinbay, Idil & Sahli, 2021; Crossland et al., 2004) and correct reading rate (Schuchard, 2005). The visual span, the number of characters a patient can see on either side of a fixation point, is reduced in central vision loss patients and this further slows reading speed (Cheong et al., 2008). Additionally, the larger the size of the scotoma, the slower the reading speed (Ergun et al., 2003).

Although the relationship between reading and the PRL is poorly understood, previous studies looking at the behaviors of simulated central vision loss participants have indicated that using a PRL in the inferior visual field space is advantageous for reading (Fine & Rubin, 1999; Petre et al., 2000). When a PRL is in the inferior visual space, the scotoma will be superior, not obstructing a line of words as the patients scans from left to right, and

not obstructing the succeeding lines. Therefore, inferior PRL locations are associated with faster reading speed and fewer number of fixation (Fine & Rubin, 1999). However, PRL location, whether vertical or lateral to the patient's scotoma, may not have a significant on reading speed (Bowers, Woods & Peli, 2004; Fletcher & Rubin, 1999). This controversy prompts further research concerning whether reading rates are influenced by the type of text presentation.

In addition to PRL location, researchers have explored if a particular text presentation improves reading in central vision loss. RSVP and scrolling are two text presentations commonly explored. See section *1.2.2. Characteristics of Reading with a PRL* for more details. As mentioned in Chapter 1, previous studies have shown that rapid serial visual presentation (RSVP) and horizontal scrolling (scrolling) are faster to read than conventional page formats (Legge et al., 1989; Rubin & Turano, 1992). RSVP is faster than standard text presentation to read because it nearly eliminates all eye movements needed (Potter, 1984) and scrolling is faster because it eliminates the saccadic eye movement to the next line. Several studies have shown that central vision patients read RSVP faster than static text and, separately, read scrolling faster than static text (Legge et al., 1989; Rubin & Turano, 1992). Although reading RSVP requires fewer eye movements than scrolling, studies comparing central vision loss patients' ability to read RSVP versus scrolling show there is no difference in the reading rate between the two (Fine & Peli, 1995).

This concept needs to be further explored to determine how text presentation and font size impacts reading ability in central vision loss. Therefore, the purpose of the first research experiment in this thesis (Chapter 2) is to explore if text presentation (RSVP and scrolling),

text size and PRL eccentricity impact reading speed in both simulated central vision loss in normally-sighted controls and patients with central vision loss.

2.2 Exploration of Dynamic Text Presentation in Bilateral Central Vision Loss: Methods

2.2.1. General Information about Recruitment

We recruited 11 bilateral central vision loss participants from New England College of Optometry (NECO) Center for Eye Care and affiliated low vision clinics, and sixteen normally sighted participants (twelve naïve undergraduate students and 4 experienced participants) from Northeastern University. Central vision loss participants were compensated for participation, and normally-sighted students received course credit for their participation. Written informed consent was obtained from each participant and the study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by the New England College of Optometry and Northeastern University Institutional Review Boards.

2.2.2. Normally Sighted Participants

The age range of participants was 18 to 52 and the median age was 19. There were 16 subjects (4 males). All participants were self-reported as normally-sighted, were required to be a native-English speaker, appropriately corrected with spectacles or contact lenses if ametropic, and had no history of any ocular pathology. Perimetry was not performed on

control participants, however, as described below, stimuli were presented to eccentric visual field of simulated central vision loss participants, where any undiagnosed central scotoma vision loss should not affect this group.

2.2.3. Central Vision Loss Participants

Seven out of 11 central vision loss participants were confirmed to have bilateral central scotomas using macular integrity assessment (MAIA) perimetry. Four central vision loss participants could not be imaged with the MAIA due to high myopic refractive error (greater than 15D). Therefore, these bilateral central scotomas were confirmed through Amsler grid, facial visual field testing or a static presentation central visual field test. The age range of the central vision loss participants was 19 to 91 years and the median was 71 years. There were 4 males and 7 females. The range of binocular near visual acuity was 0.3 to 1.00 logMAR [6/12 to 6/60 equivalent] and the median was 0.60 logMAR [6/24 equivalent]. To be eligible to participate in the research study, central vision loss participants needed a mini-mental state exam score greater than 24 to rule out cognitive impairment. See table 2.1. for participant characteristics.

Participant	Age	Gender	Diagnosis	Binocular Near Visual Acuity (logMAR)	Better Eye Near Visual Acuity (logMAR)	Binocular Contrast Sensitivity (logCS)
1	77	Male	Non-exudative AMD	0.53	0.53	1.50
2	47	Male	Degenerative myopia with maculopathy	0.54	0.62	1.50
3	70	Female	Degenerative myopia with maculopathy	0.60		1.35
4	67	Female	Macular scarring secondary to toxoplasmosis	0.70	0.22	1.35
5	70	Female	Exudative AMD	1.00	1.00	
6	19	Female	Unspecified hereditary retinal dystrophy	0.70	0.68	1.35
7	91	Female	Exudative AMD	0.49	0.60	1.35
8	37	Male	X-linked retinoschisis	0.30	0.43	1.65
9	57	Male	Choroidal Neovascularization	0.66		1.35
10	68	Female	AMD	0.44		1.20
11	75	Female	Inherited macular dystrophy	0.82		1.44

Table 2.1. *Central vision loss participant characteristics*. All participants have binocular diagnoses. Empty table cells indicate the participant did not have a measurement within 6 months of their research study visit. Binocular and better eye near visual acuity were measured with the Lighthouse Near Visual Acuity Test Modified ETDRS. Binocular contrast sensitivity was measured with Pelli-Robson Contrast Sensitivity Chart except subject 10 and 11 contrast sensitivity measurements were taken with Mars Letter Contrast Sensitivity test measured in logCS.

2.2.4. General Information about Procedures

Stimuli were presented and generated using Psychtoolbox-3 in Matlab 27 (Brainard, 1997). For the normally-sighted subjects, the experiment was displayed on a BenQ XL2720Z LCD monitor with 120Hz refresh rate and a mean luminance of 150 cd/m^2, and controlled by a Dell Optiplex 9020. For central vision loss participants, the experiment was run on a Dell

Optiplex 7040 desktop computer and presented on an ASUS HDMI VG278HE LCD monitor with a 120Hz screen refresh rate and a mean luminance of 100 cd/m^2. In both cases, eye movements were recorded with a desktop-mounted Eyelink 1000 at 1000 Hz (Cornelissen 2002) and although there was a difference in mean luminance, the luminance contrast between the optotypes and background was the same for both central vision loss and simulated central vision loss participants. Subjects' heads were secured with a chin and forehead rest to ensure they were 60 centimeters from the screen. All subjects had appropriate refractive correction for the viewing distance.

Participants read aloud 4-word phrases that were randomly drawn from sentences in the MNRead charts (Mansfield 1996). The words were presented in Arial font at a range of pre-determined font sizes. For each font size condition, the exposure duration of the text was controlled using a QUEST staircase (Watson, 1983) converging at a duration at which 50% of the words were read correctly.

2.2.5. Normally Sighted Participants Procedure

Subjects fixated on a 1 degree green dot 4 degrees superior to where the text would be presented to simulate an inferior PRL (Figure 2.1). The Eyelink 1000 binocular eye tracker was used to ensure fixation compliance. An invisible 1.5 degree bounding box around the center of the fixation stimulus was used as a tolerance window. If the subject looked outside the box in any direction from the center of the fixation stimulus, the trial was stopped and a new trial began once the subject regained fixation. If the participants removed their chin from the chin rest at any point during the experiment or between trials, the eye tracker was

recalibrated. For each text presentation mode, each subject completed 5 practice trials and proceeded with 60 experimental trials comprising 20 trials for each font size (0.5 logMAR, 0.8 logMAR, 1.0 logMAR). Only binocular conditions were tested for the normally-sighted participants. The test order between RSVP and scrolling were counterbalanced between subjects.

Normally Sighted Participants: RSVP

For RSVP, a single word was presented one at a time in the center of the screen, 4 degrees inferior from the green fixation dot and the presentation duration of each word was proportional to the word length (Figure 2.1). The trial duration was the time from the onset of the first word through the offset of the fourth word.

Normally Sighted Participants: Horizontal Scrolling

For scrolling text, the four words were horizontally displayed and presented simultaneously, 4 degrees inferior from the green fixation dot. At the beginning of the scrolling text trial, the position of the first letter of the first word was presented at the center of the screen, and the text horizontally shifted left and ended with the last letter of the fourth word presented at the center of the screen (Figure 2.1). The trial duration was the time it took for the text to scroll across the screen.

2.2.6. Central Vision Loss Participants Procedure

Prior to the reading experimental procedures, central vision loss participants completed fundus-guided perimetry using a 37-point test pattern distributed within a 10 degree diameter area of the macula to confirm the bilateral central vision loss diagnosis and to determine the location of their monocular PRLs. Central vision loss participants did not have a history of eccentric viewing training and they were not asked to use a particular PRL during the MAIA microperimetry or reading task. Fixation throughout the reading task was monitored with a calibrated Eyelink 1000 series eye tracker. Central vision loss participants completed 5 practice trials of one text presentation followed by twenty trials of the same text presentation at each of the font sizes in the following descending order: 1.3 logMAR, 1.2 logMAR, 1.1 logMAR, 1.0 logMAR, 0.8 logMAR, 0.5 logMAR. The 6 font sizes corresponded to font sizes commonly found on MNRead charts. If a participant could not read any words on five consecutive trials at the slowest speed of 1 word per second, the font size was assumed to be below their acuity level and the text presentation at that font size was terminated. Reading acuity was estimated as the smallest font size at which 2 out of 4 words could be read. The same task design was repeated for RSVP and scrolling text presentation methods and the test text was randomized between each participant.

Before each trial began, a bounding box with a sequence of X's of the same font size and character length (including spaces) as the test phrase appeared on the screen to indicate where the words would appear. This allowed the subject to find and attend to the box with their PRL. A post mask of X's was present until the experimenter recorded the number of words correctly read by the participant, and the experimenter withheld the response until the

subject was ready for the next trial. Pilot testing indicated participants responded best with this particular pre- and post-trial set-up. The reading task was performed in both binocular and monocular conditions, with the participant's better-seeing eye as defined by the eye with a better corrected near visual acuity or if equal between both eyes, the dominant and/or preferred eye as reported by the participant. The test order between RSVP and scrolling were counterbalanced between participants.

Central Vision Loss: RSVP

For RSVP, a single word was presented one at a time in the center of the screen, where the bounding box of X's was originally placed, and the presentation duration of each word was proportional to the word length (Figure 2.2). The trial duration was the time it took to present the first through the fourth word.

Central Vision Loss: Horizontal Scrolling

For scrolling text, the four words were horizontally displayed and presented simultaneously. At the beginning of the scrolling text trial, the position of the first letter of the first word was presented at the center of the screen, and the text horizontally shifted left and ended with the fourth letter of the last word was presented at the center of the screen (Figure 2.2). The trial duration was the time it took for the text to scroll across the screen.

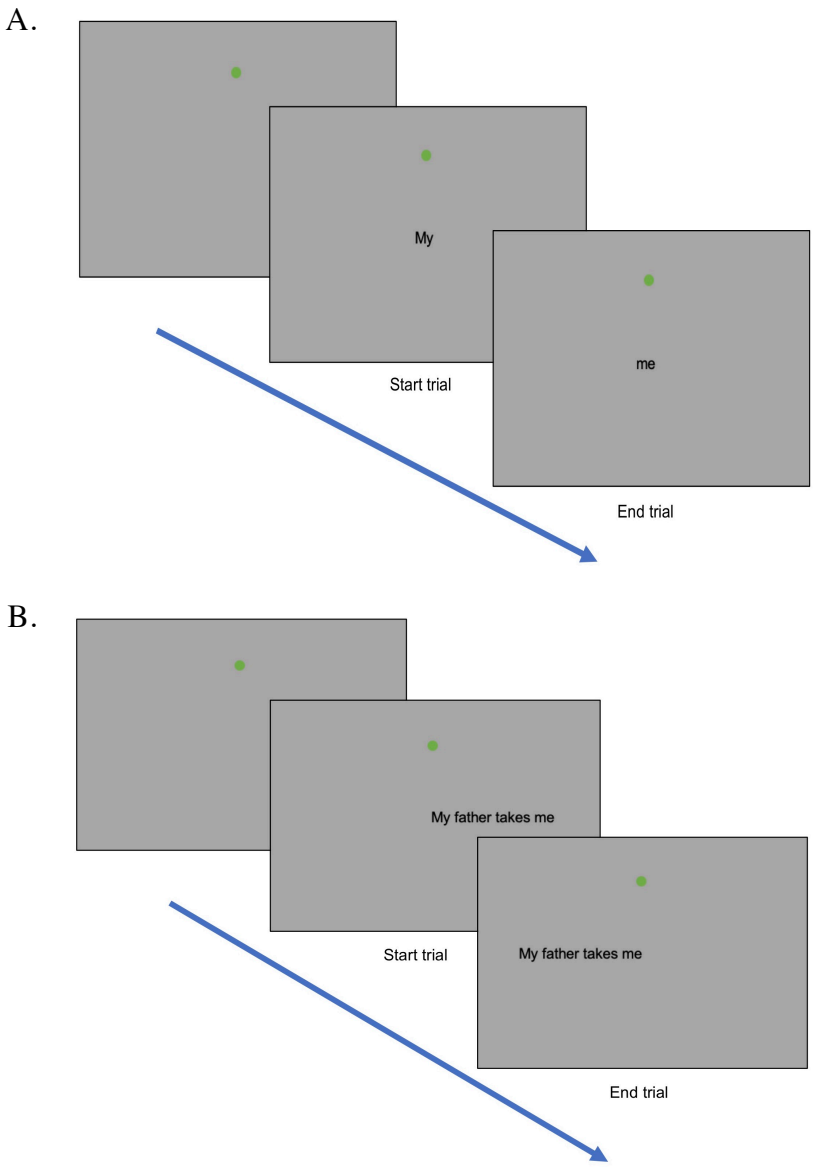


Figure 2.1. *Illustration of RSVP and scrolling procedures for simulated central vision loss participants*. **A.** A single trial of RSVP for simulated central vision loss participants began with a green fixation dot on an empty screen. The first word of a trial of RSVP appeared 4 degree inferior to the fixation dot and the word was centered in the screen. The first word disappeared and the second word appeared centered in the same location. The trial ended after the last word of the 4-word sequence appeared on the screen. **B.** A single trial of scrolling for simulated central vision loss participants began with a green fixation dot on an empty screen. The first letter of the first word was centered in the middle of the screen and the 4-word sequence scrolled from right to left. The trial of scrolling text presentation ended when the last letter of the last word reached the center of the screen.



Figure 2.2. *Illustration of RSVP and scrolling procedures for central vision loss participants*. **A.** A single trial of RSVP for central vision loss participants began and ended with a sequence of X's surrounded by a bounding box. The succeeding steps were identical to that of simulated central vision loss RSVP procedure (Figure 2.1.A). **B.** A single trial of scrolling for central vision loss participants began and ended with a sequence of X's surrounded by a bounding box and the succeeding steps were identical to that of simulated central vision loss scrolling procedure (Figure 2.1.B).

2.2.7. Data and Statistical Analysis

The proportion of words read correctly for each presentation duration from RSVP and scrolling tasks for each font size were fit with a cumulative logistic psychometric function. Threshold exposure durations (milliseconds) for words at a given font size were estimated at 60% correct corresponding to the inflection point on the psychometric function. Duration threshold estimates were then converted to words per minute (wpm) (see Equation 1). Duration threshold estimates for each font size condition in both tasks were fit with an exponential decay function (see Equation 2) when possible (Figure 2.3).

Equation 1. $$log(WPM) = log_{10}\left(\frac{(\frac{DT}{NW})}{(60*1000)}\right)$$

Where *DT* is the duration threshold estimate and *NW* is the number of words in each phrase (4 words).

Equation 2. $$log(RS) = AD + (1 - AD) * exp^{\left(\frac{log(FS) - log(RA)}{10^{T}}\right)}$$

Where *RS* is reading speed, *FS* is font size, *AD* is asymptote duration, *RA* is reading acuity and *T* is the time constant of the exponential decay function (Campbell, 1985).

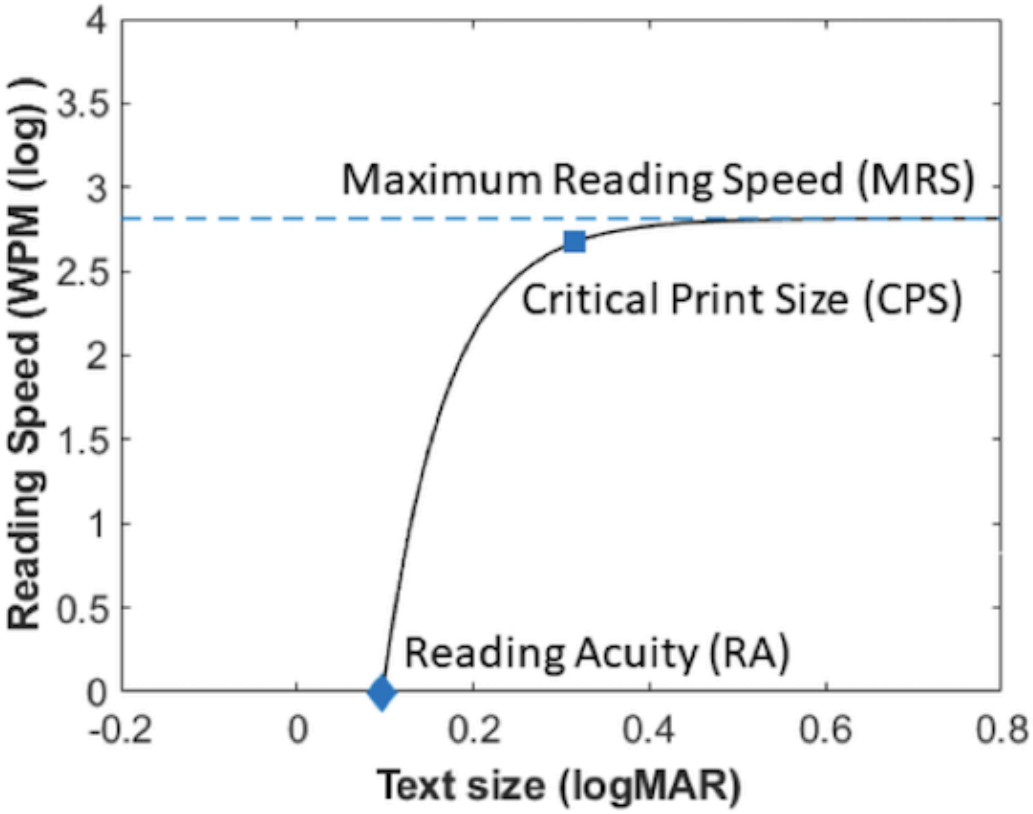


Figure 2.3. *Illustration of canonical reading curve with reading speed (words per minute, WPM) as a function of text size*. The reading curve is defined by three parameters: asymptotic duration corresponding to maximum reading speed (MRS), an exponential decay constant, and reading acuity (smallest text size that can be resolved). Critical print size (CPS, smallest text size achieved at 95% MRS) was estimated from the reading function.

Data that did not show an exponential decrease in reading speed at small font sizes (see Figure 2.11, Figure 2.13 and Figure 2.14 for examples) were fit with a straight line with slope of 0, and the corresponding *Y* was used as the MRS (see Figure 2.11).

Given that reading performance for some central vision loss participants did not follow the canonical reading curve where reading speed asymptotes at larger font sizes, we calculated an area under the log reading curve (AULC) estimate using MATLAB's *trapz()* function and the duration threshold estimates at each font size (Figure 2.4). This area approximately captures the family of font sizes and presentation durations that are readable, analogous to the area under the contrast sensitivity function (Applegate et al., 1998). We specifically did not calculate the AULC using our fitted exponential decay or straight-line functions, to capture any individual decreases in reading speed at larger font sizes. The larger the AULC value, the faster the participant's overall reading speed.

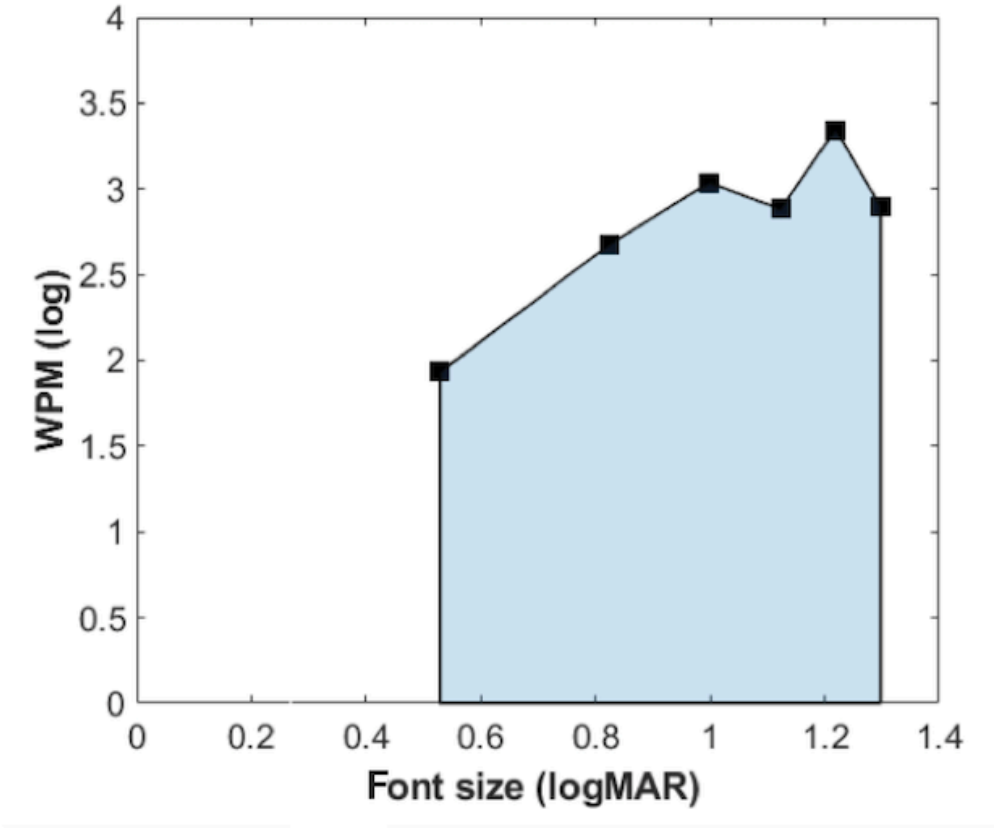


Figure 2.4. *Illustration of area under the log reading curve (AULC)*. To determine the AULC, a line was fit between each sequential font size and terminated at the smallest and largest font size tested.

Reading speed threshold estimates failed the Shapiro-Wilk test of normality, and therefore, were log transformed. Wilcoxon-signed rank related-sample tests were used to examine differences between RSVP and scrolling tasks, and Freidman's two-way analysis of variance (ANOVA) by ranks was used to examine the differences within font sizes.

Pearson correlation coefficients (one-tailed) were calculated to analyze the relationship between better eye PRL eccentricity and better eye AULC and better eye reading acuity in a subset of central vision loss participants (N=7). MAIA perimetry could not

obtained from the better eye of two participants due high myopic refractive error of greater than -16.00 diopters. The MAIA perimeter automatically adjusts for refractive error ranging from +10 to -15 diopters.

2.3. Exploration of Dynamic Text Presentation in Bilateral Central Vision Loss: Results

2.3.1. Simulated Central Vision Loss

2.3.1.1. Reading Rate in Simulated Central Vision Loss

We analyzed reading speed using three different methods, exploring differences in: trial duration threshold, maximum reading speed and AULC. For all three methods of reading speed analysis, RSVP was read significantly faster than scrolling in the simulated central vision loss participants. Trial duration threshold represents the time of the trial at which the participant read 60% of the words correctly and was converted into wpm. When exploring the median trial duration values, simulated central vision loss participants read RSVP faster than scrolling under binocular conditions (p=<0.0001). The reading speed of the median trial duration threshold was 517 wpm (11 SE) for RSVP and 215 wpm (9 SE) for scrolling.

Similar trends were noted when considering MRS. Simulated central vision loss participants showed a significantly faster MRS while reading RSVP, p=0.02. The simulated central vision loss median MRS under binocular conditions was 670 wpm (75 SE) for RSVP and 256 wpm (45 SE) for scrolling.

Lastly, simulated central vision loss participants again showed significantly higher AULC with RSVP. AULC was calculated from wpm (log) versus font size (logMAR), see Figure 2.4. AULC was significantly higher for RSVP than scrolling under binocular conditions, p=0.03. The simulated central vision loss participant median AULC in binocular conditions was 1.41 log units (0.10 SE) for RSVP and 1.21 log units (0.08 SE) for scrolling.

2.3.1.2. Effects of Text Presentation and Font Size on Binocular Reading Rate in Simulated Central Vision Loss

The effects of text presentation and font size on the binocular reading rate was explored through analysis of the duration threshold reading speeds. Simulated central vision loss participants demonstrated significantly faster reading rates for RSVP than scrolling text, p<0.0001. Additionally, they showed significantly faster reading rates as the font size increased, p<0.0001 (Figure 2.5).

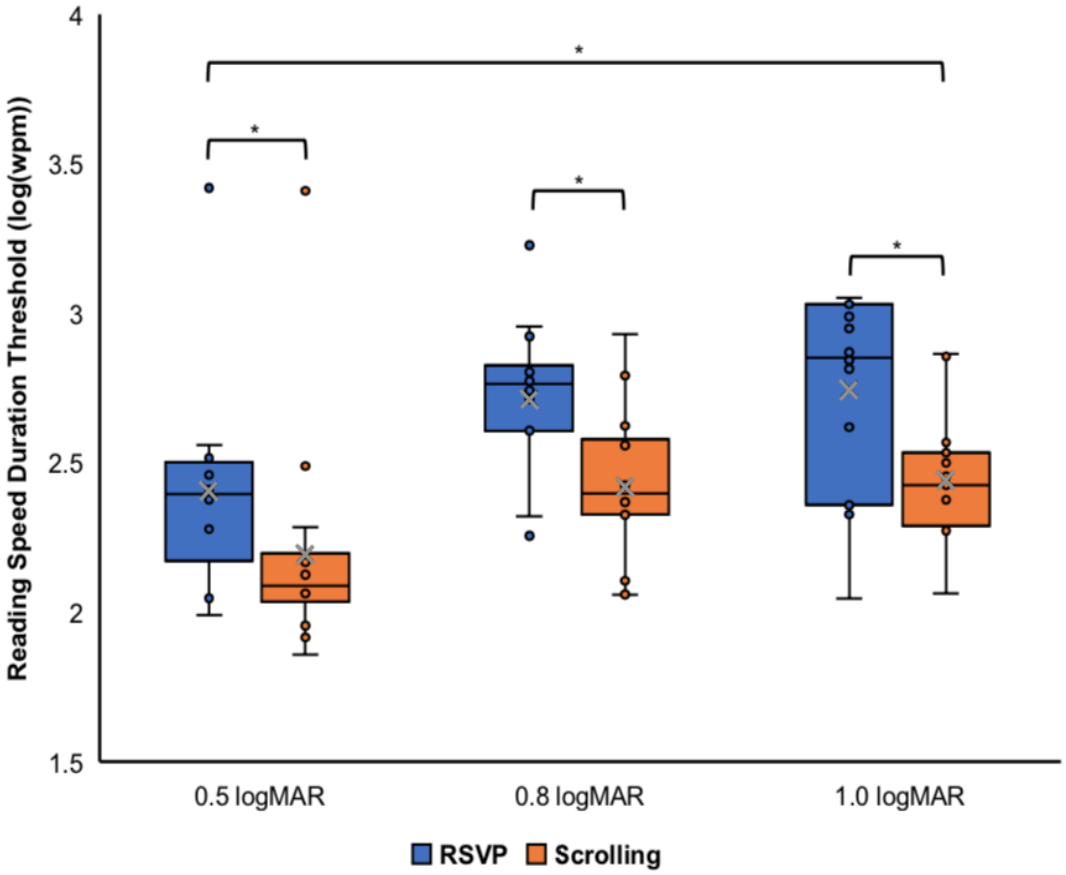


Figure 2.5. *Reading speed as a function of font size and text presentation for simulated central vision loss participants*. Box plots show the duration threshold required for reading aloud a 4-word phrase presented as 4° eccentricity in inferior visual field. Text was presented at three font sizes (0.5, 0.8 or 1.0 logMAR in ascending order respectively) and in RSVP (blue) or scrolling (orange) presentation, as indicated on the abscissa. Horizontal bars show the median, x shows the mean, the box shows the interquartile range, error bars indicate the 95% confidence intervals, the circles show individual data for individual subjects and any data points outside the error bars are outliers. Significant differences are indicated by the brackets, *=p<0.001. For reference, 120wpm = 2.08 log(wpm) and 480wpm = 2.68 log(wpm).

2.3.2. Central Vision Loss

2.3.2.1. Reading Rate in Central Vision Loss

The same three representations of reading performance (duration threshold, MRS and AULC) that were explored in simulated central vision loss were also explored in central vision loss participants but in both binocular and better eye conditions. When comparing the median trial duration threshold, regardless of font size, central vision loss participants read RSVP faster than scrolling in binocular conditions. The reading speed of the median trial duration threshold was 659 wpm (100 SE) for RSVP and 587 wpm (52 SE) for scrolling. Central vision loss participants read scrolling print faster in monocular conditions. The reading speed of the median trial duration threshold was 474 wpm (120 SE) for RSVP and 511 wpm (69 SE) for scrolling.

Similar to simulated central vision loss, MRS was also obtained from the exponential function or straight line fit. Results showed that central vision loss participants had a faster MRS while reading RSVP in binocular conditions, p=0.06, and monocular conditions, p=0.31. The central vision loss participants median MRS in binocular conditions was 819 wpm (261 SE) for RSVP and 607 wpm (123 SE) for scrolling and in monocular conditions was 560 wpm (241 SE) for RSVP and 364 wpm (118 SE) for scrolling.

When exploring the difference between reading speed of RSVP and scrolling through AULC analysis, central vision loss participants showed no significant difference between RSVP and scrolling reading rates in both binocular and monocular conditions, p=0.32, p=0.51, respectively. For both conditions, RSVP trended with faster reading speeds. The

central vision loss participants' median AULC in binocular conditions was 1.67 log units (0.19 SE) for RSVP and 1.45 log units (0.18 SE) for scrolling and under monocular conditions was 2.24 log units (0.27 SE) for RSVP and 1.46 log units (0.24 SE) for scrolling.

2.3.2.2. Effects of Text Presentation and Font Size on Binocular Reading Rate in Central Vision Loss

The effect of text presentation and font size was explored through analysis of the reading speed thresholds. Under binocular viewing conditions, central vision loss participants demonstrated no significant differences in reading rate between font sizes, p=0.12 or text presentation mode, p=0.25 (Figure 2.6). Although RSVP produced significantly faster reading rates in simulated central vision loss, in central vision loss participants, in binocular conditions, RSVP was read slightly faster in larger font sizes (1.3 logMAR and 1.2 logMAR) and scrolling was read faster in smaller font sizes (1.0 logMAR) and the font size between the two extremes, 1.1 logMAR was read at similar reading speeds for both RSVP and scrolling. Central vision loss participants behaved similarly in both monocular better eye conditions and binocular conditions.

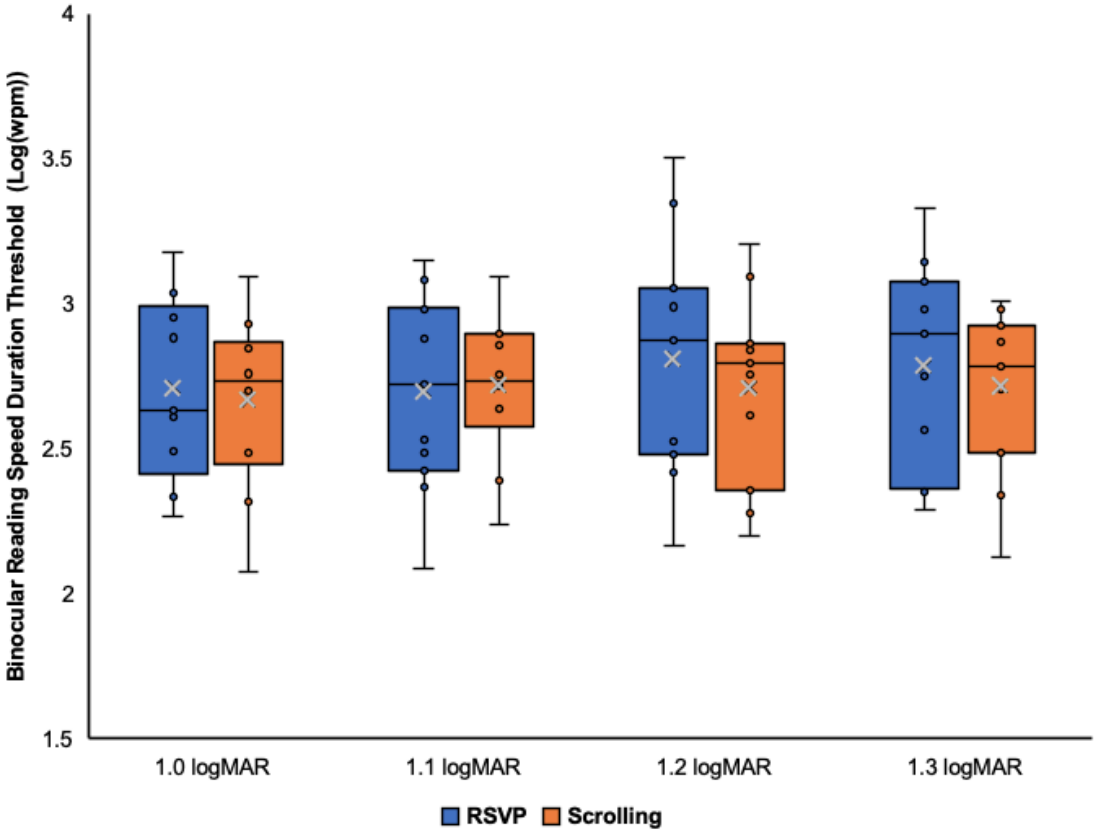


Figure 2.6. *Binocular reading speed as a function of font size and text presentation for central vision loss participants*. Box plots show the duration threshold required for reading aloud a 4-word phrase. Text was presented at three font sizes (1.0 logMAR, 1.1 logMAR, 1.2 logMAR, 1.3 logMAR in descending order respectively) and in RSVP (blue) or scrolling (orange) presentation, as indicated on the abscissa. Horizontal bars show the median, x shows the mean, the box shows the interquartile range, error bars show 95% confidence intervals and the circles show individual data for individual subjects. There were no significant differences between any of the conditions.

2.3.2.3. Effects of Text Presentation and Font Size on Better Eye Reading Rate in Central Vision Loss

Central vision loss participants behaved similarly in the better near acuity eye monocular conditions as they did in binocular conditions. In monocular better eye conditions,

central vision loss participants demonstrated no significant differences in reading rate between font sizes, p=0.36 and text presentation, p=0.25 (Figure 2.7). Again, a similar pattern was noticed in monocular viewing conditions as were noted in binocular viewing conditions. For larger font sizes (1.3 logMAR and 1.2 logMAR), RSVP was read faster, whereas for the smaller font sizes (1.1 logMAR and 1.0 logMAR), scrolling was read faster.

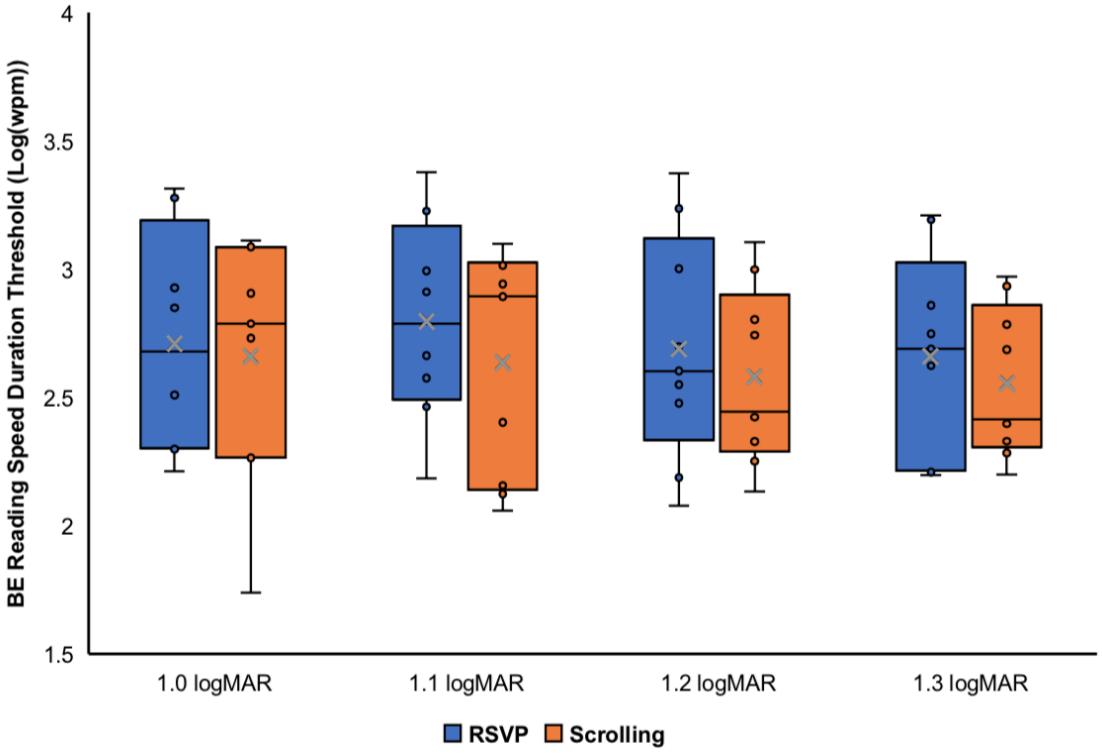


Figure 2.7. *Monocular reading speed as a function of font size and text presentation for central vision loss participants*. Box plots show the duration threshold required for reading aloud a 4-word phrase. Text was presented at three font sizes (1.0 logMAR, 1.1 logMAR, 1.2 logMAR, 1.3 logMAR in descending order respectively) and in RSVP (blue) or scrolling (orange) presentation, as indicated on the abscissa. Horizontal bars show the median, x shows the mean, the box shows the interquartile range, error bars show 95% confidence intervals and the circles show individual data for individual subjects. There were no significant differences between any of the conditions.

2.3.2.4. Effects of PRL Eccentricity on Reading Rate and Reading Acuity in Central Vision Loss

PRL eccentricity data was obtained with MAIA microperimetry in a subset of central vision loss participants (N=7). The average better eye PRL eccentricity for this subset of central vision loss participants was 4.5° and the range was 0.41° to 9.92°. PRL angular direction relative to the damaged fovea was not determined. Results showed that the average reading acuity for RSVP and scrolling under better eye monocular viewing conditions worsened with increasing PRL eccentricity, r=0.61 p=0.07 (Figure 2.8). Results were similar when examining the reading acuity for either RSVP or scrolling separately but the reading acuity for RSVP showed a stronger correlation with PRL eccentricity than scrolling. The reading acuity for RSVP under better eye monocular viewing conditions worsened with increasing PRL eccentricity, r= 0.66, p=0.05 (Figure 2.8). The reading acuity for scrolling under better eye monocular viewing conditions also worsened with increasing PRL eccentricity, r=0.55, p=0.10 (Figure 2.8).

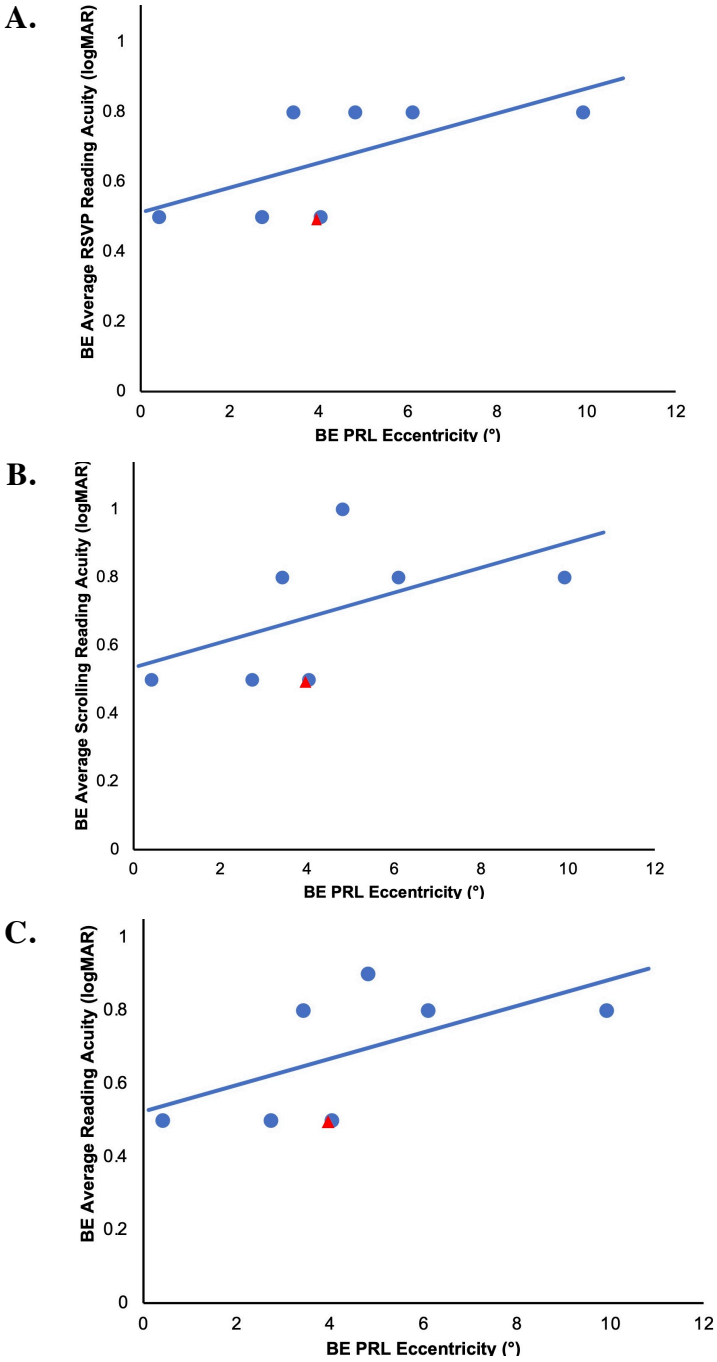
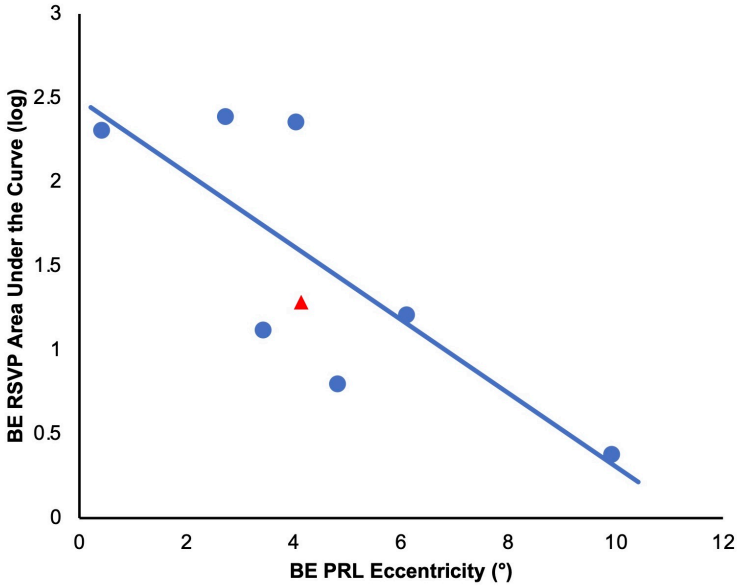


Figure 2.8. *Correlation between central vision loss better eye average reading acuities and PRL eccentricities*. The red triangle in each plot represents the simulated central vision loss average reading acuity at 4° eccentricity. **A.** Shows the correlation between the better eye RSVP reading acuity in logMAR and the better eye PRL eccentricity in degrees. **B.** Shows the correlation between the better eye scrolling reading acuity in logMAR and the better eye PRL eccentricity in degrees. **C.** Shows the correlation between the better eye average acuity for RSVP and scrolling and the better eye PRL eccentricity in degrees.

Additionally, the relationship between the PRL eccentricity and the reading rate for solely RSVP or scrolling, expressed as AULC, was explored. Results showed RSVP reading rate significantly decreased with increasing PRL eccentricity, r=-0.78, p=0.02 (Figure 2.9). Monocular scrolling reading rate had minimal correlation with PRL eccentricity, r=0.-0.15, p=0.37.

A.



B.

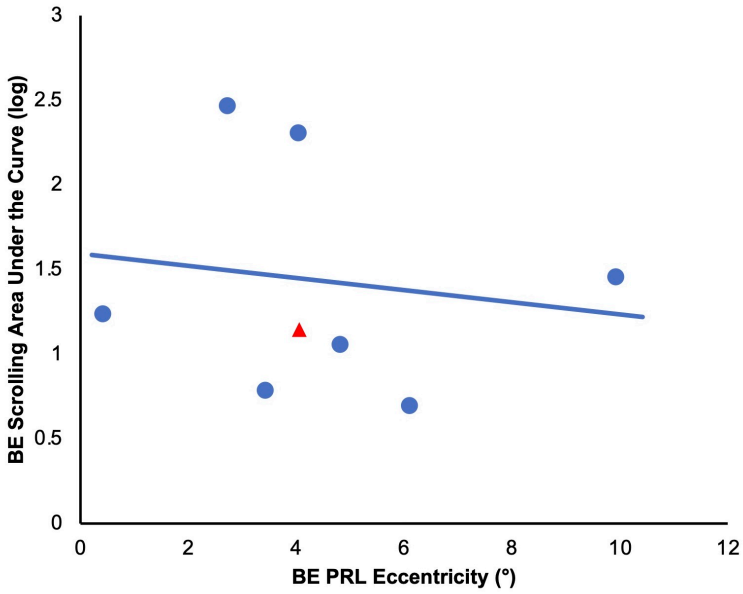


Figure 2.9. *Correlation between central vision loss better eye area under the log reading curves (AULC) and better eye PRL eccentricity*. The red triangle in each plot represents the average simulated central vision loss area under the curve at 4° eccentricity. **A.** Correlation between the better eye RSVP AULC in log units on the y axis and better eye PRL eccentricity in degrees on the x axis. **B.** Correlation between the better eye scrolling AULC in log units on the y axis and better eye PRL eccentricity in degrees on the x axis.

2.3.3. Exponential Decay Function

Nearly all reading data from simulated central vision loss participants was fit with exponential decay functions (see Figure 2.10. for a representative participant example). Of the simulated central vision loss participants, one participant performed above chance for one text presentation, which could not be fit with an exponential decay function.

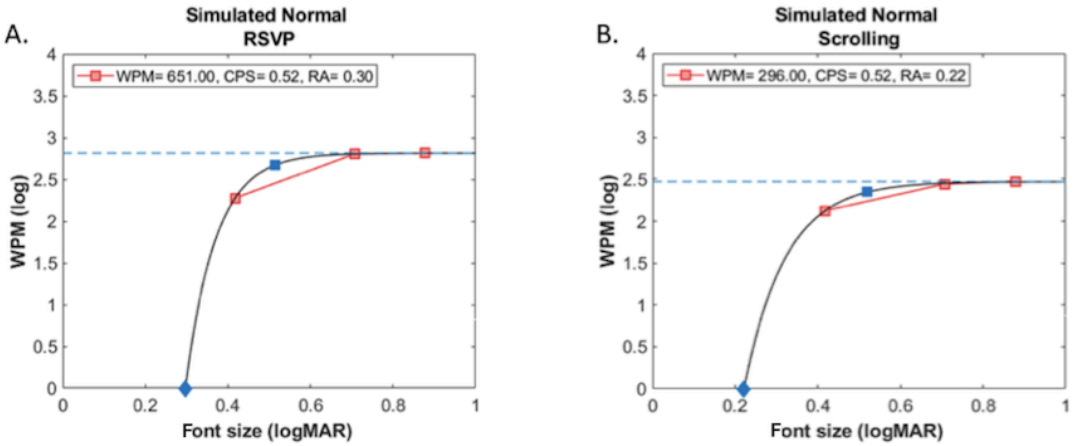


Figure 2.10. *Illustration of reading curves from one representative simulated central vision loss normally-sighted participant*. Each task has reading estimates for maximum reading speed (MRS, dashed blue line), critical print size (CPS, solid blue square) and reading acuity (RA, solid blue diamond. Individual duration thresholds at each font size are represented as red filled squares. **A.** Exponential decay reading function for RSVP task under binocular viewing. Reading shape reflects a steep rise at the smaller font size and horizontal asymptote duration at larger font sizes. **B.** Exponential decay reading function for scrolling task under binocular viewing. The shape of the reading function reflects a sharp rise at the smaller font size and horizontal asymptote duration at larger font size.

Seven out of 11 central vision loss participants had at least one condition (RSVP or scrolling in binocular or better eye viewing) which was not fit with an exponential decay function. Instead, the reading data was best fit with a flat line as reading speed did not change

as a function of font size. Other participants were fit with an exponential decay function but showed deviations from the expected curve. Some participants showed a decrease in reading speed as font size increased instead of the standard horizontal asymptote (see Figure 2.13. for a participant example).

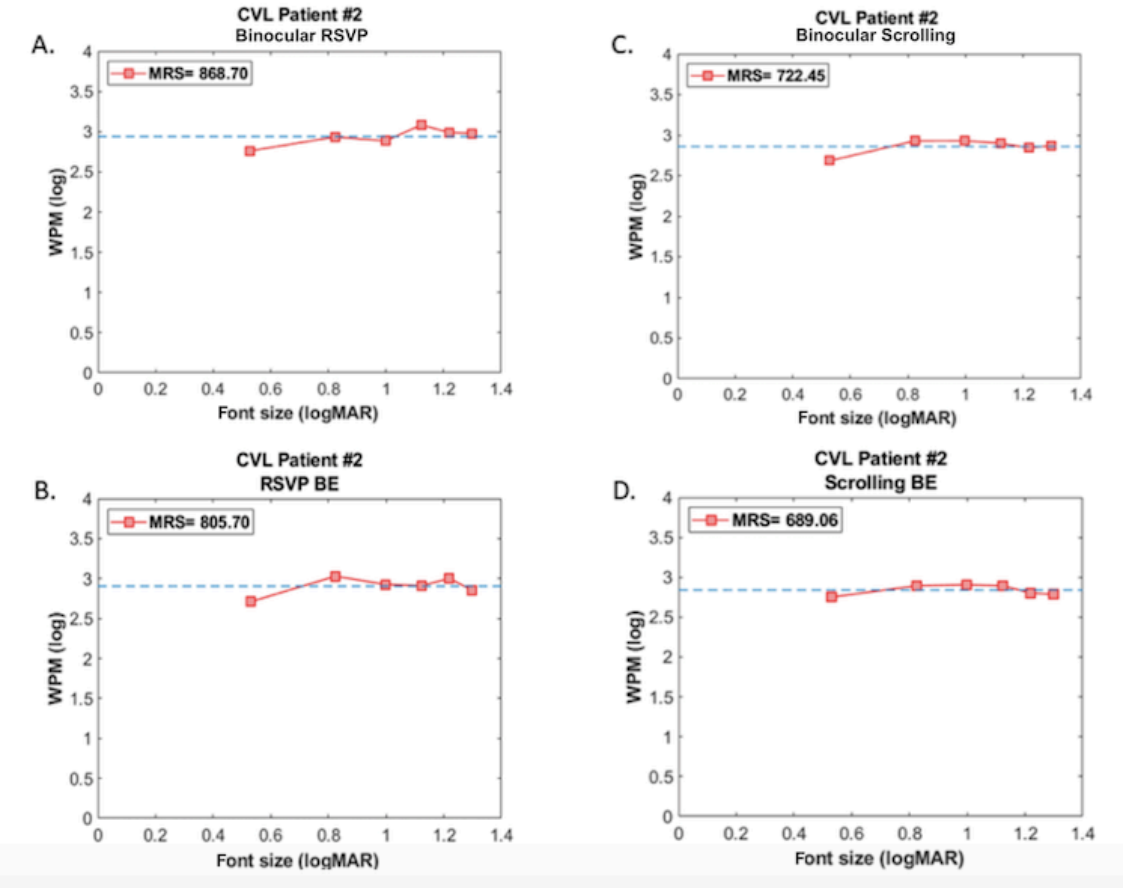


Figure 2.11. *First illustration of reading performance from one representative central vision loss participant*. Participant #2 degenerative myopia with binocular maculopathy (see table 2.1). Maximum reading speed (MRS) is represented by the dashed blue line. Individual duration thresholds at each font size represented as red filled squares. **A.** Duration threshold estimates for RSVP task under binocular viewing. Reading speeds remained relatively constant across font sizes. Duration threshold estimates for **B.** RSVP task under better eye viewing, and scrolling text under **C.** binocular and **D.** better eye viewing in each case, reading speed decreases at largest font sizes instead of reaching horizontal asymptote.

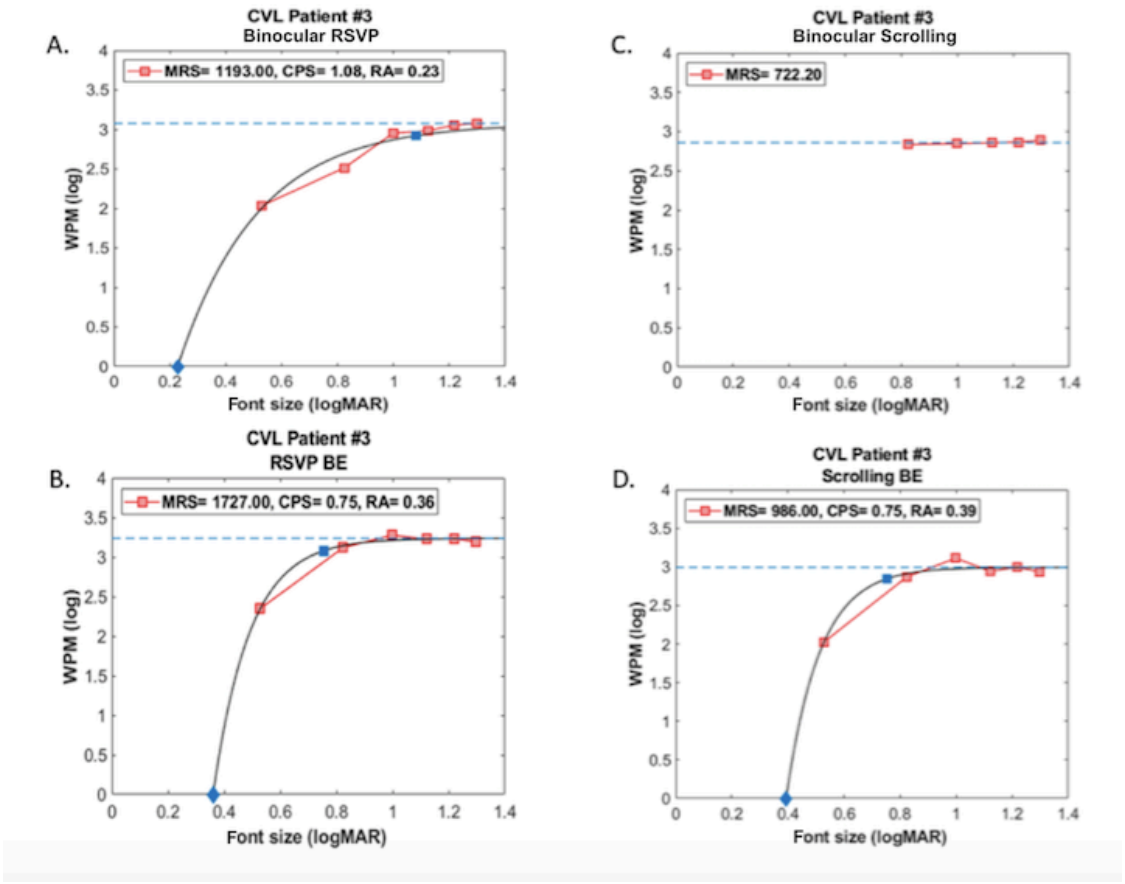


Figure 2.12. *Illustration of reading curves from one representative central vision loss participant*. Participant #3 Degenerative myopia with binocular maculopathy (see table 2.1). Each graph shows reading estimates for maximum reading speed (MRS, dashed blue line), critical print size (CPS, solid blue square) and reading acuity (RA, solid blue diamond. Individual duration thresholds at each font size represented as red filled squares. **A.** Exponential decay reading function for RSVP task under binocular viewing. The shape of the reading function reflects a shallow rise at smaller font sizes and horizontal asymptote duration at larger font sizes. **B.** Exponential decay reading function for RSVP task under better eye viewing. Reading shape reflects a steeper rise at smaller font sizes compared to binocular viewing, but still a horizontal asymptote duration at larger font size. **C.** Duration threshold data for RSVP task under binocular viewing. Data could not be fit with an exponential decay function and does not exhibit the canonical reading shape. There was no change is reading speed across font sizes. **D.** Exponential decay reading function for scrolling task under better eye viewing. Reading shape reflects the canonical shape with a steep rise at smaller font sizes and horizontal asymptote at larger font sizes.

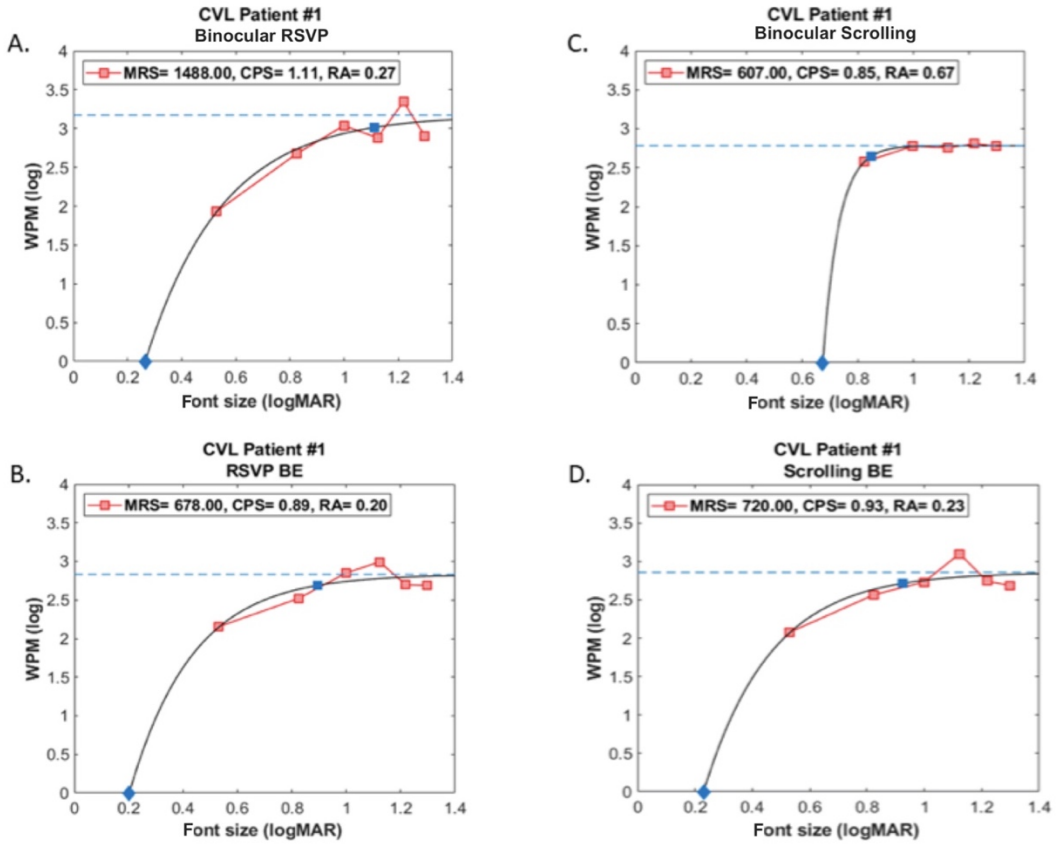


Figure 2.13. *Third illustration of reading curves from one representative central vision loss participant*. As Figure 2.12. Participant #1 Binocular non-exudative age-related macular degeneration (see table 2.1).

2.4. Exploration of Dynamic Text Presentation in Bilateral Central Vision Loss: Discussion

2.4.1. General Discussion

One purpose of this study was to explore the role of text presentation and font size on reading rate in two distinct groups: bilateral central vision loss and simulated central vision loss; owing to significant age and fixation differences, this study did not examine the direct comparison between the two groups. It is often predicted that while a central vision loss patient reads a horizontal line of text, if the patient is using a lateral PRL in relation to the scotoma, the line of words will run into their scotoma causing decreased reading ability. Therefore, RSVP text presentation is often predicted to provide better reading ability than a horizontal line of stationary text. The results of this study demonstrated no effect of font size, text presentation or interaction on central vision loss patient reading speed. We found no significant difference in reading rate, whether represented by the duration threshold, maximum reading speed or AULC, when bilateral central vision loss participants read RSVP and scrolling text. Although RSVP reading speeds were not significantly faster than scrolling in any of the conditions tested, the RSVP text presentation consistently trended to faster reading speeds in central vision loss participants. It is also of note that mean reading speeds for RSVP and scrolling text presentations were significantly higher than mean reading speeds reported for continuous text reading in central vision loss patients (Legge et al., 1992; Trauzettel-Klosinski et al., 2003). RSVP duration threshold, maximum reading speed and AULC analysis trended as read faster in both binocular and monocular conditions except for

the duration threshold of scrolling when reading in monocular conditions was slightly faster than RSVP. Two limitations to this reading study are that there was a small sample size of N=11 and a single trial contained only four words and therefore did not simulate continuous reading. However, Bowers et al. (2004) found similar results to this study among central vision loss participants, as they found no significant difference in maximum reading rates between scrolling and RSVP, two of four text presentations they tested, in both oral and silent reading conditions. Additionally, Fine and Peli (1998) also found no statistical significance between the reading rates of a fixed font size of RSVP and scrolling among visually impaired participants.

2.4.2. RSVP Versus Scrolling

In our study, there were two instances when scrolling trended faster than RSVP. When reading the two smallest font sizes, 1.0 logMAR and 1.1 logMAR, the median duration threshold was faster when reading scrolling than RSVP in both monocular and binocular conditions. The opposite occurred at the larger font sizes. The median duration threshold was faster when reading RSVP than scrolling in 1.2 logMAR and 1.3 logMAR font sizes. This trend was not seen in the simulated central vision loss participants. One significant difference between the central vision loss and simulated central vision loss groups was that simulated central vision loss participants did not experience a scotoma during the reading task. Central vision loss patients may have read RSVP faster at larger font sizes because the words consistently appeared outside the scotoma and larger font sizes provided the patients with greater magnification. Central vision loss patients may have read scrolling slower at larger

font sizes because with increased font size, the greater the chance that the words enter the scotoma and therefore patients may read scrolling faster when font sizes are smaller. Since simulated central vision loss participants did not have a scotoma and did not show this trend, the presence of a scotoma in central vision loss patients may play a role in why RSVP was read faster in larger font sizes. This particular finding has been found in previous studies with central vision loss patients. Fine and Peli (1998) found a similar trend in their follow-up study exploring the effect of font sizes. In their study, observers with low vision, defined as visual acuity of 20/60 [6/18 equivalent] or worse in the better seeing eye, read RSVP and scrolling at similar rates until the font size was 8 to 10 times larger than their acuity threshold and at this point, RSVP was read significantly faster.

2.4.3. Role of PRL Eccentricity

The second purpose of this study was to explore the role of PRL eccentricity in bilateral central vision loss participants on monocular reading rate and reading acuity. We used a single monocular PRL eccentricity found as the subject performed MAIA microperimetry. Previous studies have shown that central vision loss participants change PRLs for different word lengths (Deruaz et al., 1997) tasks (Duret et al., 1999; Timberlake et al., 2006). Therefore, it is possible that the participants changed PRL eccentricity from the MAIA microperimetry to the reading task. Additionally, binocular PRL was not determined as MAIA microperimetry only determines PRLs under monocular viewing conditions. PRLs may also be more dynamic while reading scrolling as moving text may elicit optokinetic nystagmus. Increased eye movements while reading scrolling compared to while reading

RSVP may cause a variable PRL eccentricity which was not captured with MAIA microperimetry. The results showed that reading acuity worsened with increasing PRL eccentricity. This correlation was observed for both RSVP and scrolling in this study. Additionally, PRL eccentricity impacted reading speed when reading RSVP but not scrolling text. As PRL eccentricity increased, reading speed decreased when reading RSVP but reading speed remained nearly constant when reading scrolling. Ergun et al. (2003) explored the relationship between scotoma size and reading speed in observers with subfoveal occult choroidal neovascularization in AMD and found there was a significant correlation between scotoma size and reading speed using a German-language reading test, Radner Lesetest, similar to the relationship we found with RSVP but not scrolling. Altinbay et al. (2021) explored the relationship between MRS while reading MNRead standardized cards and PRL eccentricities. They concluded that MRS was associated with PRL-fovea distance, PRL-lesion edge distance and scotoma size. Their results are similar to our RSVP results despite different reading materials. Given the results of our study in a small subset of subjects (N=7), further studies with a larger sample size will need to be performed to determine if subjects with a PRL eccentricity less than 4.5°, the average PRL of this experiment, read RSVP significantly faster and if subjects with a PRL eccentricity greater than 4.5° read scrolling significantly faster.

Although both text presentation and font size did not significantly impact central vision loss participants reading rate, it did significantly impact simulated central vision loss reading behaviors. The age difference between central vision loss participants (median age of 71 years) and simulated central vision loss (median age of 19 years) may have impacted the

results of this study. Furthermore, simulated central vision loss participants used peripheral vision at a single eccentricity (4º inferior visual field), while fixating a central point, which may have improved fixation stability. In contrast, central vision loss participants used a range of PRL eccentricities and probably had more unstable fixation. Nevertheless, there was good agreement between the performance of central vision loss and simulated central vision loss (red triangles in Figures 2.8. and 2.9) subjects. However, this study explored if simulated central vision loss within a healthy young adult population could serve as a model to predict the behaviors of older patients with pathological central vision loss. Similar to previous studies examining the reading speed of RSVP and scrolling within normally-sighted participants without central vision loss simulation (Fine et al., 1995), simulated central vision loss participants in our study read RSVP significantly faster as defined by duration threshold and the maximum reading speed was significantly faster for RSVP than scrolling in all font sizes. We speculate that task demands for reading scrolling and RSVP text, such as the visual span, which decreases with age (Warrington et al., 2019) may differentially impact older and younger observers. The smaller the font size, the slower the reading speed, regardless of text presentation. Contrary to our results, Akthar and Walker (2019) found simulated central vision loss with gaze-contingent central scotomas read horizontal scrolling faster and showed better comprehension than RSVP despite the participants showing an easier time maintaining eccentric viewing with RSVP than scrolling. Additionally, while in binocular conditions central vision loss participants read both RSVP and scrolling faster than simulated central vision loss participants despite the average central vision loss participant PRL eccentricity being 4.5º and the forced PRL eccentricity of simulated central vision loss of 4º with 1.5º

compliance window. Previous studies have shown that simulated central vision loss participants rapidly adjust to using a PRL, within a few hours (Kwon, Nandy, & Tjan, 2013). However, the simulated central vision loss subjects participated in the reading task for roughly 40 minutes, which is less than the time required for the formation of a stable PRL. Although simulated central vision loss participants read RSVP and scrolling at significantly different speeds and central vision loss participants did not, figures 2.8. and 2.9. (red triangles) show reading acuity and reading speed data for simulated central vision loss is within the distribution of central vision loss participants. For RSVP, scrolling and average reading acuity data, simulated central vision loss participants averaged a slightly better acuity for their 4º eccentricity than what the central vision loss trend line suggests at a 4º eccentricity (see Figure 2.8.). For RSVP and scrolling AULC reading speed, simulated central vision loss participants averaged slower reading speeds for their 4º eccentricity than what the central vision loss trend line suggests at a 4º eccentricity (see Figure 2.9.). The similarities between simulated central vision loss participants and central vision loss participants indicate that central vision loss simulated with gaze-contingent apparatus captures some of the reading deficits experienced by patients with pathological central vision loss, even though it does not effectively reveal differences between text presentation modes.

2.4.4. Reading Speed Functions

Additionally, there are several methods to fit reading speed data to estimate reading parameters. Two of the most common are an exponential decay function and 2-limb (hinged line) function. Of the central vision loss reading data which was successfully fit with

exponential decay function and 2-limb function, there was no significant difference in either critical print size or maximum reading speed values when determined by the two fits. We fit the reading data with exponential decay function because Cheung et al. (2008) found that the exponential decay function provided a better fit to central vision loss MNRead data than the 2-limb function and Arango et al. (2020) found critical print size values may be underestimated in 2-limb function. The exponential decay function nearly fit all simulated central vision loss data and had a 68% success rate in fitting reading data from central vision loss participants. The central vision loss participant reading data, which did not fit with an exponential decay showed one of two deviations. Either the reading speed did not change as font size changed or the reading speed decreased as font size increased. Although the exponential decay function fit the majority of reading data, it does not fit all and this suggests that not all central vision loss participants follow this particular canonical reading curve.

We examined multiple factors which may play a role in the reading speed of central vision loss participants. The results showed that font size and text presentation do not significantly impact reading speed in people with central vision loss, however, reading speed and reading acuity are correlated with PRL eccentricity. Font size and text presentation did significantly impact reading speed of simulated central vision loss participants. These findings suggest simulated central vision loss may not generalize to pathological central vision loss and the reading behavior of central vision loss patients may be individual-dependent.

Chapter 3: Eccentric Viewing Training in Central Vision Loss

3.1. Eccentric Viewing Training in Central Vision Loss: Specific Introduction

3.1.1. Eccentric Viewing Training General Background

As described previously in Chapter 2, patients with central vision loss (CVL) have reduced acuity, reduced visual span and unstable fixation even with use of a developed preferred retinal locus (PRL). The use of low vision devices, i.e. magnifiers and closed-circuit television (CCTV) help central vision loss patients read more comfortably by magnifying the text. In addition to modifying text, a technique called eccentric viewing training can be performed to train the patient to use a particular PRL for fixation while reading.

Because of the poor visual function and desire to improve the visual function of central vision loss patients, researchers and low vision experts question if eccentric viewing training may improve visual function and oculomotor control. However, there is little consensus in the field about the goals of eccentric viewing training and the most effective eccentric viewing training techniques (Stelmack, Massof & Stelmack, 2004). Eccentric viewing training is typically performed for central vision loss patients in a low vision rehabilitation site with the guidance of a low vision optometrist or a trained vision rehabilitation therapist and the goal of eccentric viewing training is to maximize a patient's remaining visual function.

In order to determine if a particular eccentric viewing technique is effective, there are several outcome measures which can be quantified. First, improvement of visual function such as visual acuity, contrast sensitivity or reading speed may indicate eccentric viewing training efficacy. Additionally, oculomotor behaviors such as improved fixation stability may indicate training success. Less common measures are saccades, facial recognition, search task accuracy and Massof Activity Inventory.

As mentioned in Chapter 1, another component of eccentric viewing training research to consider is what PRL location should be trained. One of two training approaches is to train the patient to use a different PRL to maximize function and this new retinal locus is called the trained retinal locus (TRL). Patients with central vision loss may habitually adopt a PRL in any location of the retina (Crossland et al., 2005) but some research has shown an inferior visual field space PRL may be more advantageous (Fine & Rubin, 1999; Petre et al., 2000). Therefore, some research studies train a vertically aligned TRL (Nilsson, 2003). Other research studies select the TRL to be of the area with best acuity regardless of orientation to the damaged fovea (Hassan et al., 2019). The second training approach is to train the patient to use their natural PRL such as Rubin explored (2017) as there is clinical suspicion that central vision loss patient's may tend to change a PRL to a more natural location despite a trainer-select PRL. In this research study, we trained a TRL in inferior visual space. It is currently not known if it is more advantageous to perform eccentric viewing training with a TRL or naturally-occurring PRL.

Time spent performing eccentric viewing training varies as well. For example, a single training session could be just ten minutes (Amore et al., 2013), 30 minutes (Daibert-Nido et al., 2019) or up to an hour (Deruaz et al., 2006). Some training programs even asked the patient to use take home 30 minutes of efficiency reading exercises in between in-office training sessions (Daibert-Nido et al., 2019).

3.1.2. Eccentric Viewing Techniques

Over the past couple decades, a variety of eccentric viewing training techniques have been studied. Although less commonly studied, methods can be simple sVuch as describing what eccentric viewing is to a patient and asking them to use their vision in such a way (Crossland et al., 2005). Deruaz et al. (2006) studied the effects of 10 one-hour training sessions. The investigators trained a superior or inferior PRL for each patient so that when reading, a word could be read in its entirety. The monocular training sessions were scanning laser ophthalmoscopy (SLO) led in such a way that fixation was anchored and words and letters appeared at the trained PRL. Results showed visual acuity and correct reading rate improved immediately after a training session and gains were partially retained after three months.

Other common eccentric viewing training techniques researched are also embedded in microperimeters. For example, MP-1S has one biofeedback feature, audio (Markowitz & Reyes, 2013). For this techniques, the desired retinal location is selected and the patient is asked to align that area with the fixation target. There is feedback indicating how accurate the patient fixates. For the audio feedback, there is an intermittent sound which increases in

frequency with better accuracy. The audio biofeedback feature of MP-1S is the general gist as to how feedback techniques typically function. A light feedback mechanism would be implemented in the same manner.

Amore et al. (2013) examined two different feedback techniques for eccentric viewing training, acoustic biofeedback and flickering light stimulus. Results of their study showed that both feedback techniques improved reading speed and fixation stability but only the flickering light stimulus improved retinal sensitivity. Other studies have found that eccentric viewing training with biofeedback only helps some central vision loss patients. For example, Daibert-Nido et al. (2019) found that biofeedback training, offered by the MAIA instrument, improved acuity and fixation stability in patients with acuity worse than 0.80 logMAR (20/126) and not those with better acuity.

Howe (2012) conducted a meta-analysis consisting of 17 eccentric viewing training studies of central vision loss patients. The studies exhibited a wide variety of training methods but despite the range of training methods, nearly all research studies showed a significantly faster reading rate post-training versus pre-training with no difference of the final reading speed between the successful training programs (Howe, 2012). There was a positive correlation with the number of hours spent training and the final reading speed so that the more time which was spent training, the faster the reading speed was. Additionally, a relationship between age and final reading speed was found: the older the patient was, the slower their final reading speed was. Furthermore, there was a positive relationship between visual acuity and the percent change in reading speed where the worse the visual acuity, the greater the change in reading speed was measured after eccentric viewing training. This may

indicate that patients with worse visual acuity benefit the most from eccentric viewing training.

Not all previous eccentric viewing training research studies produced favorable results. Hassan et. al. (2019) found PRL location can change after training but fixation stability did not change after training. Preliminary results from the EFFECT clinical trial show that eccentric viewing training has no measurable benefit on central vision loss patients (Rubin, 2017).

It is evident that eccentric viewing training may be beneficial for at least some central vision loss patients. Currently, there is no consensus with respect to the goals of eccentric viewing training, standardized method for eccentric viewing training or outcomes to assess the effectiveness of training (Stelmack et al., 2004). Therefore, more research needs to be conducted in order to determine: what is the most effective training method and feedback techniques, what patient characteristics are most likely to benefit from training, what PRL should be trained and are the training effects long-standing.

The purpose of this study was to explore the efficacy of five feedback mechanisms for inferior TRL eccentric viewing in central vision loss patients in two experimental set-ups: remote and in-lab. The outcome measures for this research study are area-under contrast sensitivity function (AUC), bivariate contour ellipse area (BCEA) of fixation and contrast sensitivity function (CSF) acuity. See sections *3.2.8. Bivariate Contour Ellipse Area* and *3.2.9. Area-Under Contrast Sensitivity Function* for more details regarding the outcome measures.

3.2. Eccentric Viewing Training in Central Vision Loss: Methods

3.2.1 Participant Recruitment

We recruited 12 low vision participants from New England College of Optometry (NECO) Center for Eye Care and affiliated low vision clinics, and 5 normally sighted participants from the NECO community or NECO Center for Eye Care. Written informed consent was obtained from each participant and the study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by the New England College of Optometry and Northeastern University Institutional Review Boards.

3.2.2. Low Vision Participants

A total of 12 central vision loss (CVL) participants were recruited. Some central vision loss participants participated in both the remote and in-person training (N=6) and some only completed the study with one experimental set-up (N=8). The expectation was that all participants were to complete both the remote and in-person study, however, only some participants were willing to participate twice and try the alternative system within a one-month time period. Of the 12 central vision loss participants, 6 completed the in-person eccentric viewing training (median age = 71 years $\pm$ 20 SD) and 8 of the 12 participated in the remote eccentric viewing training (median age = 61 years $\pm$ 11 SD). The range of binocular visual acuity was 0.36 to 1.04 logMAR and the median was 0.64 logMAR for in-person eccentric viewing. The range of binocular visual acuity was 0.30 to 1.14 logMAR and the median was 0.58 logMAR for remote eccentric viewing training.

Inclusion criteria for this research study included 1) history of central visual field loss with a measurable central scotoma in each eye 2) a normal mini-mental state examination score greater than 28 to rule out cognitive impairment 3) over the age of 14 and 4) visual acuity not worse than 1.3 logMAR (20/400 Snellen equivalent) in the better seeing eye. Exclusion criteria included 1) peripheral vision loss of less than 40 degrees and 2) inability to read or speak English fluently.

3.2.3. Coronavirus Disease 19 (COVID-19) Protocols

This research experiment was conducted during the COVID-19 pandemic and all safety policies and guidelines specified by the New England College of Optometry COVID task force were followed. For the in-lab experiment, during the morning of a study visit, both the participant and study personnel were screened for COVID symptoms and exposure. Additionally, all equipment to be in contact with the participant were appropriately disinfected. All involved in the research experiment wore a mask and the study personnel additionally wore goggles. A plastic shield was placed between the participant and the investigator to prevent transfer of airborne particles. For the remote experiment, the equipment sent to the participant was properly disinfected between each study session.

3.2.4. Experimental Procedures: In-Person Procedure

Two different versions of eccentric viewing training were studied: in-person and remote. Both procedures were similar with subtle differences. The in-person eccentric

viewing training was conducted at the New England College of Optometry Center for Eye Care in a single two-hour study visit. Participants underwent the eccentric viewing training on a Dell Optiplex 7040 desktop computer and presented on an ASUS HDMI VG278HE LCD monitor. The monitor was located 50 centimeters from their eyes. Participants kept their chin and forehead placed in a chinrest throughout the duration of the experiment (see Image 3.1). An tobi 1000 eye tracker was used in the in-person eccentric viewing training system and was calibrated prior to the experiment start. The training portion of the experiment was programmed on MATLAB 5.3.1 and forced the participant to use a 7.5 degree inferior visual field space PRL (location at 90 degree orientation). During the in-person study visits, an experimenter initiated the program with two conditions called *Freeview* and *Preview* (see *3.2.6. Training Feedback* below for more details). Then the experimenter randomized five different feedback techniques. The training ended with a final Freeview condition which was compared with the initial Freeview condition to quantify any effect of the feedback interventions. In addition to initiating each feedback condition, the experiment also was responsible for giving verbal instructions to the participant regarding each feedback protocol. The participant was allowed to take breaks, if necessary, but at the completion of a break, the eye tracker was re-calibrated.

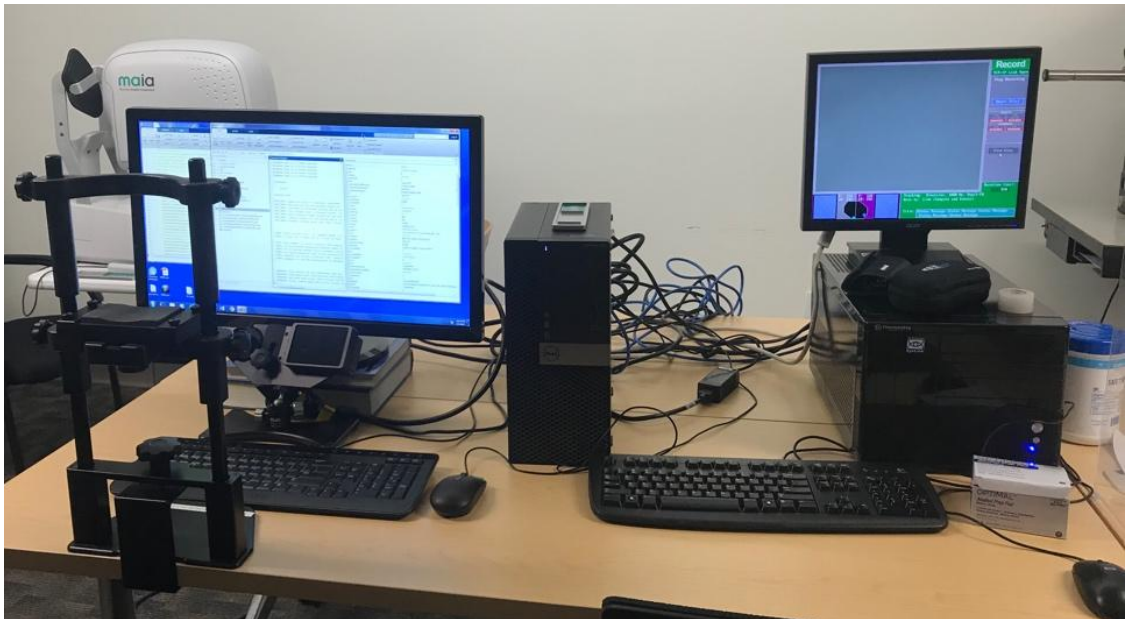


Image 3.1. *In-person eccentric viewing training system set-up*. The computer monitor with the training program is situated on the left of the table with a chinrest placed 50 centimeters from the center of the screen. Just below the computer monitor is the EyeLink eye tracker appropriately positioned and calibrated. The computer monitor on the right is connected to the eye tracker for the experimenter to oversee.

3.2.5. Experimental Procedures: Remote Procedure

The remote eccentric viewing training procedure was performed in two study visits, of one to two hours in duration. The remote system was mailed to a participant's house and contained a PC laptop and one of two eye trackers: G EyeX or GazePoint GP3. At the beginning of the first session, an experimenter joined the participant on a Zoom call to ensure the set-up of the laptop and program occurred correctly. The participants also received a laminated booklet with instructions and pictures detailing how to set up the system including how to properly position the eye tracker to ensure it was reliably recording eye movement data. When the participant was ready, the computer automatically began the experiment. The

experiment was guided and the participant was instructed by MATLAB built-in speech commands. The experimenter was also available on Zoom if the participant had any questions or concerns. The participant completed the second session the next day, and at completion, mailed the equipment back to the study team.

3.2.6. Training Feedback

The following procedures were the same for both the in-person and the remote eccentric viewing training systems. A total of 8 conditions were tested. Of the 8 conditions, 5 included feedback (e.g., tactile, auditory, visual). During each condition, the contrast sensitivity function at the new inferior TRL was assessed through bandpass-filtered HOTV letters using an adaptive algorithm (Hou et al., 2015). The letters appeared in the center of the screen. The contrast sensitivity function was fitted after 25 correct responses with a maximum of 50 trials per condition. The participant controlled the pace of the experiment. First, the participant clicked the mouse when they were ready for a trial to begin and this initiated the feedback screen (or blank screen if Preview or Freeview). The feedback occurred for 2000 milliseconds. Then the stimulus screen appeared for 150 milliseconds. The stimulus screen contained one of the four letters (H, O, T, V) in the center of the screen. Then, after the 150 milliseconds, the four possible letters (H, O, T, V) appeared at the bottom of the screen and the participant used their mouse to click which letter they believed they saw during the trial (see Image 3.2.).



Image 3.2. *HOTV selection screen of the in-person eccentric viewing training system*. During a trial, a letter (either H, O, T or V) appears at the center of the screen in varying sizes and contrast levels. After the letter disappears all four letters in large print are displayed at the bottom of the screen as imaged above. The participant uses the computer mouse to select the letter they believe they saw. The screen for the remote eccentric viewing training system was configured the same way.

The order of the eight conditions tested were Freeview, Preview, and then the following conditions with feedback in random order: Audio, Contracting Ring, Gaze-Contingent Ring, Image of Hand and Tactile feedback followed by Freeview. The definitions for each condition are as follows:

Freeview: The participant was asked to look slightly off the center of the screen, in any direction. This condition simulated typical viewing behavior and served as a baseline before any training intervention. See Figure 3.1.

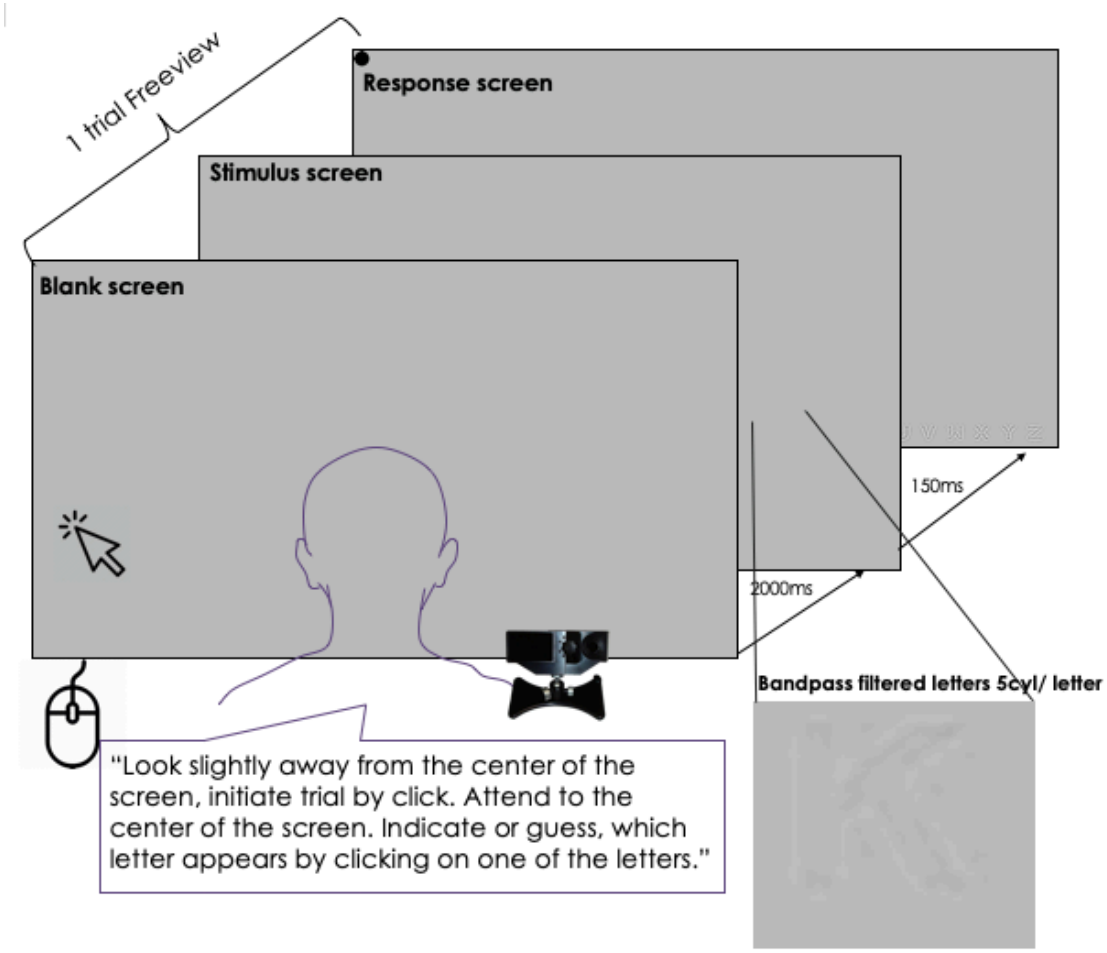


Figure 3.1. *Demonstration of Freeview*. (Modified from Skerswetat et al., 2021)

Preview: The participant was asked to look at a white triangle superior to the center of the screen. When the trial was initiated by the participant, the triangle disappeared but the participant was asked to try to maintain fixation at the location they saw the white triangle. There was no background feedback in Preview. This condition provided a baseline measure of performance with minimum intervention to compare with feedback methods. See Figure 3.2.

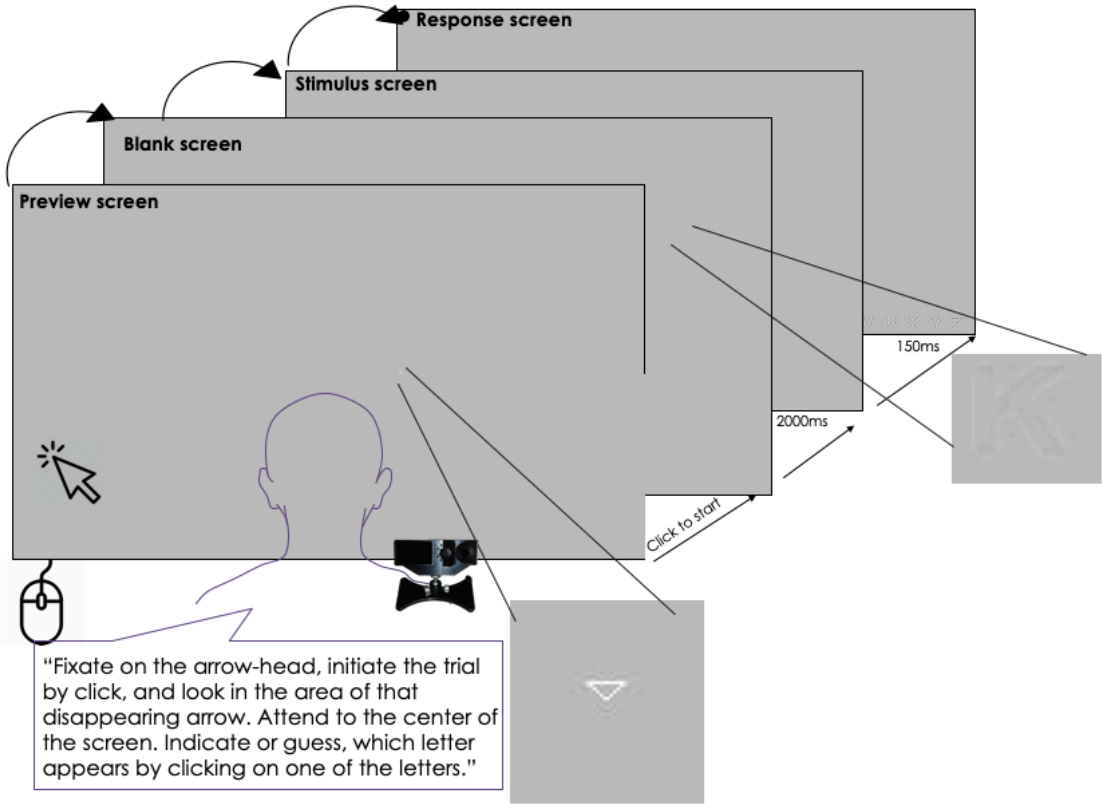


Figure 3.2. *Demonstration of Preview*. (Modified from Skerswetat et al., 2021)

Audio: The Audio feedback was the same as Preview except when the participant initiated the trial and the white triangle disappeared, the participant heard a pitch. The audio pitch varied with the patient's gaze direction: pitch decreased as the distance increased between the TRL gaze direction on screen and the target location at the center of the screen. Thus, the low pitch was a cue to the patient to regain accurate fixation. See Figure 3.3.

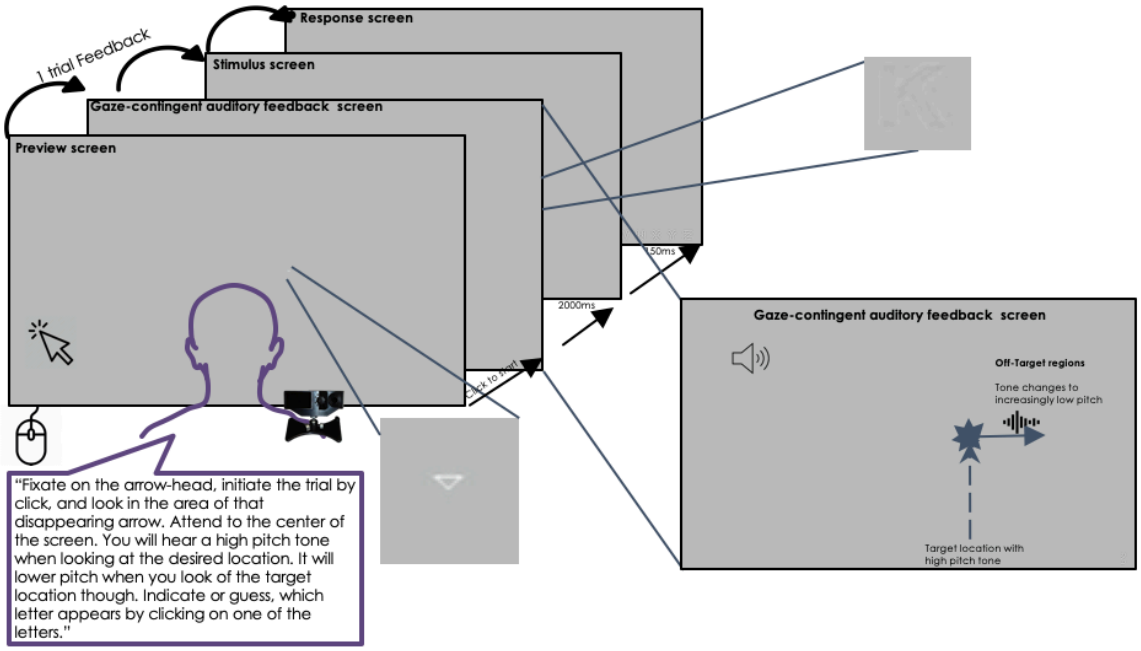


Figure 3.3. *Demonstration of Audio*. (Modified from Skerswetat et al., 2021)

Contracting Ring: The Contracting Ring feedback was the same as Preview except when the participant initiated the trial and the white triangle disappeared, the participant saw a ring which changed in diameter. The ring was centered on the PRL location and the size of the ring increased with the distance between the PRL gaze direction and the target location at the center of the screen. Thus, the ring diameter increased if the participant showed inaccurate fixation and this was the cue to the patient to maintain steadier fixation. See Figure 3.4.

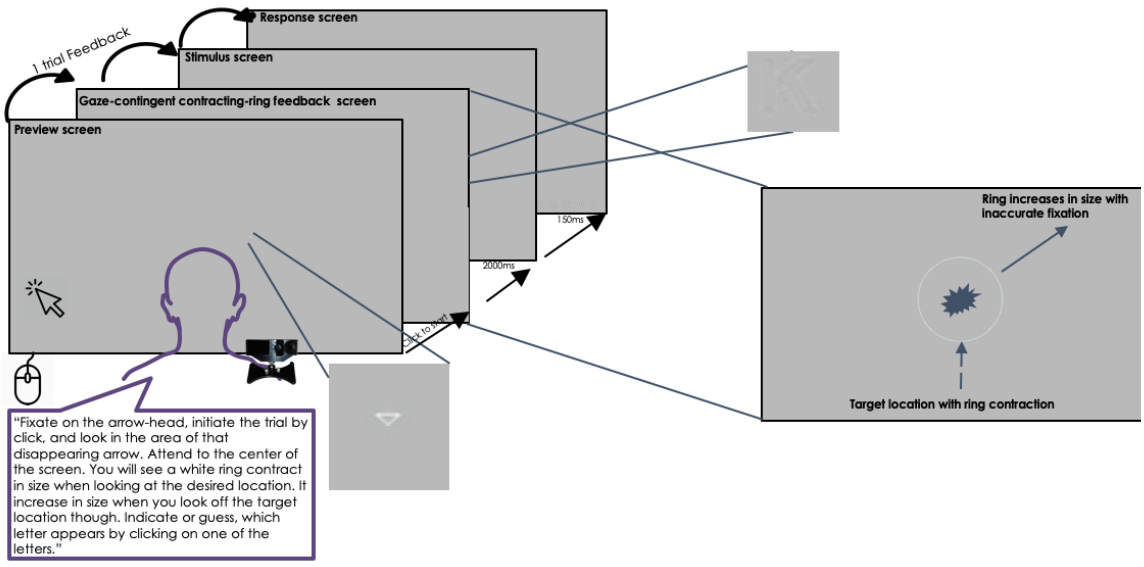


Figure 3.4. *Demonstration of Contracting Ring*. (Modified from Skerswetat et al., 2021)

Gaze-Contingent Ring: The Gaze-Contingent Ring feedback was the same as the Contracting Ring condition except that the size of the ring was unchanging. This feedback provided feedback concerning gaze direction, but removed feedback concerning gaze precision. See Figure 3.5.

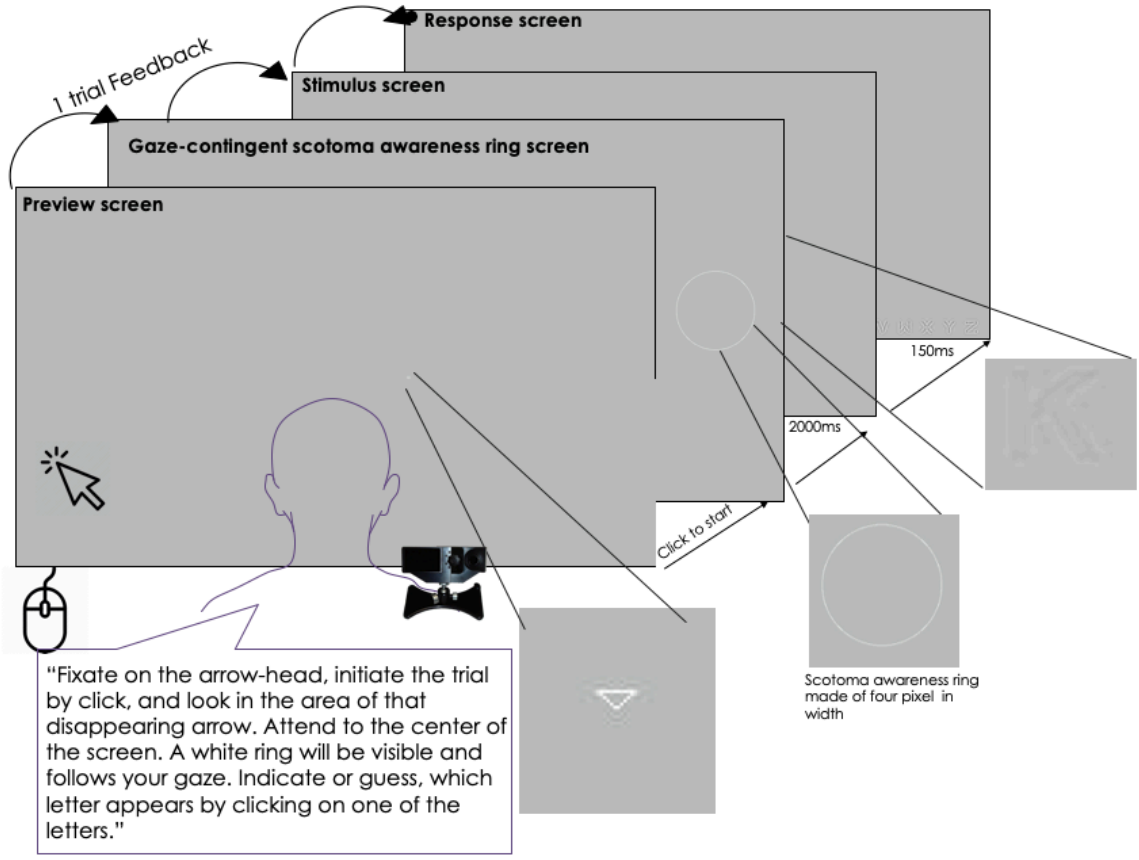


Figure 3.5. *Demonstration of Gaze-Contingent Ring*. (Modified from Skerswetat et al., 2021)

Image of Hand: The Image of Hand feedback was the same as Preview except when the participant initiated the trial and the white triangle disappeared, an image of a hand appeared on the left side of the screen pointing at the center of the screen where the letter will appear. This method attempted to leverage evidence that visual perception is augmented in the area around the location of the hands and severed as a visual control for the Tactile condition below. The participant knew not to look at the center of the screen where the hand pointed, but instead look superior to that location. See Figure 3.6.

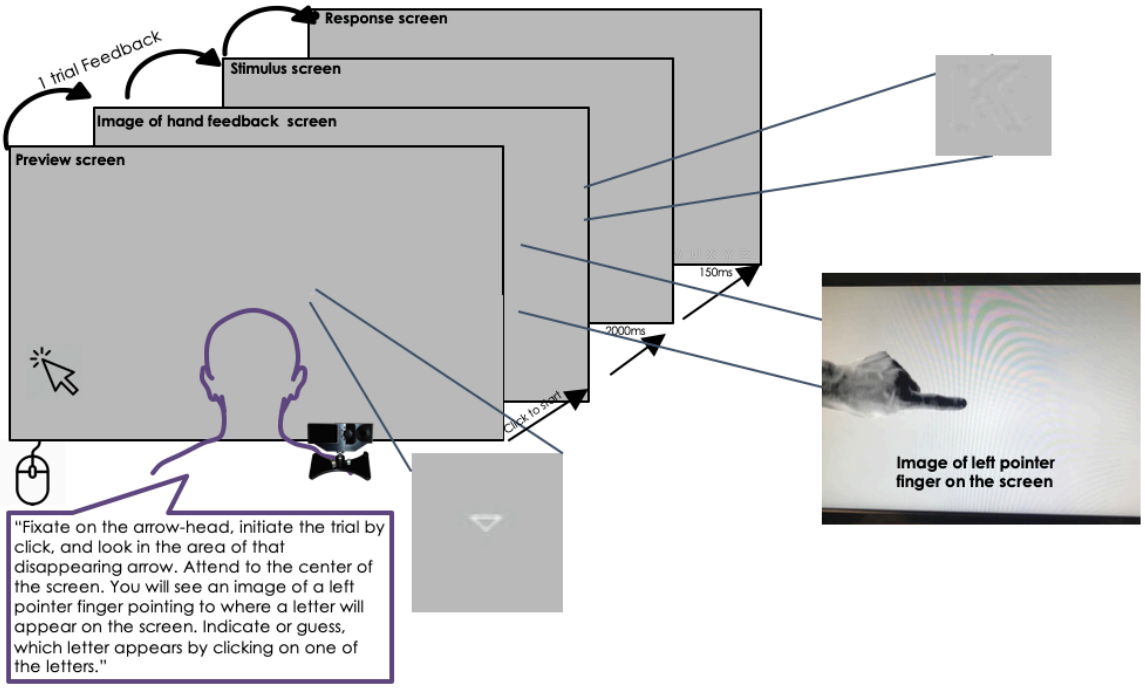


Figure 3.6. *Demonstration of Image of Hand*. (Modified from Skerswetat et al., 2021)

Tactile: The Tactile feedback was the same as Preview except the participant was asked to use their left pointer finger and touch the computer screen just to the left of the center of the screen where the letter will appear. The participant knew not to look at the center of the screen where their finger was pointing, but instead look just superior to that location. During this feedback, the participant placed their arm on an elbow rest for support. This method attempted to leverage evidence that visual perception is augmented in the area around the location of the hands. See Figure 3.7.

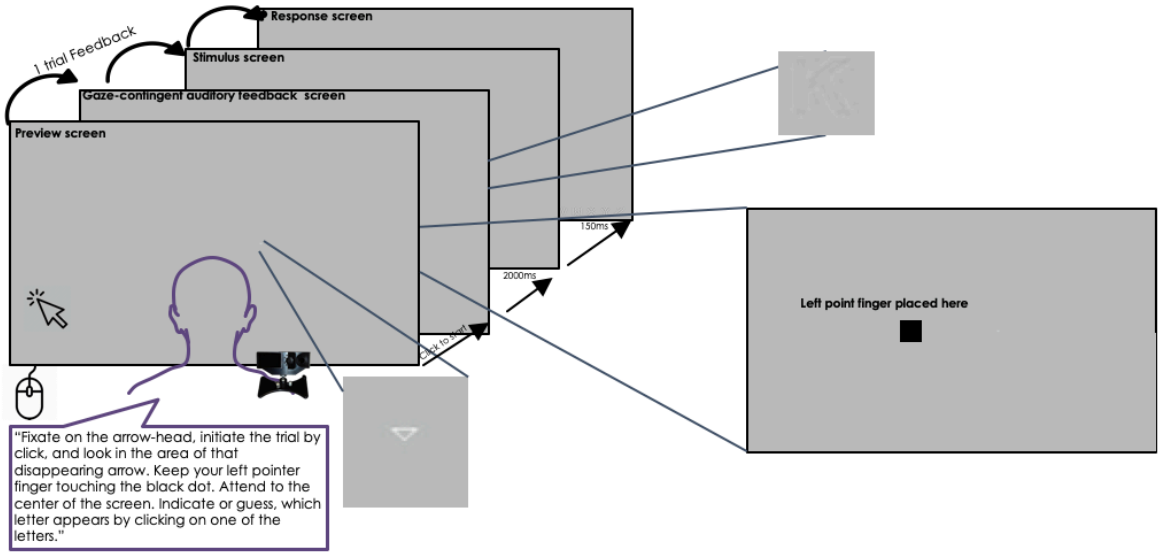


Figure 3.7. *Demonstration of Tactile*. (Modified from Skerswetat et al., 2021)

3.2.7. Data and Statistical Analysis

To quantify the impact of the different feedback intervention methods, we employed one oculomotor control outcome and two visual function endpoints. Oculomotor control was estimated from fixation stability, quantified as the bivariate contour ellipse areas (BCEAs) of fixation during the experimental trial in each condition. Visual function was quantified from the patients' contrast sensitivity in each condition. The minimum contrast required for the patient to identify test letters at a range of spatial frequencies was fit with a Contrast Sensitivity Function (Watson, 2000). The area-under the contrast sensitivity function (AUCs) and CSF acuities were calculated. Analysis-of variance models and planned multiple comparisons were used to determine statistical effects of each feedback.

3.2.8. Bivariate Contour Ellipse Area

The BCEA outcome measure was derived from the eye tracking data from both the remote and in-person experiments. The definition of BCEA in the context of this experiment was the area of the computer screen (measured in pixels in x and y axis) which the participant directed fixation 95% of the time during the feedback condition (See Figure 3.8). The smaller the BCEA value, the better the fixation whereas the larger the BCEA value, the worse the fixation accuracy. BCEA plots were acquired for each feedback condition in the remote and in-person experiment. The BCEA represents oculomotor performance during the experiment.

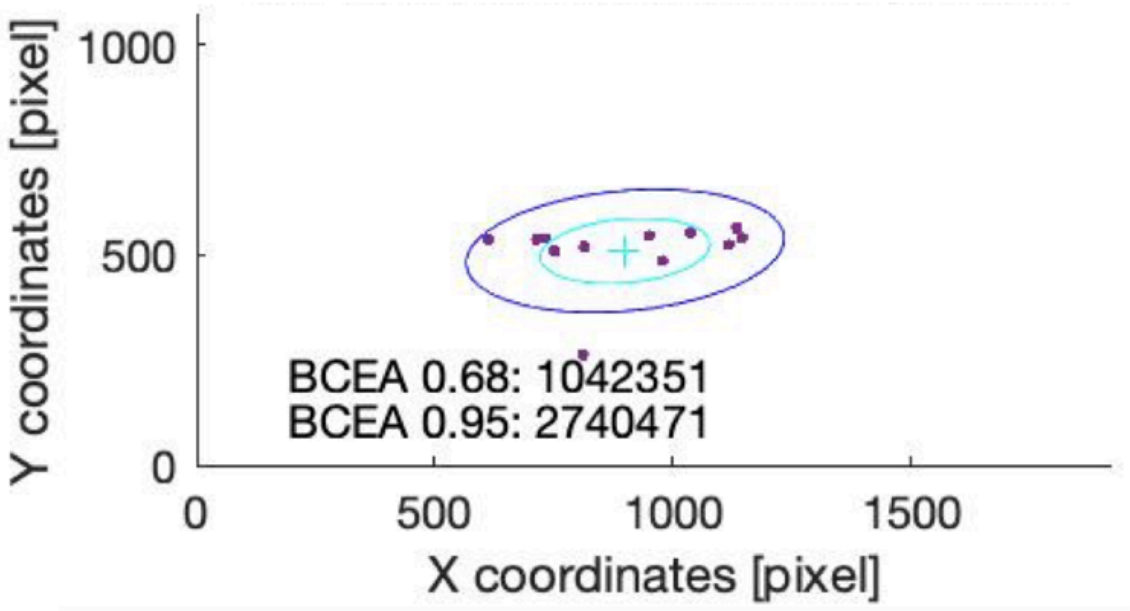


Figure 3.8. *Example of BCEA outcome measure*. The y axis represents pixels in the y direction of the computer screen and the x axis represents pixels in the x direction of the computer screen. Each point represents the average area of fixation of a single participant during the 2000 millisecond feedback screen, in x, y coordinates. The outer purple ring represents BCEA of 95% of the points and the inner blue ring represents the BCEA of 68% of the points. The corresponding value, in pixels, of each BCEA is listed in the figure.

3.2.9. Area-Under Contrast Sensitivity Function (AUC)

The AUC outcome measure was derived in a similar fashion as a standard contrast sensitivity function. There was a single AUC plot per feedback condition in the remote and in-lab experiments and each plot represented all participants. The graph plotted the lowest amount of contrast needed to correctly detect one of the H, O, T, V letters at varying font sizes. A single value was obtained from the AUC by calculating the area under this resultant curve where the larger the AUC value, the greater the contrast sensitivity and the smaller the AUC value, the worse the contrast sensitivity. In addition to CSF acuity, AUC represents perceptual performance during the experiment.

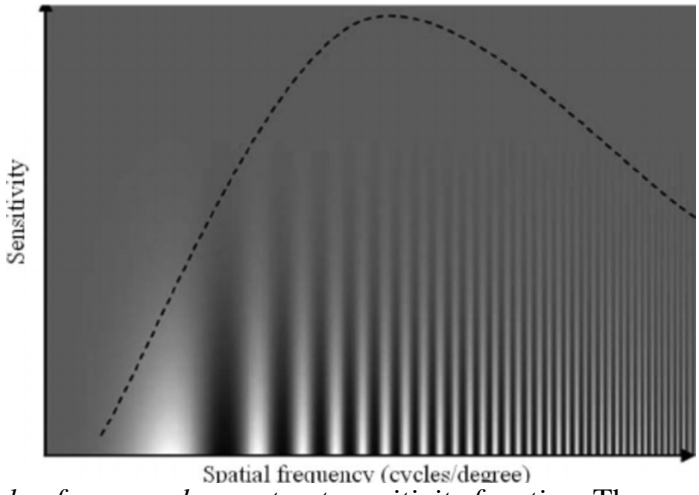


Figure 3.9. *Example of area-under contrast sensitivity function*. The x axis is the spatial frequency and the y axis is sensitivity. The contrast sensitivity is determined for each spatial frequency detected. The sensitivities are plotted and form a curve where the peak represents the maximum contrast sensitivity and the largest x-intercept represents the acuity. To represent contrast sensitivity across all spatial frequencies, the area under the curve was measured.

3.3. Eccentric Viewing Training in Central Vision Loss: Results

Results showed no significant differences in CSF acuity, BCEA and AUC across all feedback mechanisms in both the in-lab system (Figure 3.10) (for CSF acuity: $F(4,40)=0.52$, $p=0.72$, for BCEA: $F(3,45)=1.13$, $p=0.23$, for AUC: $F(4,40)=0.60$, $p=0.66$) and remote system (Figure 3.11) (for CSF acuity: $F(5,52)=0.24$, $p=0.95$, for BCEA: $F(4,34)=0.35$, $p=0.84$, for AUC: $F(5,52)=0.49$, $p=0.79$). However, the results showed several mild trends. CSF acuity and AUC were slightly better with the feedback of Audio compared to other feedback conditions. There was also no significant difference between the remote and in-lab experiment systems.

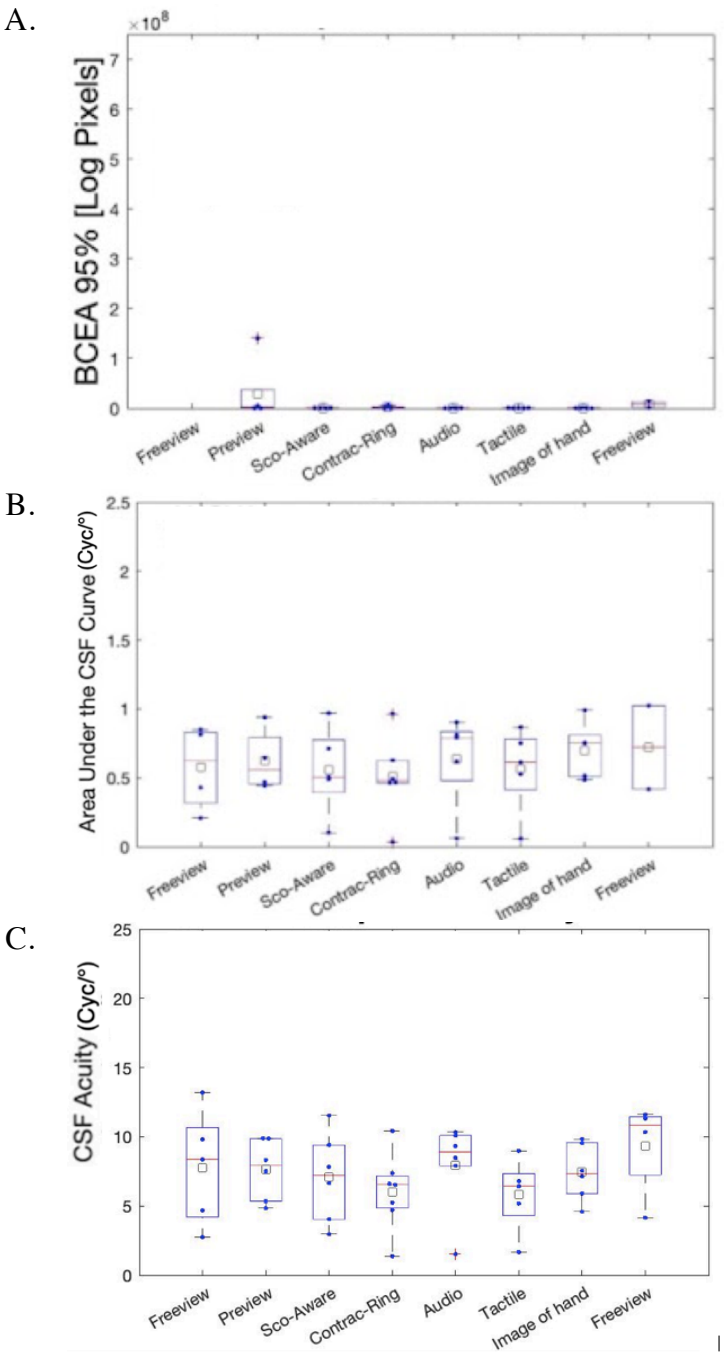


Figure 3.10. *Effects of feedback conditions in the in-lab eccentric viewing system*. Each graph contains 8 box and whisker plots for the 8 conditions tested: Freeview, Preview, Gaze-Contingent Ring (Sco-Aware), Contracting Ring, Audio, Tactile, Image of Hand, final Freeview. **A.** Demonstrates the effects of the feedback conditions on 95% BCEA. **B.** Demonstrates the effects of the feedback conditions on AUC. **C.** Demonstrates the effects of the feedback conditions of CSF acuity.

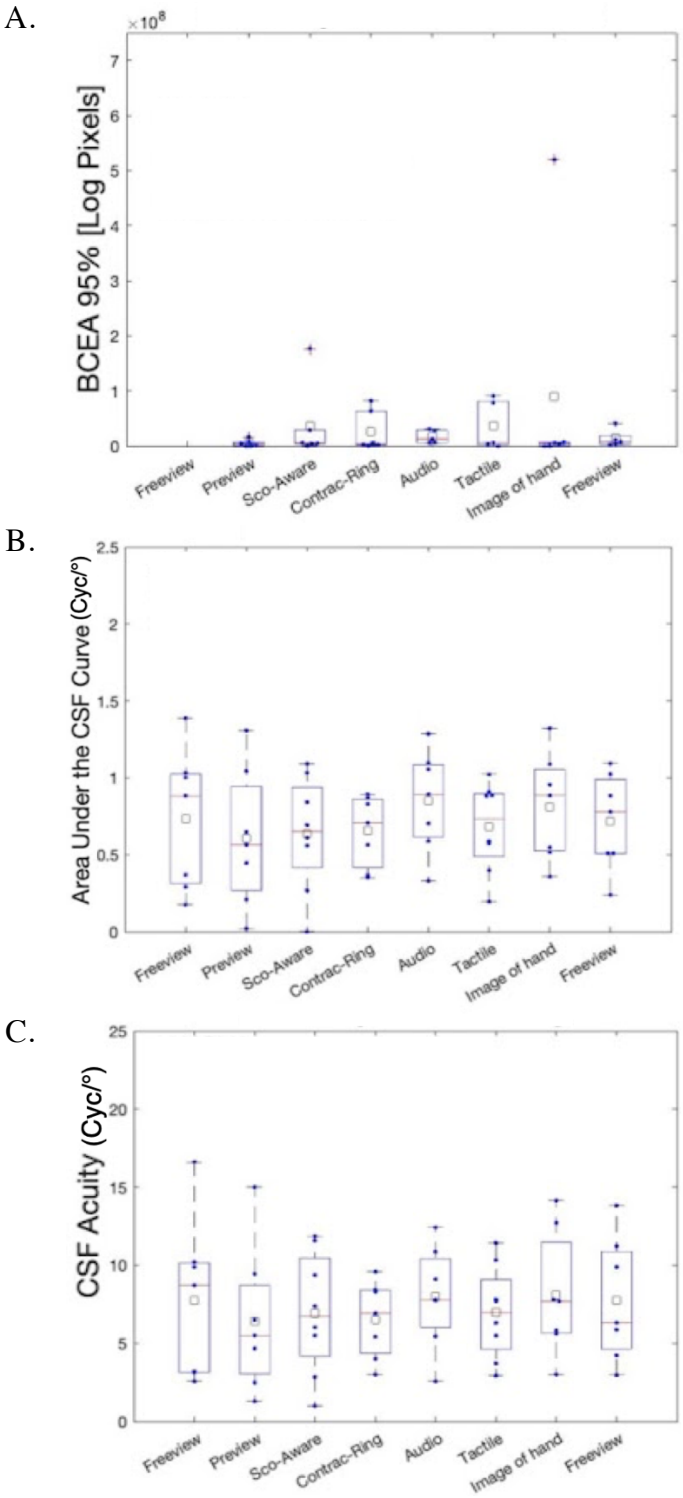


Figure 3.11. *Effects of feedback conditions in the remote eccentric viewing system*. As for Figure 3.10.

3.4. Eccentric Viewing Training in Central Vision Loss: Discussion

The purpose of this experiment was to explore which feedback techniques (Audio, Image of Hand, Contracting Ring, Gaze-Contingent Ring, Tactile) enhance peripheral vision oculomotor and perceptual function in central vision loss patients. Previous studies have showed that a variety of eccentric viewing training techniques improve oculomotor and/or perceptual visual performance in central vision loss participants (Amore et al., 2013; Daibert-Nido et al., 2019) but there is currently no consensus regarding the optimal training technique (Stelmack et al., 2004). Therefore, this research experiment sought to only compare the feedback techniques to help resolve the question of what is the most efficacious way to train eccentric viewing in the central vision loss population. This research study did not train the central vision loss participants to use their natural PRL or compare performance with the trained PRL versus natural PRL.

Instead of the use of a natural PRL, the experiment forced the central vision loss participants to use a 7.5 degree inferior PRL in relation to their already established PRL. Prior to the start of the study visit, it was confirmed that a subject did not have a superior visual field PRL because their central scotoma, located inferior to their fixation, would obstruct the target. This was confirmed either by MAIA microperimetry or asking the subject if when looking 7.5 degrees superior with their natural PRL, they were able to see the center of the screen, where the letters appear. An inferior PRL was selected by the experimenters because previous studies have shown that an inferior PRL is an advantageous location for reading (Fine & Rubin, 1999; Petre et al., 2000). MAIA microperimetry was acquired for 5

of 6 in-lab participants. MAIA images were successfully acquired for both eyes of 3 of the 5 subjects. One of the participants had an eye which the MAIA could not acquire an adequate quality fundus photo and the other participant had an eye which had great PRL variability and the MAIA was unable to properly track the eye movement; therefore, these two subjects have a MAIA microperimetry result for just one of their eyes. See Appendix 1 for MAIA images and more detailed information.

In order to compare the benefits of the feedback techniques, the oculomotor and perceptual performance during each technique was compared to Preview (no feedback) through analysis-of variance models and planned multiple comparisons. The results showed that there was no significant difference in performance across all feedback techniques. We believe this is one of the first experiments to directly compare the role of senses, other than visual, in assistance with eccentric viewing. Camors et al. (2019) showed that tactile feedback aided visual search within patients with peripheral vision loss secondary to glaucoma or retinitis pigmentosa. Additionally, McLntire et al. (2010) showed that audio cues improved visual search performance in normally-sighted individuals. And Amore et al. (2013) showed that audio feedback eccentric viewing training (where the increase in audio frequency increases with more accurate fixation) improved reading speed and fixation stability of central vision loss patients. Overall, studies have shown that both tactile and audio cues assist visual function, primarily visual search. Therefore, we wanted to explore the role of audio and tactile cues in eccentric viewing training with a hypothesis that the feedback techniques would be as beneficial as the visual feedback techniques which are

frequently studied in the eccentric viewing training field of research. However, surprisingly, there was no significant difference across all techniques and Preview.

Variations of the feedback techniques may yield more significant results than the methods utilized in this research study. For example, a different style of audio cue may have been more productive. Instead of a constant pitch that ranges from low to high, perhaps a beep of the same pitch but different frequencies would be better, such as the biofeedback feature within the MP-1S (Markowitz & Reyes, 2013). Instead of using only one finger for Tactile, perhaps participants need to use an entire hand or both the right and left pointer finger for more significant results. Additionally, perhaps the visual cues needed to be larger (larger Image of Hand, Contracting Ring and Gaze-Contingent Ring).

Additionally, there is currently no agreement regarding standard outcome measures for eccentric viewing training research (Stelmack et al., 2004). Therefore, we only analyzed three reliable outcome measures (BCEA, AUC and CSF acuity). Since researchers are unsure of the optimal outcome measures to judge training significance, there is a possibility that alternative measures would generate different results. For example, outcomes measures could include more clinical data such as maximum reading speed (whether oral or silent), critical print size (smallest print read at maximum reading speed) or threshold print size (smallest print read regardless of reading speed). Additional outcome measures could be more real-life such as visual search, facial recognition and visual span.

An additional challenge in researching eccentric viewing training is the effect of learning. With respect to our research experiment, it is predicted that participants will perform better as time passes throughout the experiment as they become more familiar with

the protocol. Therefore, if the learning effect impacts the experiment, then it is predicted that the participants performed worst on the first feedback condition then progressively performed better with each feedback technique. In attempt to reduce the learning effect, we randomized the order of feedback techniques for each participant. However, we cannot be certain that the learning effect was entirely negated.

Another limitation to this research study was with respect to sample size. This was a preliminary investigation with 6 participants with our in-lab method and 8 participants in our remote method. The low number of participants limits the extent of data analysis and conclusions which can be drawn but nevertheless still demonstrates that feedback techniques with modifications and different outcome measures need to be further explored. Additionally, this research study demonstrated that an eccentric viewing training program can be created and successfully executed both in-lab and remotely. The benefit of having a successful remote eccentric viewing training system is that there is a shortage of low vision optometrists in the United States especially in more remote areas. Therefore, more central vision loss patients in the country could benefit from eccentric viewing training if a remote training system was successfully implemented.

Chapter 4: Blur Perception in the Low Vision Population

4.1. Blur Perception in the Low Vision Population: Introduction

4.1.1. Blur Perception: General Background

Nearly every eye care patient is familiar with the procedure of clinical refraction as it is a critical component of optometric care. The purpose of refraction is to produce a focused image on the retina. While low vision patients tend to have reduced acuity secondary to their ocular pathology, it is nevertheless imperative that the clinician maximizes a patient's vision through the process of refraction. Current standard clinical practice for low vision refraction is to utilize the just noticeable difference rule (JND rule) (DeCarlo, Woo, & Woo, 2006; Faye et al., 2000). The JND rule suggests that the selection of bracketing lenses shown to the patient during refraction should be selected according to the patient's visual acuity such that JND=MAR/5. For example, if a patient has an entering visual acuity of 20/200, the equivalent minimum angle of resolution (MAR) is 10 arcmin. Therefore, the predicted JND will be 2.00D (10/5=2). The difference between the two lenses presented to the patient will be the JND value (2.00D). Therefore, the bracketing lenses will be -1.00D and +1.00D. Alternatively, the JND can be found by: JND=Snellen denominator/100. In this example, 2.00D is attained again. The bracketing lenses become smaller during the refraction procedure as visual acuity improves. The assumption behind this approach is that patients with poorer visual acuity will not be able to discriminate dioptric blur as reliably and therefore, the clinician needs to present bracketing lenses with larger differences in dioptric

power. There are a few studies which provide some evidence to support this approach. Greene et al. found that patients with reduced visual acuity also have a larger depth of focus (Green, Powers, & Banks, 1980), and Legge et al. (1987) reported low vision patients have increased tolerance to defocus. However, there are no studies to date that have explored how other factors such as visual field loss, central scotomas, contrast sensitivity, nystagmus, and different types of ocular pathologies relate to perception of optical defocus.

4.1.2. Blur Perception in Normally Sighted

Previous blur perception studies in normally sighted individuals has shown that blur adaptation varies between people. Inter-subject blur adaptation variability exceeded test and re-test variability when normally sighted participants were asked about their perception of blur following a brief exposure to either a blurrier (low-pass filtered image) or sharper (high-pass filtered image) image (Vera-Diaz, Woods, & Peli, 2010). Additionally, perception of blur in normally sighted may depend on personality. For example, Woods et al. (2010) found that perfectionism correlates significantly with Badal optometer blur tolerance and disorganized factors and low self-confidence correlated positively with Badal optometer blur tolerance. Furthermore, in normally sighted myopic patients, long term blur experienced without refractive error correction caused a shift in the blur adaptation function (Pesudovs & Brennan, 1993).

4.1.3. Blur Perception in Low Vision

Similarly, low vision clinicians have anecdotally reported variations in dioptric blur perception in low vision patients. With some reports that patients can often perceive smaller or larger differences in dioptric power than what the JND rule would predict and therefore one may need to adjust accordingly to the patient's responses in order to prescribe the most accurate refraction (Andrade, Ross, & Bailey, 2017). While few studies have explored blur perception and adaptation within the low vision population. Vera-Diaz et al. (2017) found that short term blur adaptation can be measured in patients with central vision loss despite experiencing long term blur secondary to central vision loss.

Given these reports, Bailey (2017) proposed a modified technique for low vision clinical refraction, involving large step bracketing to discourage assumptions based upon the patient's dioptric blur discrimination abilities. In Bailey's proposed method, two lenses of opposite sign and same power are presented to the patient over the best estimated refractive correction. The patient notes how their vision appears through three different views: the plus lens, minus lens and no lens (best estimated refractive correction). The clinician notes the emphasis of rejection (e.g., terrible, slightly blurry, no difference) to all three presentations and determines if the patient suggested a preference for the more minus or more plus lens. If the patient does not reject either the plus and minus lens, then the bracket size becomes larger. The bracket size ideally begins large and becomes smaller (+/- 8.00D, +/- 3.50D, +/- 1.25D). However, there have been no studies comparing the Bailey approach to the JND rule to date, and little understanding exists as to how low vision patients perceive dioptric defocus.

The purpose of this study was to examine dioptric blur discrimination in low vision patients, in order to better inform our clinical procedures of refraction. We also aimed to explore how other visual factors such as visual field loss and decreased contrast sensitivity impacts low vision patients' perception of dioptric blur. Specifically, three groups of the low vision population were considered: central vision loss (CVL), peripheral vision loss (PVL) and albinism. Since central vision loss, peripheral vision loss and albinism patients all experience different visual perceptions, we hypothesized that responses to dioptric blur may differ in these populations. Patients with central vision loss have neural blur due to reduced spatial resolution secondary to a retinal etiology. Patients with peripheral vision loss have reduced field of view. Patients with albinism have neural blur due to increased retinal image motion secondary to nystagmus. We aimed to compare dioptric blur discrimination of low vision patients to normally sighted participants.

4.2. Blur Perception in the Low Vision Population: Methods

4.2.1. General Information about Recruitment

We recruited 20 low vision observers from New England College of Optometry (NECO) Center for Eye Care and affiliated low vision clinics, and 5 normally sighted observers from the NECO community or NECO Center for Eye Care. Written informed consent was obtained from each participant and the study was conducted in accordance with

the tenets of the Declaration of Helsinki and was approved by the New England College of Optometry Institutional Review Board.

4.2.2. Normally Sighted Participants

We recruited 5 normally sighted participants, with a median age of 68 years (range 60 – 81 years). Eligibility criteria for normally-sighted participants was as follows: presbyopic/pseudophakic, recent normal eye examination within the past 12 months, have no known ocular pathology, have best-corrected visual acuity of 20/30 or better in each eye, have a normal mini-mental state exam score (i.e., greater than 24) and be over the age of 18 years.

4.2.3. Low Vision Participants

A total of 20 low vision participants were recruited and categorized as one of the following: central vision loss (n=6), peripheral vision loss (n=9) or ocular albinism (n=5). The age range across all low vision participants was 35 to 89 years and the median age was 64 years. All low vision participants had to be presbyopic/pseudophakic or have a documented complete accommodation dysfunction, have best-corrected visual acuity between 20/40 and counting fingers at 1 foot, have a normal mini-mental state exam score and be over the age of 18. Those receiving new or active treatment for their ocular condition were not eligible to participate.

4.2.4. Experimental Procedures

The study procedures were the same for both normally sighted controls and low vision participants. The study was conducted at New England College of Optometry Center for Eye Care in a single two-hour session. Baseline measurements were taken for each eye. The right eye was always tested first for participants who had two eyes qualify for the study. Five low vision participants either did not have a fellow eye which met the inclusion criteria or was prosthetic. Pupil size was measured to the nearest 0.5 millimeter with a handheld ruler in ambient room lighting which remained the lighting conditions throughout the duration of the study visit. Entering best-corrected visual acuity was measured with the ETDRS Bailey-Love visual acuity chart. The central 10 degrees of the visual field were tested monocularly with the Berkeley central visual field test (Mishra, Shrestha, & Korani, 2014). Calibration procedures to determine appropriate viewing distance according to computer screen size were performed prior to testing, to ensure the appropriate visual angle of the stimuli. The visual field test consisted of 50 points within the central 10 degrees. The 50 points were recorded as either seen or not-seen. Contrast sensitivity was measured monocularly with the MARS contrast sensitivity chart. For all monocular tests, central vision loss and peripheral vision loss participants used a black occluder to cover the non-testing eye. Additionally, the room illuminance was measured using Sekonic Iluminometer model 246. All participants underwent the research in the study in similar testing conditions with the same equipment to minimize any variances.

All participants were refracted in a trial frame to determine the best-corrected visual acuity, if not recently performed within the last 3 months. Participants were then monocularly presented with a series of randomized lenses over the refraction. The lenses were masked to both the experimenter and the participant. The series of lenses ranged from -10.00D to +10.00D on a logarithmic scale in either direction from plano. The participants were asked to focus on a line of letters at their visual acuity threshold and rate how blurry each lens presentation was compared to their best-corrected standard view and how confident they were in their answers. The blur rating scale ranged from 0 (no difference) to +6 (very blurry). If a participant believed a lens made their vision clearer they were to rate the clarity in the negative range where -6 represented very clear. Participants were also asked to rate their confidence in their responses. The confidence rating scale ranged from 0 (not confident) to 3 (very confident). Blur ratings were plotted against lens powers (Figure 4.1).

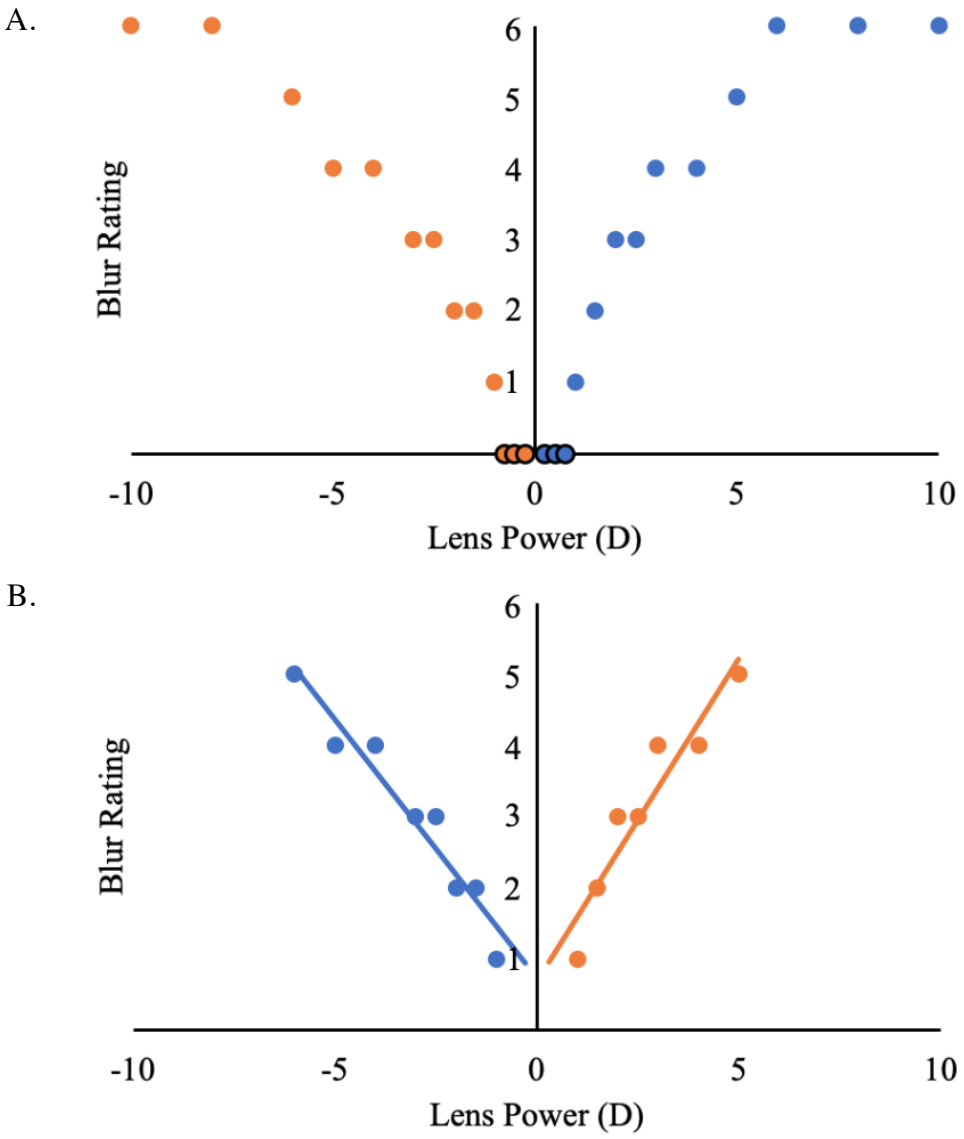


Figure 4.1. *Example participant data and approach to analysis*. **A.** All data points from the experiment were first plotted where the x axis is the lens power and the y axis is the participant's blur rating for that particular lens. Orange data points represent plus defocus and blue data points represent minus defocus. **B.** All lens powers with a blur rating of 6 or 0 were eliminated. The slope of the best fit line and R^2 values were determined for both the plus and minus defocus.

4.2.5. Data Analysis

In exploring the relationship between blur perception to dioptric defocus, the slopes of the blur rating functions to minus and plus defocus were calculated. Before calculating the slope values, within the 26-point graph, all lens powers which had a blur rating of +6 were eliminated, as this represented a ceiling effect. Additionally, all lens powers which had a blur rating of 0 were eliminated as this represents the participant's inability to perceive blur, a floor effect. Two trendlines are fit with the remaining data, one for minus defocus blur ratings and one for plus defocus blur ratings. The R^2 values of the trendline represent the variability of responses where the lower the R^2 value, the more variable the subject answers. The slope of the trendline represented the sensitivity to dioptric blur where the larger the slope value the greater the sensitivity to dioptric blur (Figure 4.1).

4.2.6. Correlation Between Low Vision Eyes

Fifteen of 20 low vision participants had two eyes which qualified for the research study. Five participants had very poor acuity in one eye, outside the inclusion criteria. Between-eye analysis was performed to determine if right and left eye data could be combined, or if there were potential within-subject effects. We explored the correlations between right eye and left eye data. When examining the p-values of the correlations between right and left eye data we found no strong correlations, ($r \leq 0.50$ for plus slope, minus slope) (Iverson & Gergen, 1997). Because there was no convincing evidence that right eye and left eye measures were correlated given the presence of asymmetric ocular pathology in low vision participants, each eye was treated as its own data point.

4.2.7. Statistics

Welch's student t-tests, unpaired and unequal variance, were used to determine differences between low vision and normally-sighted. Pearson correlations were used to explore relationships between clinical measures (visual acuity, contrast sensitivity and visual field) and dioptric blur sensitivity. All data analysis was computed in SPSS Statistics version 26.

4.3. Blur Perception in the Low Vision Population: Results

4.3.1. Blur Sensitivity Between Normally-Sighted and Low Vision Participants

As expected, low vision participants had poorer clinical measures than normally-sighted (see Table 4.1.) and room illumination and pupil size were similar across all participants.

	Visual Acuity (logMAR)	Contrast Sensitivity (logCS)	BCVFT Score	Pupil size (mm)	Room illumination (lux)
Low Vision	Median = 0.8 Range = 0.32-1.82	Median = 1.08 Range = 0.04-1.76	Median = 33 Range = 0-50	Median = 3 Range = 2-4	Median = 440 Range = 400-480
Normally-Sighted	Median = 0.02 Range = -0.12-0.22	Median = 1.58 Range = 1.0-1.76	Median = 50 Range = 45-50	Median = 3 Range =3-3	Median = 440 Range = 420-440

Table 4.1. *Low vision and normally-sighted clinical measures*. Clinical measures acquired before lens presentation included visual acuity measured on ETDRS chart, contrast sensitivity measures on MARS chart, Berkeley Central Visual Field score (where a 50/50 score meant an intact central 10 degrees visual field), pupil size and room illumination. No participant had anisocoria or pupil abnormalities and the pupil size range and median represent each eye individually. The room illumination was measured exactly where the participant sat for the lens presentation.

Low vision participants demonstrated more variability in their positive and minus blur rating responses than the normally sighted participants ($t(36)=-3.86, p<0.001$) and this is indicated by the lower plus and minus R^2 values in the low vision population compared to the normally-sighted population. Low vision participants showed slightly less sensitivity to both plus and minus blur than the normally sighted but this was not statistically significant ($t(11)=-1.18$, $p=0.61$ for plus defocus, $t(14)=-0.11$, $p=0.79$ for minus defocus). This indicates that once low vision participants are able to perceive blur (at dioptric values greater than their JND), they have similar, but slightly less, dioptric blur sensitivity compared to normally-sighted. When examining the differences between responses to plus and minus defocus, both low vision and normally-sighted individuals were more sensitive to plus defocus rather than minus

but there was no difference in variability of responses to minus and plus defocus (Table 4.2.).

	Plus R^2	Minus R^2	Plus Slope	Minus slope
Low Vision	μ = 0.61 +/- 0.27 SD	μ = 0.64 +/- 0.25 SD	μ = 0.85 +/- 0.55 SD	μ = -0.61 +/- 0.38 SD
Normally-Sighted	μ = 0.84 +/- 0.08 SD	μ = 0.81 +/- 0.10 SD	μ = 0.90 +/-0.49 SD	μ = -0.63 +/- 0.23 SD

Table 4.2. *Blur variability and blur sensitivity values for low vision and normally-sighted*. R^2 values indicate blur answer variability where the smaller the R^2 value is, the more variable the participant's answers were. Slope values indicate dioptric blur sensitivity where the greater the slope value is the more sensitive the participant is to dioptric blur.

4.3.2. Correlations Between Clinical Measures and Blur Sensitivity in Low Vision

Although there was a clinical significance between the slope values for plus and minus slope, there was no statistical difference ($t(58)=1.31$, $p=0.10$) and therefore, the slope value for the correlations was calculated as the average of the plus slope and absolute value of the minus slope. We found a significant correlation between visual acuity and slope where the worse the visual acuity (larger logMAR value), the poorer sensitivity to dioptric blur the participants exhibited ($r=-0.35$, $p=0.04$). However, this trend may have in part, been driven by the low vision participants with acuity worse than 1.0 logMAR (Figure 4.2). Although there are negative correlations between slope and visual acuity worse than 1.0 logMAR and slope and visual acuity better than 1.0 logMAR the negative correlation is more convincing for visual acuities worse than 1.0 logMAR due to less data dispersion.

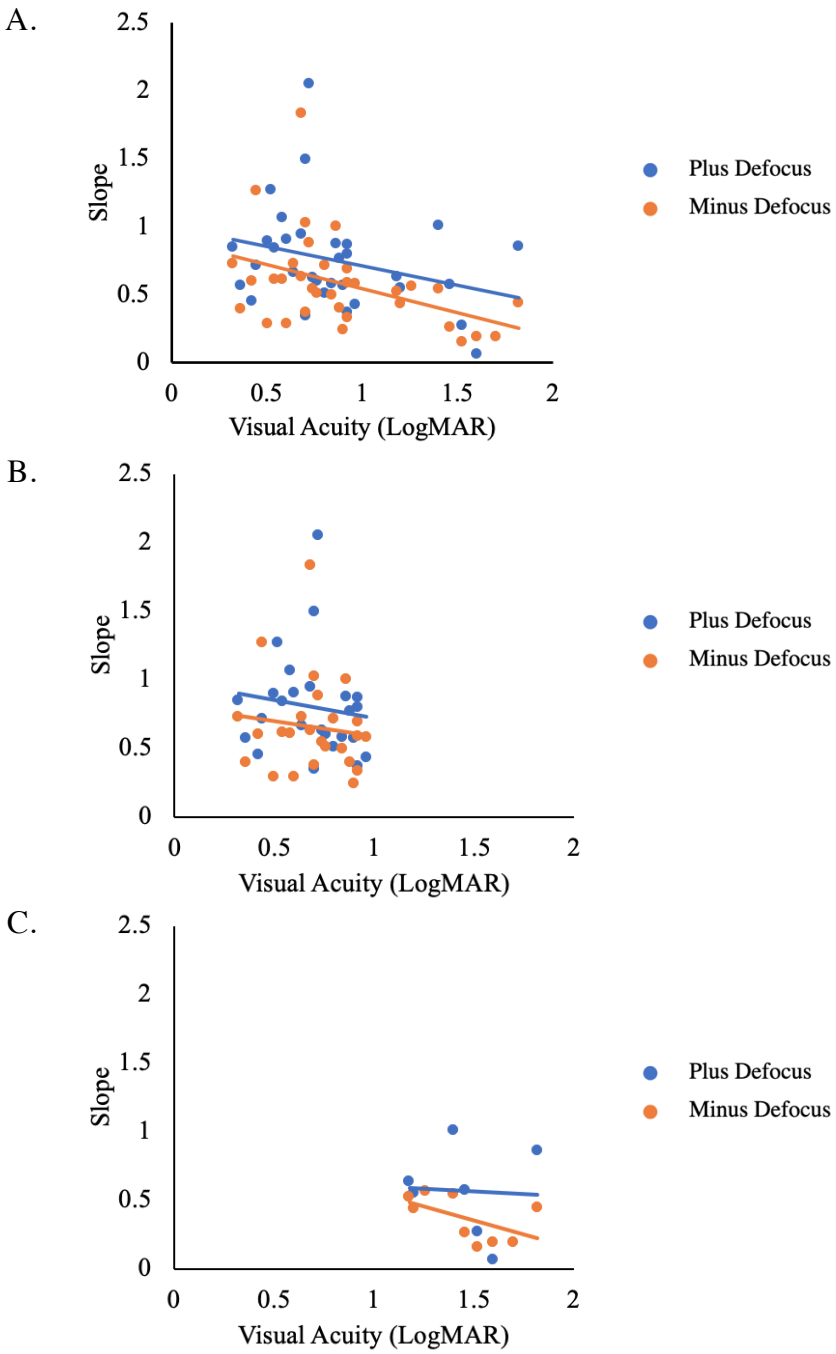


Figure 4.2. *Relationship between visual acuity and slope within the low vision participants*. Orange data points represent minus defocus and blue data points represent plus defocus. **A.** Correlation between all participants' visual acuity and slope value demonstrates a negative correlation where the worse one's acuity, the lower the sensitivity to dioptric blur. **B.** Correlation between participants with visual acuity better than 1.0 logMAR and slope value demonstrates a negative correlation but wide dispersion of data. **C.** Correlation between participants with visual acuity worse than 1.0 logMAR and slope value demonstrates a negative correlation with less data dispersion.

Additionally, there was a positive correlation between contrast sensitivity and sensitivity to dioptric blur in the low vision population where the better the contrast sensitivity measure (larger the logCS value), the more sensitive the low vision participant was to dioptric blur (r=0.43, p=0.10). Despite the correlation between the two measures, there was considerable variability. Some participants who had a contrast sensitivity worse than 0.8 logCS exhibited better blur sensitivity than some participants who had contrast sensitivity worse than 1.0 logCS (Figure 4.3).

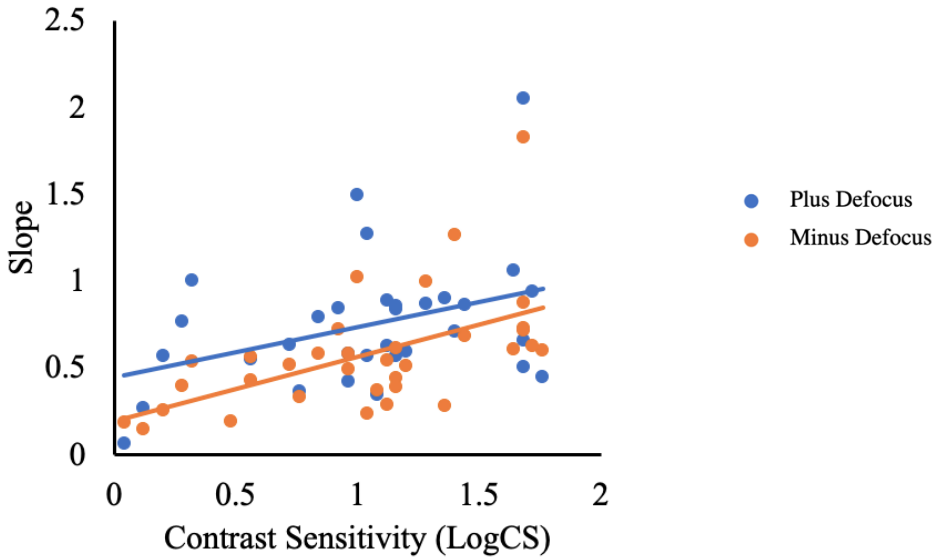


Figure 4.3. *Correlation between contrast sensitivity and slope within the low vision participants*. Orange data points represent minus defocus and blue data points represent plus defocus. There is a positive correlation between contrast sensitivity and slope where the better the contrast sensitivity, the more sensitive to dioptric blur.

Lastly, there was a positive correlation between BCVFT score and sensitivity to dioptric blur in the low vision population where the more intact the visual field was (higher

BCVFT score), the more sensitive the participant was to dioptric blur (r=0.40, p=0.02). However, similar to the contrast sensitivity data, there was a significant amount of variability with these BCVFT score data. For example, some participants who had a BCVFT score worse than 20 still had better dioptric blur sensitivity than some participants with BCVFT score better than 40 (Figure 4.4).

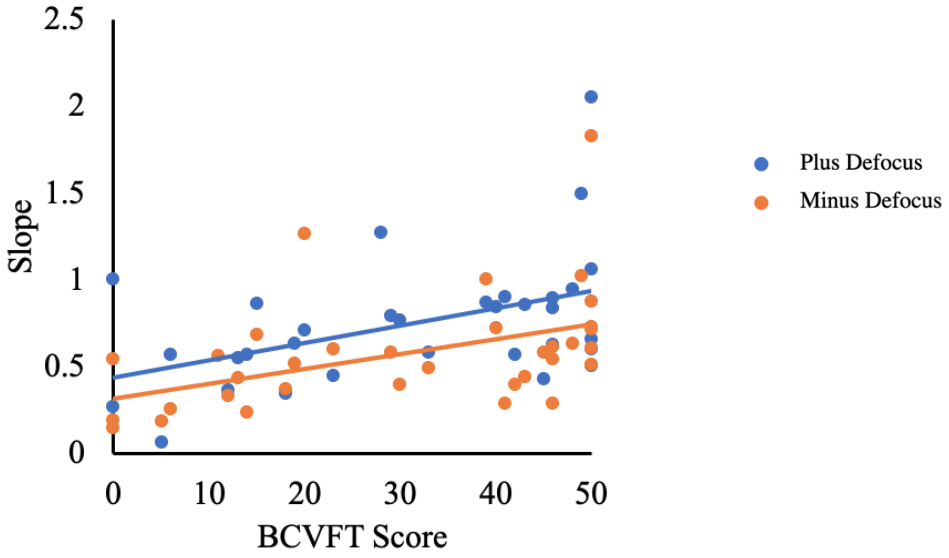


Figure 4.4. *Correlation between Berkeley Central Visual Field Test (BCVFT) Score and slope within the low vision participants*. Orange data points represent minus defocus and blue data points represent plus defocus. There is a positive correlation between BCVFT score and slope where the better the BCVFT score (more intact the central visual field), the more sensitive to dioptric blur.

4.3.3. Blur Sensitivity in Low Vision Sub-Groups

The sample size of each low vision sub-group (central vision loss (CVL) n=11, peripheral vision loss (PVL) n=14 and albinism n=10) was not sufficient to thoroughly examine statistical differences between each group. However, there were several trends noted. Albinism participants had worse sensitivity to dioptric blur than central vision loss and peripheral vision loss participants despite having better visual acuity, contrast sensitivity and visual field measures (CVL visual acuity μ=1.00 logMAR contrast sensitivity μ=0.74 logCS BCVFT score μ=21; PVL visual acuity μ=0.88 logMAR contrast sensitivity μ=0.94 logCS BCVFT score μ=23; Albinism visual acuity μ=0.76 logMAR contrast sensitivity μ=1.38 logCS, BCVFT score μ=43*)*. All three groups were more sensitive to plus defocus than minus defocus. Additionally, central vision loss participants had the most variability in their dioptric blur rating answers compared to peripheral vision loss and albinism which had similar variability in dioptric blur rating responses (Table 4.3).

	R^2	Plus Slope	Minus Slope
CVL	μ=0.52 $\pm$ 0.27 SD	μ=0.87 $\pm$ 0.49 SD	μ=0.76 $\pm$ 0.51 SD
PVL	μ=0.66 $\pm$ 0.25 SD	μ=0.67 $\pm$ 0.29 SD	μ=0.58 $\pm$ 0.22 SD
Albinism	μ=0.68 $\pm$ 0.24 SD	μ=0.82 $\pm$ 0.39 SD	μ=0.74 $\pm$ 0.28 SD

Table 4.3. *Blur sensitivity characteristics within CVL, PVL and albinism groups*. R^2 values are the average of R^2 plus and minus. Minus slope values shown in table are the absolute value of the minus slopes derived from participant data.

4.4. Blur Perception in the Low Vision Population: Discussion

4.4.1. General Discussion

As predicted, low vision participants were more variable with their dioptric blur rating responses compared to the normally-sighted participants. This may be clinically significant during the procedure of low vision refraction. For example, a patient may be variable and inconsistent with their answers regarding "which lens is better" and thus subjective refraction results should also be compared to objective measures prior to prescribing. However, to our surprise, low vision participants and normally-sighted participants had similar sensitivity to dioptric blur. There was no significant difference between low vision and normally-sighted plus slope values and low vision and normally-sighted minus slope values. The blur sensitivity was defined as how sensitive the participant was to changes in dioptric defocus at lens powers larger than the participants' just-noticeable-difference. All low vision participants had a range of lower power lenses which they did not notice a difference (between the lens and their manifest refraction) and all normally-sighted participants did not have a range of just-noticeable-difference lenses. Overall, this indicates that low vision and normally-sighted participants perceive an increase in dioptric blur at the similar linear rate of change at lens powers larger than one's just-noticeable-difference.

Additionally, there was a difference in how normally-sighted and low vision participants perceived plus defocus versus minus defocus. Both groups of participants were more sensitive to plus defocus despite all participants either being complete presbyopes or

pseudophakes. A greater sensitivity to plus defocus in a group of pre-presbyopes or phakics would be predicted because this group of patients can accommodate through the minus defocus, to clear their vision and therefore report minus lenses are less blurry than positive lenses. However, the participants in this research study were all presbyopes and pseudophakes so the ability to accommodate does not explain why all participants were more sensitive to plus blur. This result has clinical implications. For example, if a patient has 20/200 entering Snellen acuity, a clinician may show the patient +1.00D and -1.00D over the patient's habitual prescription. If the patient's manifest prescription was in fact in the middle of the two lenses shown (+1.00D and -1.00D), the patient may still report that the -1.00D lens is clearer than the +1.00D lens given the results of our study which patients are more sensitive to plus defocus instead of minus defocus. To avoid the blur sensitivity imbalance, a clinician may consider showing +0.75D and -1.25D.

While there were modest trends between clinical measures (visual acuity, contrast sensitivity, visual field) and plus and minus defocus, there were considerable variability in these data (see Figures 4.2., 4.3., 4.4). There was a modest trend between visual acuity and plus and minus slope values, but the results showed a wide dispersion of data where some participants with visual acuity of 1.0 logMAR were more sensitive to dioptric blur than some participants with visual acuity of 0.5 logMAR. There was a clearer trend noted in participants who had acuity worse than 1.0 logMAR. This indicates that low vision participants with visual acuity better than 1.0 logMAR may have variable blur tolerance but low vision participants with visual acuity worse than 1.0 logMAR are more likely to have worse blur tolerance. There was a modest trend between contrast sensitivity and plus and minus defocus,

but there was no solid relationship because of variable data dispersion across all contrast sensitivity values. Similar to the clinical measure contrast sensitivity, there was a modest trend between BCVFT score and plus and minus defocus but there was no solid relationship between the two measures because of the carriable data dispersion. We cannot reliably predict dioptric blur sensitivity off of contrast sensitivity or BCVFT values.

The lack of relationship between visual acuity, contrast sensitivity, visual field and plus and minus defocus comes as a surprise because our hypothesis was the worse the three clinical measures are, the worse the blur sensitivity. Due to the lack of relationship, other factors not measured in this research study may impact sensitivity to dioptric blur including personality which has been previously studied (Woods et al., 2010), duration of disease, use of refractive error correction or age. This research study either did not have a large enough sample size to determine if other factors impact sensitivity to dioptric blur or did not include those other outcome measures.

Although this research study did not identify any factors which contribute to blur sensitivity, subtle differences between the three low vision groups (central vision loss, peripheral vision loss, albinism) were noted. Most notably, albinism participants had worse blur sensitivity than central vision loss and peripheral vision loss participants despite having better clinical measures (visual acuity, contrast sensitivity, BCVFT scores). Further work is needed to explain blur discrimination in this patient population. It is unknown why albinism participants showed worse blur tolerance than the other low vision groups, however, the natural history of the condition and characteristics differ significantly from central vision loss and peripheral vision loss and therefore the attributes of albinism may impact blur tolerance.

The characteristics of albinism differ from central vision loss and peripheral vision loss because central vision loss and peripheral vision loss are most commonly progressive conditions which impact either the central or peripheral portion of the visual field.

Lastly, we were not surprised that the right eye and left eye data was not correlated. Typically, ocular conditions which cause vision loss are bilateral but highly asymmetric. These common progressive conditions include both central vision loss (age-related macular degeneration, myopic degeneration, etc.) and peripheral vision loss (e.g. glaucoma, retinitis pigmentosa, etc.). The clinical importance of the lack of correlation of blur sensitivity between two eyes of a single participant is that while refracting a low vision patient, a clinician cannot assume that the second eye of refraction will respond and perceive blur from lenses the same way as the first eye.

4.4.2. Limitations

There were several limitations to this research study but first and foremost, the study was limited by sample size. The low vision group had 20 participants (35 eyes) and the normally-sighted group had 5 participants (10 eyes). This limited our ability to explore multiple predictors of blur discrimination.

Another limitation of this research study is that the participants had a range of pupil sizes. The median pupil size for both normally-sighted and low vision was 3 millimeters but the range of pupil size for the low vision group was 2 to 4 millimeters (all normally-sighted participants had a pupil size of 3 millimeters). Pupil size contributes to the resolution of the visual system where a large pupil has reduced diffraction but is limited by aberrations, and a

small pupil has reduced aberrations but is limited by diffraction. A small pupil also increases depth of focus and therefore increased tolerance to refractive error. Many studies have examined the effect of pupil size on visual acuity and in general, smaller pupil sizes (around 3 millimeters) provides a better acuity than a larger pupil size (around 7 millimeters) (Dakin, Patel, & Asimellis, 2018; Leibowitz, 1952; Atchison, Smith, & Efron, 1979). Fewer studies have examined the effect of pupil size on blur sensitivity however, Atchison et al. (2005) explored blur limits with varying pupil sizes and letter sizes. Results showed that in general, blur limits reduced (i.e. blur sensitivity improved) as pupil size increased from 3 millimeters to 7 millimeters and when font size decreased to the participants' visual acuity thresholds. Based on previous literature, pupil size may impact the results of this study where the smaller the pupil size, the less sensitive the participant may be to blur. However, there was a small range of pupil size in this research study and only 6 of 35 eyes had a pupil size of 2 millimeters. The sample size was too small and the pupil size range was too small in this research study to determine if pupil size had an impact on blur sensitivity in the low vision population. Future studies need to be conducted to explore the implications of pupil size in blur sensitivity in low vision.

Another limitation to this research study is subjectivity of the blur rating responses from the normally-sighted and low vision participants. The instructions given to the participants were to simply rate how blurry a lens made their vision compared to subjective refraction. There are several ways a participant may define blur when rating each lens. For example, Atchison et al. (2005) used three different blur definitions. First noticeable just noticeable blur was defined as the lens which changed the crispness of the letter but the

letters remained clear and legible. Just troublesome blur was defined as the lens which caused a lack of clarity of the entire letter but the letters remained legible. Just objectionable blur was defined as the lens which caused a level of blur that is intolerable. In our research study, a participant may have judged whether a lens was rated as "0" blur or "1" blur based on any of the three definitions. The data becomes more inconsistent when each participant has their own definition of blur but the data is also more representative of real-life refraction. During the procedure of refraction patients are asked to compare different views and determine the most clear view. Patients have their own way of determining and defining blur during the procedure of refraction and that was also reflected in this research study.

Additionally, there were several limitations to the methodology of this research study. First, the BCVFT test only the central 10 degrees of the visual field and was a seen or not-seen visual field test rather than a threshold test. A Humphrey Visual Field 30-2 would give more data such as thresholds and test points in the central 30 degrees. The BCVFT scores provided enough data to determine that similar to visual acuity and contrast sensitivity, there is a modest trend between the clinical measure and blur sensitivity but no clear, reliable relationship. Given the results, it is difficult to predict if a more robust technique such as the Humphrey Visual Field would change the results of the study.

Additionally, participants were allowed to view a lens for unlimited time. Most participants took between 1 and 20 seconds to elicit a blur rating response. We recognize that compensation for blur requires increased viewing time (i.e. longer temporal integration) up to 300 milliseconds (Kwon, Liu, & Chien, 2016) but the impacts of time viewing a blurry target for greater than 300 milliseconds is unknown. Therefore, we do not know if those

participants who viewed the ETDRS chart for 20 seconds with each lens developed greater blur sensitivity than those who viewed the ETDRS chart for 1 second with each lens.

4.2.3. Overall Conclusions

This study shows that dioptric blur sensitivity in the low vision population is more complex than expected. One cannot reliably predict blur sensitivity based on of clinical measures such as visual acuity, contrast sensitivity or visual field. Because there is no clear correlation between visual acuity and dioptric blur sensitivity, we can't reliably predict blur sensitivity from visual acuity and therefore we find no strong support for the just noticeable difference rule, a guide to determining which lenses to present during low vision refraction (see *4.1. Blur Perception in the Low Vision Population* for details). However, this does not mean that low vision optometrists need to discontinue the use of the just noticeable difference rule. Low vision optometrists can still use large bracket sized lenses for those with poorer vision but it may be reasonable to deviate from the just noticeable difference rule when indicated by unreliable or inconsistent patient answers.

Chapter 5: General Conclusions

With over 217 million people worldwide who suffer from moderate to severe vision loss (Bourne et al., 2017), 55% specifically with central vision loss (Goldstein et al., 2012), exploration of evidence-based methods to maximize remaining vision is an important area of study to maximize quality of life. This thesis sought to explore methods to optimize remaining vision in central vision loss via three distinct research projects and purposes:

1) Explore text presentation methods on the ability of central vision loss patients to read (Chapter 2).
2) Explore the role of eccentric viewing training, via different feedback methods, and its potential impact on reading and visual function enhancement (Chapter 3).
3) Understand how patient's perception of blur may be affected by acuity loss, contrast loss, visual field loss, and how this might affect the clinician's approach to refraction (Chapter 4).

5.1. Exploration of Dynamic Text Presentations in Bilateral Central Vision Loss

In Chapter 2 we explored the impact of text presentation and font size on reading rate in central vision loss and simulated central vision loss participants. Additionally, we considered the impact of PRL eccentricity on reading rate in central vision loss participants. Similar to previous studies, we found no significant difference in reading rate between rapid

serial visual presentation (RSVP) and horizontal scrolling text presentation methods in patients with central vision loss (Bowers et al., 2004; Fine et al., 1995). However, we did note that RSVP was consistently read faster at larger font sizes consistent with findings of Fine et al. (1998). However, in our study, this finding was only evident in the central vision loss group of participants and not the normally-sighted controls. RSVP may be read faster at larger font sizes because all words appear outside of the scotoma in contrast to scrolling where the words may begin or end within the scotoma. Additionally, consistent with previous reports, we found that reading speed decreases with increasing PRL eccentricity (Ergun et al., 2003; Altinbay et al., 2021). The clinical importance of this finding is that when training a central vision loss patient to use a PRL, we may consider a retinal location closer to the damaged fovea rather than further.

Contrary to the results from the central vision loss participants, font size and text presentation did significantly impact the reading speed of simulated central vision loss participants. Font size and text presentation had no significant effect on reading speed in central vision loss participants. This indicates that simulated vision loss may not always be an appropriate model to study the visual function of patients with central vision loss. It may be that duration of disease and vision impairment may account for this difference. Some studies suggest it may take considerable time with a simulated scotoma, over several sessions, before those with simulated vision loss demonstrate similar visual function and behaviors to patients (Kwon et al., 2013). Simulated central vision loss were not exposed to a simulated central scotoma and PRL prior to this experiment. The central vision loss participants were well adapted to a central scotoma and a habitual PRL. If duration of disease

plays a role in the difference between the results of central vision loss and simulated central vision loss participants then we would predict that over time the simulated central vision loss participants may read scrolling print faster once adapted to a central scotoma and PRL.

Additionally, a difference between simulated central vision loss and central vision loss participants is the nature of the disease. For simulated-central vision loss, the scotoma was well-defined and discrete versus the central scotomas in central vision loss patients are more variable in size and shape. Additionally, the central vision loss patients may have variable retinal sensitivity in other areas of the retina outside of the scotoma which may interfere with preview of a word while reading.

5.1.1. Future Directions

With the use of our outcome measure, reading speed of four words, we found no significant difference of reading speed between RSVP and scrolling. However, future studies need to be performed exploring different outcome measures such as silent reading rate and reading comprehension. These two outcome measures may be more transferable to everyday reading tasks. In future studies, other measures such as change of PRL location and stability need to be explored to examine how oculomotor control changes while reading. PRL location and stability may influence reading speed of different text presentations and font sizes.

5.2. Eccentric Viewing Training in Central Vision Loss

In Chapter 3 we explored the impact of eccentric viewing training feedback techniques on oculomotor and visual function with central vision loss participants. In this study we sought to directly compare the impact of multiple senses (tactile, audio and visual) on the outcomes of eccentric viewing training. Other studies have shown that audio (Markowitz et al., 2013) and visual cues (Amore et al., 2013) have assisted successful eccentric viewing training programs. However, we found no significant difference between all feedback conditions in the central vision loss participants. The importance of this study was to help explore optimal methods for eccentric viewing training, with the eventual goal of determining best practice. While eccentric viewing training is offered at many low vision clinics, there continues to be no consensus with respect to the goals of eccentric viewing training, or what the relevant outcomes to assess the effectiveness of training should be (Stelmack et al., 2004). We found a slight trend indicating audio feedback may be helpful, but these findings were not significant.

5.2.1. Future Directions

Other research studies need to be completed to fully understand the relevant mechanisms and to explore the efficacy of eccentric viewing training. Future experiments exploring the effects of the various different types of feedback during eccentric viewing training on additional outcome measures such as maximum reading speed (whether oral or silent), critical print size (smallest print read at maximum reading speed), threshold print size

(smallest print read regardless of reading speed) and 'real-life' measures such as visual search, facial recognition and visual span. Additionally, further studies with a larger sample, may be helpful to further explore variations of feedback techniques, specifically, Audio is feedback condition which trended better results (CSF acuity, AUC, BCEA) than the other feedback conditions. The Audio feedback may have trended better results because it incorporates an additional sense, auditory, in helping the brain memorize a fixation location.

5.3. Blur Perception in the Low Vision Population

In Chapter 4 we explored what clinical measures impact blur perception in central vision loss, peripheral vision loss and albinism participants. If how low vision patients perceive blur is understood, then the process of refraction can be optimized. When refracting a low vision patient, clinicians commonly use one's entering visual acuity to help guide which lenses to present during refraction. Current standard practice for low vision refraction utilizes the just noticeable difference rule (JND rule) (DeCarlo, Woo & Woo, 2006). The JND rule suggests that the selection of bracketing lenses shown to the patient during refraction should solely be based on their visual acuity such that JND=MAR/100. The bracketing lenses become smaller during the refraction procedure if visual acuity improves.

The results of this study suggest that clinicians should not solely base blur perception predictions on visual acuity. Additionally, other clinical measures tested in this experiment (visual acuity, contrast sensitivity and visual field integrity) did not successfully predict blur perception.

5.3.1. Future Directions

Additional measures need to be explored such as personality traits (Vera-Diaz et al., 2017), duration of disease, disease diagnosis, PRL location if central vision loss, degree of disease asymmetry, etc. as these may impact blur perception and have not yet been explored. The clinical significance of knowing what measures impact blur perception is that the process of refraction may produce a more reliable and accurate end point for a low vision patient. Additionally, we used dioptric blur but several other ways to measure blur. One way to induce blur is with a Badal Optometer which also uses a lens but it is perfectly placed such that the lens posterior focal plane which is the same location as the anterior focal plane of the eye (Atchison et al., 1995). Another way to induce blur is to modify the image with low-pass and high-pass digital image filters (Vera-Diaz et al., 2010). Exploration of blur perception in low vision with these alternate methods could further contribute to our understanding of blur perception in this population.

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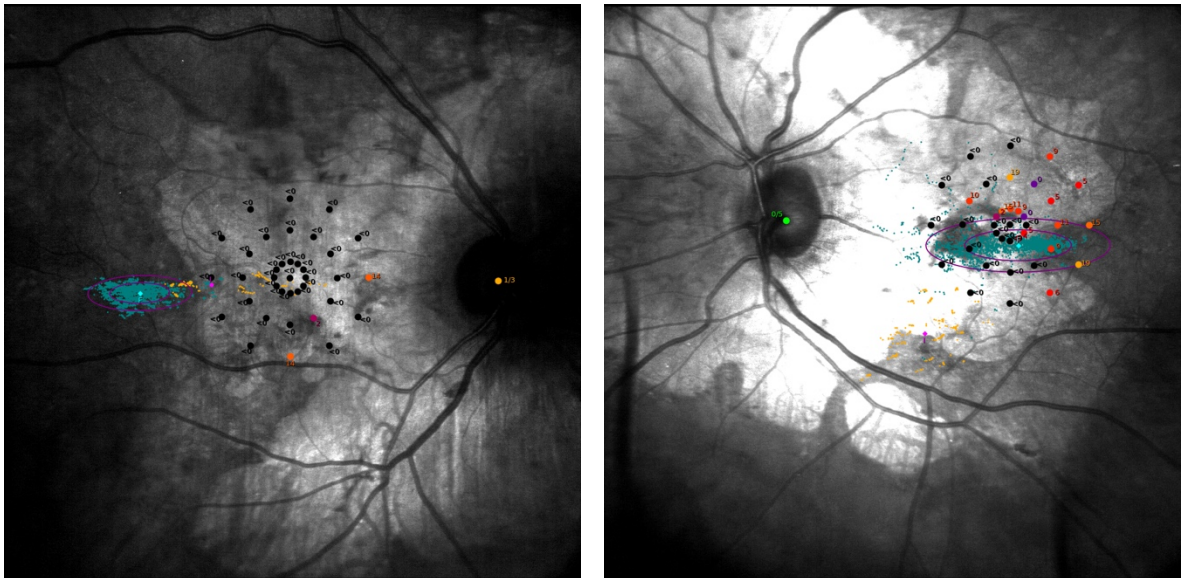
World Health Organization. (2021). Blindness and vision impairment. https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment

Xie, X.Y., Liu, L., & Yu, C. (2020). A new perceptual training strategy to improve vision impaired by central vision loss. *Vision Res, 174*, 69-76.

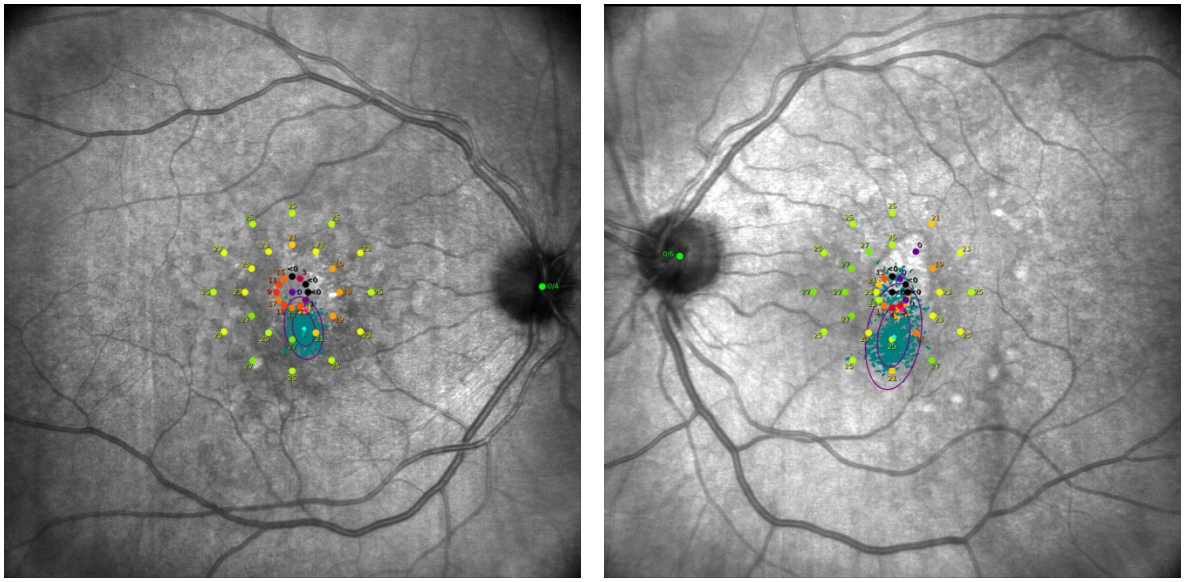
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Appendix I: MAIA Imaging of In-Lab Eccentric Viewing Training Participants

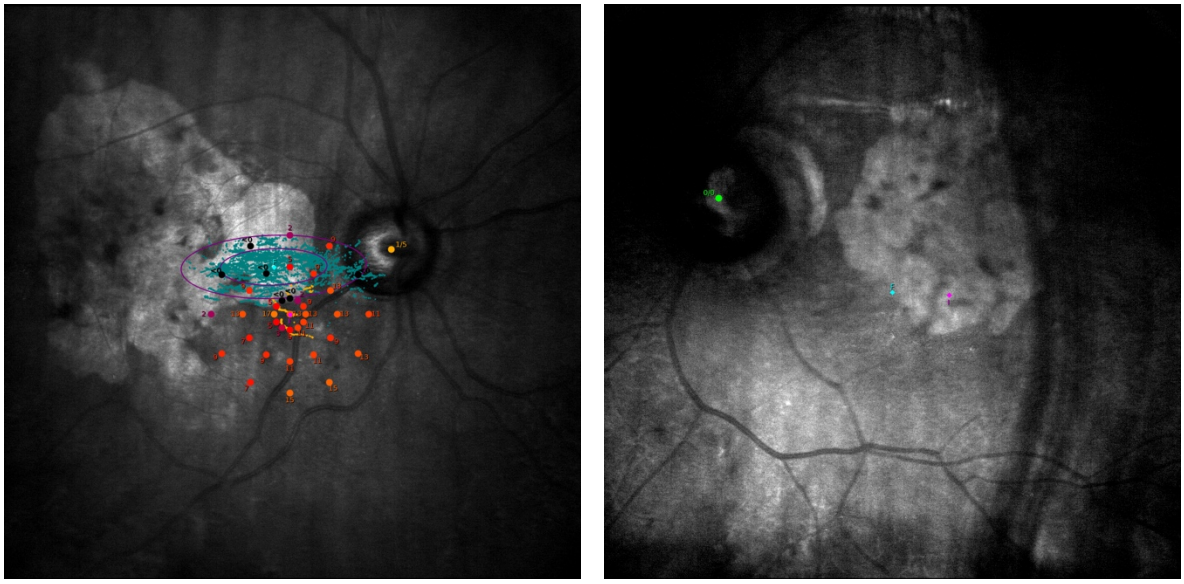
The figures below demonstrate the MAIA images for 5 of 6 in-lab eccentric viewing training participants. Of the 8 eyes tested, 4 had a superior PRL, 2 had a left visual field PRL, 2 had a right visual field PRL and none had an inferior visual field PRL. When describing the location of a PRL in visual field space, for example, a left visual field PRL means the PRL/fixation is to the left of the scotoma in visual field space.



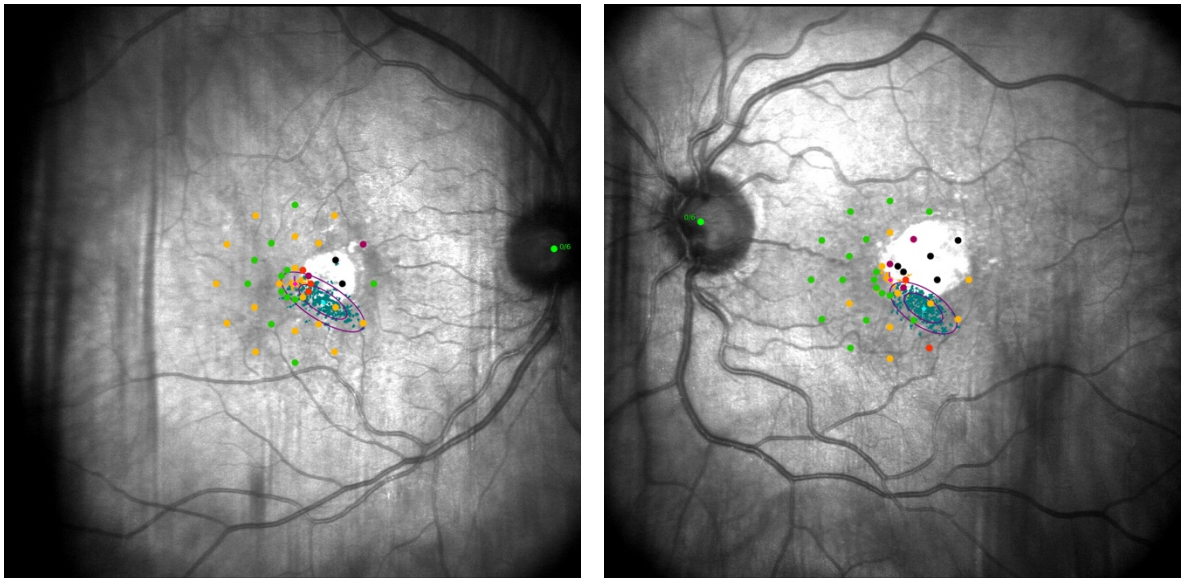
Patient #1. Patient #1 has myopic degeneration of both eyes. Right eye (MAIA image on the left) shows a PRL in the left visual field space. Left eye (MAIA image on the right) shows a PRL in the right visual field space.



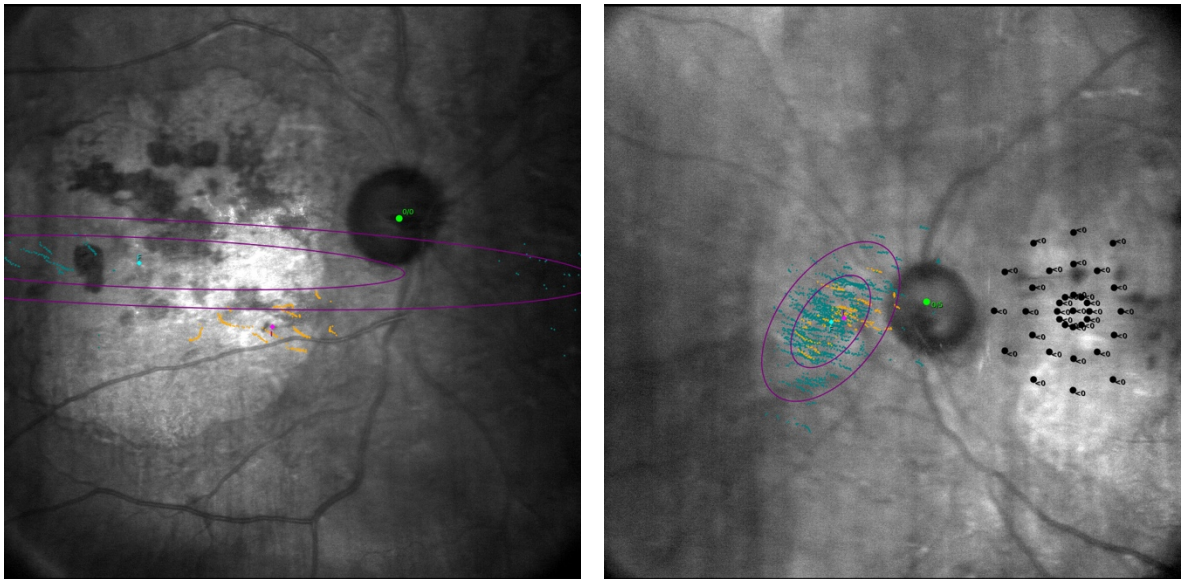
Patient #2. Patient #2 has non-exudative age-related macular degeneration of both eyes. Right eye (MAIA image on the left) has a superior visual field space PRL. Left eye (MAIA image on the right) has a superior visual field space PRL.



Patient #3. Patient #3 has exudative age-related macular degeneration of both eyes. Right eye (MAIA image on the left) has a right visual field PRL. The MAIA was unsuccessful in obtaining a fundus photo and microperimetry results for the left eye (image on the right) for unspecified reasons, likely due to poor image quality.



Patient #4. Patient #4 has non-exudative macular degeneration of both eyes. Right eye (MAIA image on the left) has a superior visual field PRL and the lefty eye (MAIA image on the right) has a superior visual field PRL.



Patient #5. Patient #5 has myopic degeneration of both eyes. The MAIA was unable to successfully complete a microperimetry test on the right eye (MAIA image on the left). The test completed approximately 25% of the test. The poor test results are likely secondary to variable PRL location evident by the large 95% and 68% BCEAs. The left eye (MAIA image on the right) has a left visual field PRL.