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Adaptation To A Simulated Central Scotoma With Visual Search Tasks

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ADAPTATION TO A SIMULATED CENTRAL SCOTOMA WITH VISUAL SEARCH TASKS

by

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ABSTRACT

This study characterized the perceptual and oculomotor adaptation to a simulated central scotoma in normally-sighted subjects and characterized the effects of two different scotoma profiles on the adaptation process.

Twelve normally-sighted subjects, 6 for each type of scotoma profile, practiced a search task (finding an “O” target among “C” distracters) for 11 blocks (162 trials per block). Search reaction time (RT) and eye movement data were collected. A head-mounted eye tracker was used to simulate two 10 deg circular central scotomas (CS), one with a sharp change from seeing to unseeing (S-CS) and the other with a gradual transition (G-CS). The half-height diameter of the G-CS was equal to the diameter of S-CS.

Search RT was 4.5 times of the foveal value when the subject was first exposed to the simulated central scotoma. Practice resulted in ~250% improvement in both groups. The S-CS group took 1-2 fewer blocks to reach half the initial RT value than the G-CS group. Search RT was highly correlated with the number of fixations and least correlated with fixation duration. The initial eye movement scanpath was disorganized, and became more organized with practice. Saccade amplitudes became smaller and saccadic velocities became slower than foveal search values after practice in both groups. At the end of adaptation,

subjects were able to consistently use one retinal location near the border of the simulated scotoma, a Preferred Retinal Locus (PRL). The PRL was more concentrated in the S-CS group than the G-CS group.

This study demonstrated that normally-sighted subjects could learn to adapt to a simulated scotoma while performing a visual search task. This adaptation process occurred by making more organized eye movements and by using one retinal location more consistently, a process that bore resemblance to adaptation observed in central scotoma patients. A scotoma with sharp edge appeared to support faster and better adaptation than one with a gradual edge. This difference might be attributable to the difference between the two scotoma profiles in generating salient visual cue about the location and extent of the scotoma to guide eye movements.

Keywords: low vision, central scotoma, visual search, adaptation, eye movements, and simulation.

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1. Background and Significance

1.1. Low Vision

Low vision is among the top 10 causes of disability in the United States (Owsley, McGwin et al. 2009). It is defined by the World Health Organization (WHO 2007) as having best corrected vision of poorer than 20/60, but equal to or better than 20/400 in the better eye; or visual fields less than 20 degrees in the better eye. To contrast, legal blindness is defined in the U.S.as having best-corrected visual acuity of 20/200 or worse in the better eye, or visual fields equal to or less than 20 degrees in the better eye (Social Security Act 2006). Both definitions take into account peripheral or central vision loss, and the study of the impact of central scotomas has been an important aspect of low vision research.

1.2. Central Scotomas

Scotomas are defined as areas in the visual field that have reduced light sensitivity compared to the normal sensitivity. Their existence and extent are empirically determined by the sensitivities to light intensity at different testing locations on the field**.** Absolute scotomas are retinal areas that have no light perception, whereas relative scotomas are retinal areas that have some light perception but require higher light intensities than normal (Schuchard, Naseer et al.

1999). Central scotoma is a visual field loss that is centered or is located around the fovea.

The most prevalent etiology of central scotomas is Macular Degeneration, and there are two classifications: Juvenile macular degeneration and Age-related macular degeneration (AMD). AMD is the leading cause of irreversible blindness in those over 55 years old in the United States (Klein, Klein et al. 1999). It affects approximately 1.75 million Americans (Friedman, O'Colmain et al. 2004) and usually starts out unilateral, but over time progresses bilaterally (Schuchard 1995). There are two forms of AMD: dry and wet. Dry, or non-exudative, AMD is the most prevalent form and affects approximately 90% of patients (Karan, Lillo et al. 2005). Wet, or exudative, AMD is caused by the leaking of sub-retinal fluid from new choroid vessels. It occurs in ~10% of AMD patients but accounts for ~80% of new cases of legal blindness in developed countries (Kahn, Leibowitz et al. 1977; Ferris, Fine et al. 1984) .

The etiology of AMD is not well understood, but its development has been associated with smoking, high fat diets and oxidative stress (Schmidt, Haines et al. 2005; Kaiser and Do 2007). Recent genetic studies have shown pro-inflammatory genes that encode proteins involved in the complement cascade (complement factors H and B as well as complement component 2) may be associated with an increased risk of developing AMD (Kaiser and Do 2007). It has been suggested that up to 75% of AMD cases may be caused by these genetic variations (Edwards, Ritter et al. 2005; Gold, Merriam et al. 2006), and Vascular Endothelial Growth Factor-A (VEGF-A) is believed to play a critical role in the de-

velopment of wet AMD. Endovascular development is promoted through VEGF-A effects on angiogenesis and vascular permeability (Kaiser and Do 2007).

Juvenile Macular Degeneration is an inherited dystrophy and the most common form is Stargardts disease (Rotenstreich, Fishman et al. 2003). Stargardts is usually diagnosed before age 20, and the prognosis is generally poor with most patients having visual acuity between 20/200 and 2/400 (Rotenstreich, Fishman et al. 2003). In 1997, the gene for autosomal recessive Stargardts (ABCA4), was isolated and provided a definitive diagnosis in the majority of Stargardts cases (Allikmets 1997). The reported phenotypes resemble the atrophy seen in AMD, and demonstrate macular atrophy with varying presence of peripheral flecks (Allikmets 1997; Rotenstreich, Fishman et al. 2003; Lois, Halfyard et al. 2004; Cideciyan, Swider et al. 2005).

There is no definitive cure for either type of macular degeneration. Injection of anti-VEGF agents for treatment of wet AMD has been shown to be effective in reducing or stopping sub-retinal neovascularization, and in many cases improves visual acuity (Martin, Maguire et al. 2011). However, there is no treatment that can revive degenerated retinal neural cells. In dry AMD, high antioxidant supplements are being studied in their effects in slowing the progression of the disease (Fahed, Ghazi et al. 2011). With an increasing elderly population, AMD and central vision loss associated with it have become a serious public health issue in developed countries (Friedman, O'Colmain et al. 2004). It has been projected that by the year 2020 over 3 million Americans may suffer with

AMD (Cook, Patel et al. 2008). The only proven method to restore some functional vision lost to macular degeneration is low vision rehabilitation.

1.3. Central Scotomas and impacts on vision

Damage to the central area of the retina, called the fovea, impairs vision in several ways. The fovea is the location that provides the finest spatial and contrast acuity, the default reference for oculomotor control, and the default location for focal attention. Damage of the fovea disrupts the well-practiced visual-perceptual-oculomotor coordination that supports normal visual performance. Recovering from such an interruption requires an adaptation process in which a less involved peripheral retinal location substitutes for the diseased fovea. This location is called the Preferred Retinal Locus (PRL) (Von Noorden and Mackensen 1962; Whittaker, Budd et al. 1988; White and Bedell 1990; Guez, Le Gargasson et al. 1993; Fletcher and Schuchard 1997).

There are different theories on what determines the optimal location of the PRL. The function-driven theory suggests that certain PRL locations may be more appropriate for specific visual activities such as reading; whereas, the performance-driven theory states that when the macula becomes dysfunctional, the visual system selects a peripheral location to maximize visual performance (Cheung and Legge 2005). Finally, the retinotopy-driven explanation of PRL location comes from a cortical mechanism point of view that retinotopic reorganization of the V1 neurons, with spontaneous remapping, would favor a PRL in close proximity to the borders of the retinal defect (Sunness, Applegate et al. 1996;

Fletcher and Schuchard 1997; Schumacher, Jacko et al. 2008; Dilks, Baker et al. 2009).

A consistent, stable PRL can take many years to develop (White and Bedell 1990). Multiple PRLs may be used depending on the target luminance, visual task or size of the scotoma (Sunness, Applegate et al. 1996; Lei and Schuchard 1997; Duret, Issenhuth et al. 1999; Schuchard, Naseer et al. 1999; Deruaz, Whatham et al. 2002), (Whittaker, Budd et al. 1988). Also, difficulty in breaking the oculomotor habit of directing the diseased fovea to the target of interest can impede the PRL adaptation process (Whittaker, Budd et al. 1988).

One of the primary goals of low vision rehabilitation is to enhance the use of remaining vision. One of the first steps of rehabilitation for macular degeneration patients is scotoma awareness training (Goodrich and Quillman 1977; Scheiman, Scheiman et al. 2007). This training teaches the patient to realize that there is an area in their vision that is not functioning normally, typically by showing the patient that a visible target can become invisible when it falls into one part of visual field and then becomes visible again when it is out of that area. Once the patient is aware of this area of no vision or poor vision, the patient is taught how to avoid this area in seeing. This avoidance can lead to improved eye movement control and help patients develop a more consistent and stable visual behavior (Watson and Wright 1995; Schuchard 2005). An increase in scotoma awareness enhances the next stage of rehabilitation: Eccentric Viewing (EV) training (Scheiman, Scheiman et al. 2007).

Eccentric Viewing is the behavior of using a peripheral retinal location to view objects in space. However, there are few established protocols to conduct EV training. Even low vision specialists in the same institutions use different EV training methods and curricula (Stelmack, Massof et al. 2004), and there have been no systematic evaluations of effectiveness of any of EV training methods. The success rate of EV training is highly variable, and rehabilitation outcomes depend on the trainers' experiences. Therefore, there is a pressing need to improve our understanding of the underlying mechanisms that determine the formation and consistent use of a peripheral retinal location when the fovea is damaged.

Many studies on the effects of central scotomas on functional vision have focused on reading. Reading requires a special set of visual and oculomotor skills that involve recognizing a word and a stereotypical pattern of eye movements from word to word in a predictable and confined space. In contrast, tasks such as looking for things, or navigation, require locating and identifying objects in a large and usually cluttered environment. Such tasks require a different set of visual skills that involves moving the eyes and focal attention over a 2-dimensional space to locate a particular object among a set of similar objects. A visual search task is a close approximation of these real world tasks.

1.4. Visual Search

Visual search is a task in which the subject looks for a target object(s) among other distracter objects that differ from the target in one or more visual

features. Visual features are basic physical properties of visual stimuli, such as color, luminance, size or orientation.

Visual search tasks are typically classified into parallel and serial search, according to how search performance is related to the number of items to be searched (set size). Parallel search is typically observed when the target and the distracters differ by only one visual feature, for example, a red square target among green square distracters. It is characterized by a shallow slope of the reaction time by set size curve, indicating that an increase in the number of search items has little or no effect on search time. Serial search is typically observed when the target and the distracters differ in more than one feature, for example, a green vertical bar target among green horizontal or red vertical bar distracters. Serial search is characterized by a steeper slope of the reaction time by set size curve, indicating that each additional search item requires an additional amount of time to search. The classification of parallel and serial search is related to, but is not determined by the search stimuli. It is known that practice can substantially reduce the slope of the reaction time by set size curve for some search stimuli (Ellison and Walsh 1998; Dewhurst and Crundall 2008).

Different theories of visual processing during visual search have been proposed. Early studies (Treisman and Gelade 1980) theorized that the visual search mechanism has a distinct two-stage linear architecture in the main visual pathway (Wolfe and Horowitz 2004). These components are called the pre-attentive and attentive stages. Simple features, such as size, or color, could be extracted pre-attentively in parallel. However, the detection of a conjunction of

multiple features, such as a green color and a vertical bar orientation, needed focused attention. Later studies (Wolfe, Cave et al. 1989) suggest the pre-attentive component may be separated from the main visual pathway and is used more to guide the deployment of attention for object recognition in the attentive stage.

To achieve optimal visual search performance, an intact peripheral vision and a healthy foveal vision are needed, especially for the more demanding serial search tasks. The fovea includes the central 1° of the visual field (Perry and Cowey 1985) and is the oculomotor center for guiding eye movements and the default locus for focal attention. The fovea also provides the finest spatial detail and contrast sensitivity, and has the greatest visual field representation in the cortical and sub cortical regions. It has been estimated the fovea is represented by almost 20% of the surface area of the primary visual cortex (Baseler, Brewer et al. 2002). This finding emphasizes the importance of the fovea in all aspects of visual information processing (Dow, Snyder et al. 1981).

To maximize the efficiency of the fovea, we must have the ability to rapidly align the eyes onto a target of interest that is spotted by the peripheral retina. The fovea must stay on the target for a sufficient period of time for optimal analysis as demanded by the task (Munoz 2002). These rapid eye movements are called saccades, and target analysis is done during fixations (Schuchard 2005). This alternation of saccade-fixation is repeated several hundred thousands of times a day and is critical for complex tasks such as visual search (Munoz 2002) .

Another critical element in visual search is attention deployment. When we

are looking for a specific target in the typical visual environment, the amount of visual information, due to the presence of distracters, is usually too much for our limited perceptual and cognitive processing. There are two built-in filters to concentrate our processing capability on the target. The first is the anatomic fovea, which dramatically reduces the spatial extent of information that can be processed at the same time. The second is focal attention, which focuses the processing power at one local region at a time. Attention deployment and the fovea are closely linked in such a way that the fovea is the default locus for focal attention. When saccadic eye movements are made to direct the fovea to the target of interest, focal attention goes with the fovea. This is the overt deployment of attention. Attention can also be deployed independent of eye movement, for example, attending to objects at different locations within one eye fixation. This is the covert deployment of attention. Covert and overt attention deployment assures efficient processing of visual information over a large field of view with the accuracy and sensitivity of the fovea, and is the basis for all vision related daily activities (Zelinsky 2008; Findlay 2009). With central vision loss, this well-rehearsed processing routine is irreversibly damaged, and the patient has to learn to adapt to their new visual condition by establishing new ways of deploying attention and making eye movements. This adaptation is a goal of low vision rehabilitation, but the process of adaptation and factors that may contribute to the adaptation are not well understood.

1.5. Simulation Study of Central Scotoma

Most studies of central scotomas have been performed with low vision subjects. However, the variability in scotoma size, shapes, and locations seen in low vision subjects introduces many confounders making the results highly variable and difficult to generalize. Researchers have tried to control these variations by using simulated scotomas produced by gaze-contingent computer displays. Simulation studies also have the advantage of being able to use subjects as their own control which reduces individual variations (Bertera 1988). The best known successful story of using a gaze-contingent display and simulated visual impairment are from studies of the role of the fovea and parafovea in reading. Rayner & Bertera (Rayner and Bertera 1979) found masking the fovea more detrimentally affected reading performance than masking the parafovea. They concluded that while reading the fovea is more important for providing semantic information, whereas the parafovea provides more gross information.

1.6. Simulated Central Scotoma research

Previous studies on simulated central scotomas and visual search have found suboptimal fixation duration, accounting for increased search times (Bertera 1988; Cornelissen, Bruin et al. 2005). Cornellisen, et al (2005) also found as the scotoma size increased, subjects made a greater frequency of return eye movements to previously fixated areas. Finally, detrimental effects on search times have emphasized the importance of the fovea in visual search (Bertera 1988; Bertera and Rayner 2000). A limitation to these previous studies

is that they are simplistic in the types of scotomas studied. In the clinical population, many scotomas are seen with different gradients of vision loss across the scotoma border (Bertera 1988). It has been shown in past studies on low vision patients that factors such as duration of the disease and size of the scotoma can affect the adaptation process (White and Bedell 1990; Schuchard 1995). A question remains as to how different gradients across a scotoma boundary affect the adaptation process. It has been theorized that a sharper scotoma border may be advantageous (vs. a gradual border) because the sharp transition from the scotoma edge to normal retina allows for better eye movement control (Bertera 1988). However, this conjecture has never been tested.

1.7. Purposes and Hypothesis of the Current Research

Normal central vision is critical for maintaining normal vision-related daily activities. Irreversible loss of central vision due to diseases such as macular degeneration has a great impact on the patient's physical and mental health, lowers the quality of life, and is associated with a reduction of the life span.(De Leo, Hickey et al. 1999). To compensate for the loss of central vision, individuals have to learn to adapt to their condition so that the remaining vision can be used more efficiently. However, there are many gaps in our knowledge about the process of adapting to a central scotoma. This research will use simulation technology to study the initial impact and subsequent adaptation in a visual search task to a condition where the foveal input is deprived by simulated central scotomas of different visual profiles.

There are **two purposes** to this research: to characterize the perceptual and oculomotor behavioral changes during the adaptation processes, and to characterize the effects of the scotoma edge profile on the adaptation to a simulated central scotoma.

There are **two hypotheses**:

1) Practicing with a simulated central scotoma will result in some adaptive behavioral changes that alleviate the initial impacts of foveal information deprivation on oculomotor control and attention deployment.

2) The process of adapting to a simulated central scotoma is quicker and more complete with a scotoma that has sharp edges than with one that has gradual edges.

Two specific aims are set:

1) To measure and analyze the process of adapting to foveal input deprivation by having normally-sighted subjects repeatedly practice a set of visual search tasks with a simulated central scotoma.

2) To measure and analyze the effects of scotoma profiles on adaptation to foveal input deprivation by employing two groups of normally-sighted subjects practicing the same set of visual search tasks using simulated central scotomas with different edge profiles.

2. METHODS

2.1. Research Design

The main goal of this research was to characterize the impacts of simulated central scotomas with different profiles on visual performance and the subsequent adaptation. To achieve this goal, a between-group adaptation comparison experiment was conducted in which normally-sighted subjects were randomly assigned into two study groups to practice a set of visual search tasks with simulated central scotomas of different profiles. Search and oculomotor performance throughout the practice sessions were recorded. Various statistical analysis tools were employed to quantify the differences and similarities of the adaptations to different central scotomas.

2.2. Subjects

A total of 12 normally-sighted subjects between the ages of 22-39 were enrolled into the study (8 female, 4 male). Inclusion criteria included best corrected monocular and binocular visual acuities of 20/20, or better; normal visual fields; and no known history of any ocular or systemic disease that may affect vision. Subjects were recruited from UAB students and staff and the local community utilizing word of mouth, flyers, and advertisements in the UAB campus newspaper. Subjects were ambulatory to travel to our laboratory for testing, and understood all instructions pertaining to the tasks. Prior to any testing, the purpose, procedure and any risks of the study were explained to the subject, and an informed consent was obtained following protocols approved by the UAB IRB.

Entrance and control testing took approximately 4-6 hours to complete. The visual search testing took 6-13 hours to complete.

2.3. Entrance tests

The subject's history was taken by a practicing optometrist (the author) to assess any remarkable ocular or systemic history that might exclude the subject from the study. High contrast monocular and binocular acuities were assessed at 4 meters with the Bailey-Lovie acuity chart. The chart is standardized for 6-meter usage. In accordance with the instructions, +0.175 Log MAR was added to the measured acuities. To rule out any peripheral pathology that may affect visual search performance, a 20° visual field test was performed in a dark room using a microperimeter (MP-1 by Nidek Technologies, Vigonza, Italy). The subject was seated comfortably in front of the perimeter and was asked to look into the objective of the device with the tested eye. The fellow eye was covered by a translucent occluder to reduce occasional blackout in the viewing eye (Fuhr, Hershner et al. 1990). A chin/head rest combination was used to stabilize the head position. The central fixation target was a red 2° illuminated cross on a dark background with a luminance of 1.27 cd/m^2(4 asb). Prior to testing, subjects were asked if the fixation cross was clear. If not, a built-in spherical error component was adjusted until best clarity was achieved. Then, an infrared picture of the fundus was taken. This picture was used to mark two retinal landmarks, one at the center of the optic disc and the other one of the retinal blood vessels. These landmarks were used by the device to track and compensate for eye movements

during perimetry. The perimetry stimulus target was a round, white light spot with Goldmann III size dimensions (26' of arc diameter) and was presented for 200ms in random order at 29 predetermined locations in the 20° visual field. The microperimeter has an internal LCD display with a 45° field of view. The luminance of the highest stimulus intensity is 127cd/m^2. Subjects were instructed to maintain steady fixation at the center of the fixation cross throughout testing. The subjects were instructed to press a hand-held clicker when a light flash was detected while keeping fixation on the cross. A fast threshold strategy was utilized during the visual field procedure. Depending on the subject's pupil size and ability to keep steady fixation, the perimetry took 6-15 minutes per eye. After completion of the perimetry, a color fundus picture was taken of each eye. A registration procedure was used to align the color fundus picture with the infrared picture so that the perimetry results could be superimposed on the color picture and the spatial relationship between functional and morphological findings could be determined (Tarita-Nistor, Gonzalez et al. 2008). The results were analyzed by the microperimeter software and interpreted by the examiner. If any gross peripheral pathology was noted, the examiner would inform the subject that they could not participate in the study. This did not occur in any of the subjects tested.

2.4. Equipment

An eye tracking device (Eyelink II, SR Research) was worn during the experimental testing (**Figure 2.1**). The Eyelink II uses dedicated hardware to monitor the shapes and positions of the pupils to determine eye positions in the head. It consists of a headband that weighs about half a pound. Two video cameras with infrared illuminators on the headband take real-time video images of the pupils of the eyes at 250 or 500 Hz. The Eyelink II has two computers, one for eye tracking (host) and the other for stimulus display and response collection (display). The gaze position data generated by the host computer and other information were transmitted to the display computer through a high-speed Ethernet connection. Using the pupil tracking mode, the communication between the host and display computer allowed the display computer to receive a set of gaze position data every 2 ms (500Hz) with a delay of about 2 ms. The display computer used the gaze position data to manipulate the video display to achieve a gaze contingent display. Instantaneous gaze position information at 2 ms intervals, eye movement events (saccades, fixations, blinks) and response key presses were written in a data file for offline analyses. Test stimuli were shown on a 21" color monitor with a maximum luminance of 165 cd/m^2. At a viewing distance of 60 cm, the display area of the monitor subtends

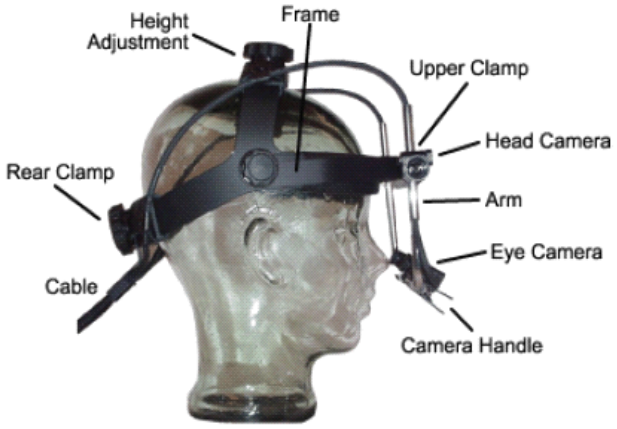

Figure 2.1. Eyelink II Gaze Tracker.

an angle of 37.30 deg x 28.50 deg, and each pixel subtends 2.62 arcmin. The monitor runs at a 120 Hz frame rate.

The subject's head position did not have to be restricted rigidly because a head camera on the headband took real-time images of four infrared markers pasted on the monitor casing with known spatial positions and used these images to compensate for head motion. However, because the accuracy of gaze position on the display computer screen was critically important for the simulated scotoma study, a chin-rest was used to stabilize head position throughout the research. A more stringent method of immobilizing the head, a dental imprint bite-bar, was compared with the chin-rest on six naive subjects in a fixation stability task. The results showed no significant differences in fixation stability between the chin-rest and bite bar, ($F(1,106) = .925$, $p=0.334$), justifying our use of the chin-rest (see **APPENDIX A** for more detail).

2.5. Visual Search with a Simulated Central Scotoma

2.5.1. Simulating a Central Scotoma

Fast eye tracking allows real-time manipulation of a computer graphics display according to the most recent gaze position. This gaze-contingent display method was used to deprive foveal input and simulate the effect of a central scotoma. Specifically, the Eyelink II eye tracker ran at a 500 Hz sampling rate, providing the display computer with a set of x,y gaze positions every 2 milliseconds. When the display monitor was running at a 120 Hz frame rate, there were about 4 sets of gaze position data per frame. Open-GL alpha-blending was used

to manipulate local transparency of an underlying stimulus image, which is the search stimulus. To simulate a central scotoma, an area around the current gaze position is set to opaque so that the area has the color of the stimulus background (white) and the features of the underlying search stimulus become invisible, while the rest of display area is set to complete transparency and thus the underlying stimulus is visible without attenuation. If such image manipulations can be accomplished within one video frame duration, foveal input in every video frame is blocked regardless where the subject is looking, thus effectively simulating a central scotoma. The quality of simulation depends on the display size, the computational power of the display computer and the quality of the display program. The display computer has a 3.09 GHz Pentium 4 CPU with 2 GB of memory, which is much more powerful than the Eyelink manufacturer's hardware requirements for a gaze-contingent display. The SONY 21" monitor was run at a low 800x600 resolution and a 120 Hz frame rate. PsychToolbox-3 (Brainard, D. H. (1997) The Psychophysics Toolbox, Spatial Vision 10:433-436) and Eyelink toolbox (by Cornelissen, F, Peters, E. and Palmer, J.) were used to implement the gaze-contingent display.

For simulation research, the delay between an eye movement and the updating of the display screen should be as short as possible. Cornelissen, et al (2005) used an Eyelink I to create gaze contingent display and reported an average delay of 20 ms (maximum of 28ms). They used a 120 Hz refresh frequency with an Eyelink sampling rate of 250 Hz. The display monitor in this study has the same refresh rate (120 Hz), but a faster eye tracker sampling rate (500 Hz) was

used. The display computer had a Pentium 4, 3.60 GHz processor and a dedicated nVidia 9800 GT video card. A benchmark test of system drawing speed showed that the average redrawing time of the search stimulus was 2.1 ms. Therefore, the system could collect 4 sets of gaze position data and redraw the stimulus 4 times according to the gaze position data within the duration of one video frame (~8 ms). It was thus unlikely that our simulation delay exceeded Cornelissen's maximum delay. None of the subjects in the study reported a temporal "lag" with the simulated scotoma and their eye movements.

The size, shape, and location relative to the fovea and the profile of the simulated scotoma are under the control of the experimenter. Therefore, this method has great potential to study the impact of a wide variety of visual field deficits on human vision. In this research, two types of 10 deg diameter circular scotomas centered at the gaze position were simulated. The first scotoma had sharp peripheral edges, as shown by the red dashed line in **Figure 2.2.**

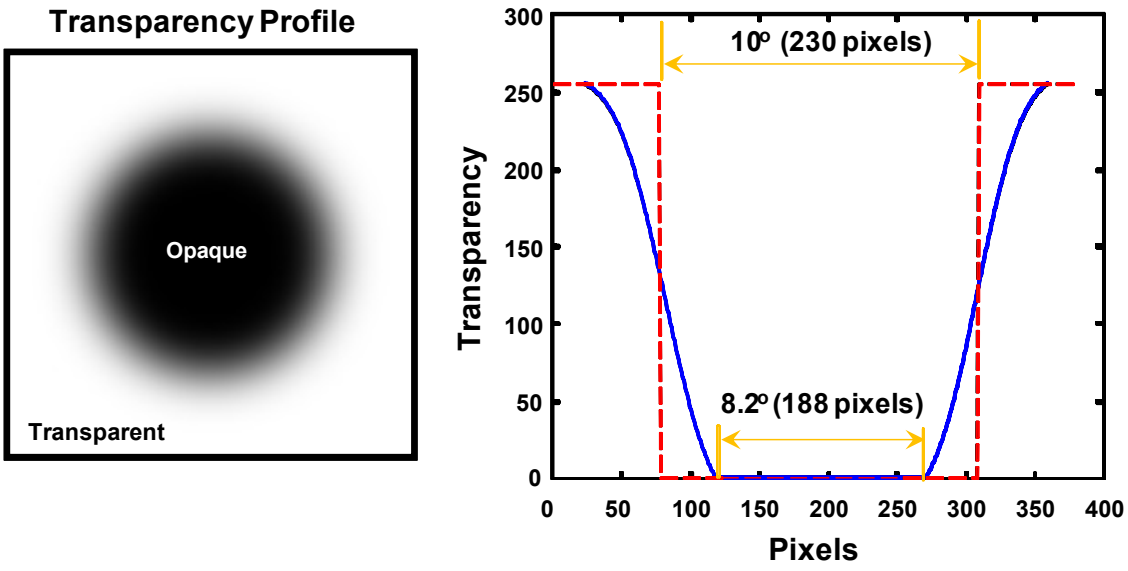

Figure 2.2. Transparency profile of the Sharp (red dashed line) and Gradual (blue line) edge profiles.

The transition from complete transparency (255) to complete opacity (0) was abrupt. When the edge of this scotoma cut through a visual feature, for example, a black stroke of a high-contrast “C”, the continuity of the stroke was interrupted as shown in **Figure 2.3a**.

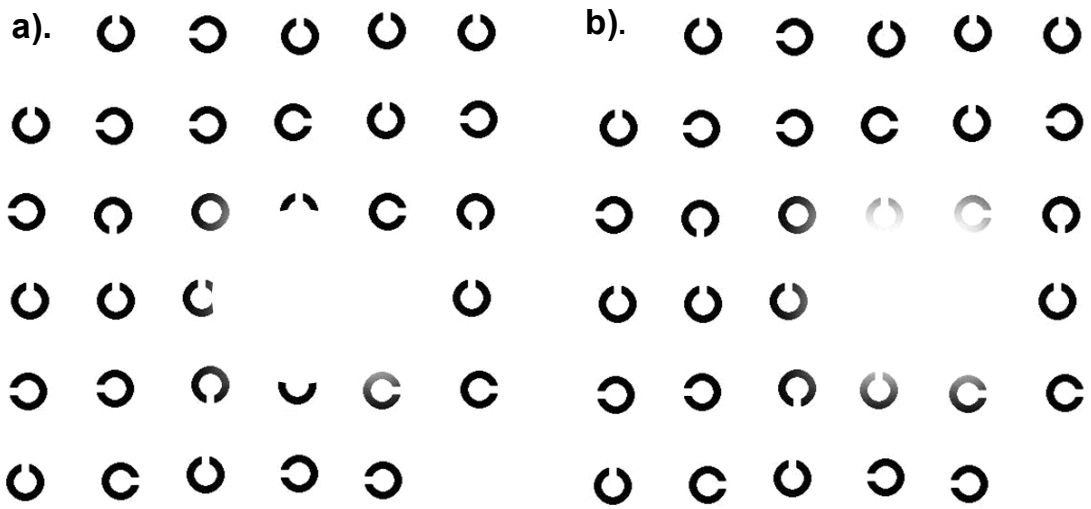

Figure 2.3. The effects of the (a) Sharp and (b) Gradual-edged scotomas on search stimulus.

Therefore, when such a scotoma was moving over an array of underlying visual features, a dynamic change of visual features was clearly visible in peripheral vision. This dynamic change could provide the subject with information about the location and extent of the scotoma, facilitate the development of strategies to avoid the scotoma, and make adaptation to the scotoma quicker. The second scotoma (blue curve **in Figure 2.2)** had smooth Gaussian edges and a half-height diameter of 10 deg. The transition from complete transparency to completely opaque occurred over 1.8 degrees of visual angle. The effect of intermediate transparency was a reduction in contrast of the underlying stimulus, as shown in **Figure 2.3b**. Presumably, this is similar to the effect of a relative scotoma that is often found around an absolute scotoma associated with AMD.

Because of this gradual change of stimulus attenuation, the transient appearance and disappearance of the background visual features was weaker and less noticeable than that observed with a sharp-edged scotoma. Therefore, the gradual edges might provide less salient information about the position and extent of the scotoma, and thus might impede developing strategies to avoid the scotoma and prolong adaptation to the scotoma.

While the gradual edges attenuated the stimulus somewhat outside of the area delineated by the sharp-edged scotoma, they also revealed the stimulus somewhat within the area delineated by sharp-edged scotoma. This made the amount of information deprived by the two scotomas comparable. To assess the effect of contrast attenuation on search performance, a control study was conducted (**see APPENDIX B)** in which search performance at various level of stimulus contrast was measured. The results indicated that search performances (reaction time) were not significantly affected until the contrast level was below the 25%. The accuracy was not significantly different at any of the contrast levels tested. Therefore, even though some features of the search stimulus were attenuated by the gradual edges outside the confine of the 10 deg sharp edges, they did not affect search performance.

If the eye tracker lost track of the eye, the entire display screen was set to the background color so that there was no search stimulus visible. In previous simulated central scotoma studies, we found that some subjects could develop a strategy to bypass the central scotoma. For example, by squinting or moving the eyes to an extreme lateral position the eye tracker would lose track of gaze posi-

tion and the subject could use foveal vision to inspect the stimulus. Blanking the screen when tracking was lost eliminated this possibility. Employing a chin rest also helped to prevent “cheating”. When tracking was lost, the Eyelink automatically labeled it as a “blink start” event, and when tracking was regained, labeled it as a “blink end” event. Cheating by forcing a loss of tracking thus appeared in the Eyelink data file as a very long blink. This provided an opportunity to screen out cheating trials, because average normal blink durations don’t exceed 300 milliseconds (Evinger, Manning et al. 1991). The video display was blanked to background luminance during normal blinks, but there was no indication that the subject noticed any stimulus flickering after blinks (Volkmann et al., Science 1980; Vision Res, 1982).

2.5.2. Visual Search Stimulus

The main experimental task was to search for a target “O” embedded among “C” distracters of various spatial orientations. The search stimuli were full contrast (black on white) letters “O” and “C” that might appear at any of the 36 locations of a 6 x 6 virtual square grid. The Weber contrast was 0.84 (165 cd/m^2-27 cd/m^2/165 cd/m^2). At a 60 cm viewing distance, the virtual grid extended 20.32°x 20.32°, and the distance between adjacent grid positions was 4.1 degrees. Small amounts of random positional jitter (up to ±13.2 arcmin) were applied to the search items around their nominal positions to avoid perfect alignment of search items. The height and width of the “O” and “C” were always the same and were always 5 times of the stroke width. The size of the search items

was individually determined for each subject in a control experiment (see control experiments section). Set sizes of 1, 8 and 32 items were tested an equal number of times under all conditions. The stimulus of a positive (target-present) trial contained a target (letter 'O') and the rest of the search items were distracters (letter 'C' of various orientations). The stimulus of a negative (target-absent) trial contained no target and all of the search items were distracters. Each search session consisted of 54 trials, 36 position trials (the target was on every one of the 36 grid positions once) and 18 negative trials.

The search stimulus (**Figure 2.4**) was presented as the background image on the computer screen, upon which the gaze-contingent central scotoma moved according to the measured instantaneous gaze position, blocking foveal input of the search items. The stimulus was presented continuously until the subject pressed a response button.

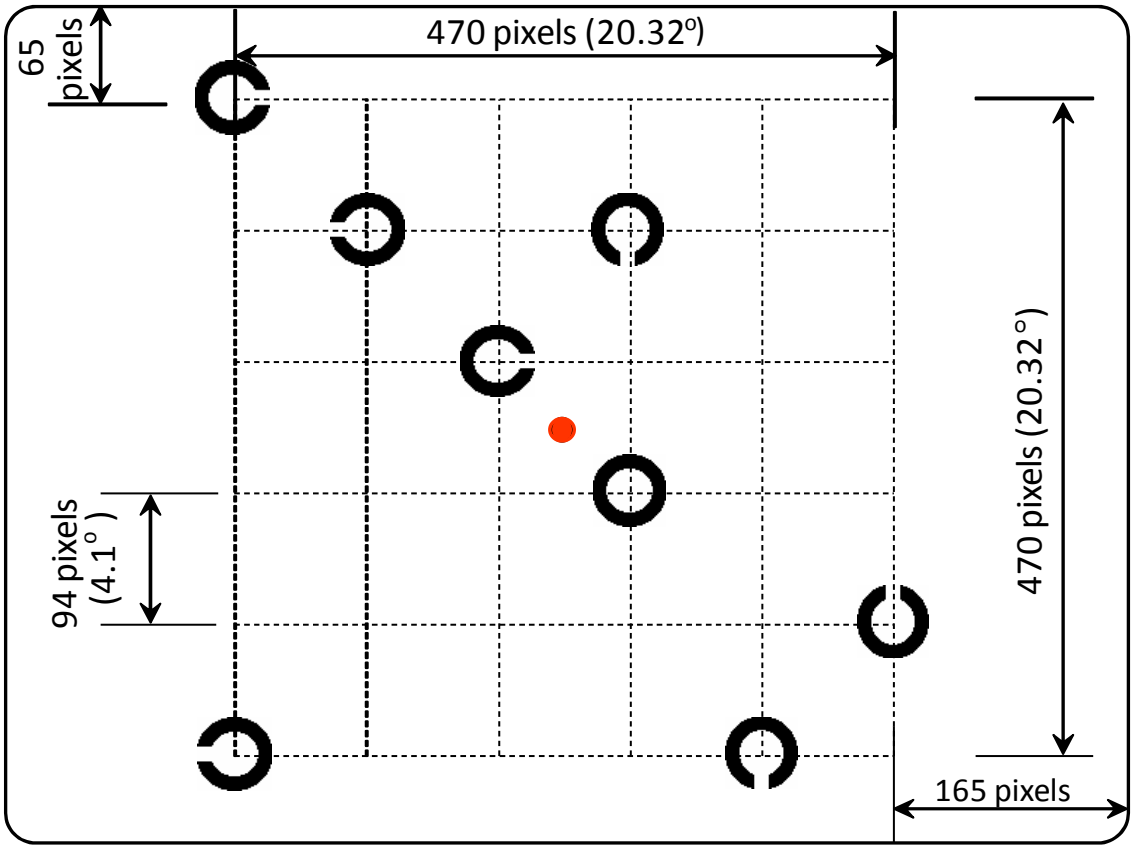

Figure 2.4. Search stimulus (Letter "O") surrounded by distracters (Letter "C"s) of various orientations

Prior to each test, the subject was given a description of the nature of the stimuli and the responses they needed to make. The C stimulus could have 4 different orientations during the task procedure. All experiments (control and experimental) were performed binocularly (**see APPENDIX C**), and in a normally lit room.

2.5.3. Visual Search Task

The search stimulus was first explained to the subjects. They were instructed to press the left arrow key on a keyboard of the display computer as soon as they determined that the target was present and to press the right arrow

key as soon as they determined that the target was absent. They were informed that the accuracy of their responses was important and that they had a maximum of 45 seconds to make a response in a trial. If no response was made within 45 seconds, the trial was labeled as a “timeout” and was not included in the analysis. Subjects were given practice trials to familiarize themselves with the task and key presses.

If the search involved using a simulated central scotoma, the subjects were also advised that the task and procedure were the same except there would be a central “blind spot” in front of their vision as they were performing the task.

2.5.4. Procedure

After entrance examination and tests, subjects were randomly assigned to two groups. The “S-CS” group performed 11 blocks of visual search with a Sharp-edged simulated central scotoma. The “G-CS” group performed 11 blocks of visual search with a Gradual-edged simulated central scotoma.

Prior to testing, the experimenter secured the headband of the Eyelink II on the subject’s head so that it did not slide on the head with small head motions. The orientation and focus of the eye cameras were adjusted so that they formed clear images of the subject’s pupils. The eye tracking provided a real time video display of the eyes through the eye cameras, which made the adjustment easy.

Subjects were seated comfortably at 60 cm from the computer screen with a chin rest used for head stability. Prior to beginning each search session, the eye tracker performed a calibration and validation procedure to associate eye position to spatial locations on the display computer screen. The subjects were instructed to fixate and follow a 0.29° diamond shape embedded at the center of a 1.8° yellow circle as it moved in random order through 9 predetermined locations on the monitor. Calibration and validation were successful if the average offset between repeated fixations at the nine screen positions was equal to or less than 1.0 degree. A drift correction was performed before each search trial to correct for small disturbances in headband position that might have happened in the previous trial and to ensure an accurate central fixation for the current trial. **Figure 2.5** shows the view of the drift corrected target and the positions of the two eyes on the host computer monitor. When the subjects fixated on the drift correction target, he/she pressed the space bar on the keyboard to start the trial. If the fixation could not be brought close enough to the drift correction target, a trial would not start and recalibration was needed. If drift correction was successful, the central scotoma was turned on and the subject started to search with the scotoma.

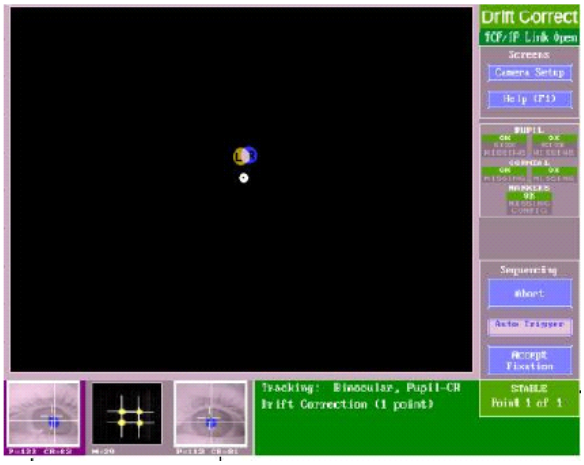

Figure 2.5. Drift correction screen for the Eyelink II.

To determine the relative adaptability to simulated scotomas with different profiles, the main body of the experiment consisted of 11 visual search blocks. The number of visual search blocks was determined in a pilot study of six subjects, which indicated that the improvement of performance typically began to asymptote before 11 blocks. Each practice block consisted of three 58-trial search sessions, one for each of the 1, 8 and 32 set sizes. The set size was constant in each search session, which consisted of 36 positive (target-present) and 18 negative (target-absent) trials. The order of set sizes in each block was randomized. The subject took a break after each search session and performed calibration and validation before starting the next session. Each block took about 10-15 minutes to complete.

After completing the 11 search blocks with one type of scotoma, 5 subjects from each group performed another 7 blocks of search using the other type of scotoma. This counter-balanced design provided information about transferring training effects to a different type of visual deprivation.

2.6. Control Experiments

Three control experiments were performed.

2.6.1. Central and peripheral recognition threshold size

The purpose of this control experiment was to determine the stimulus sizes to be used in the foveal and simulated scotoma search experiments. Visual search performance is known to be affected by the salience (the perceptual differences between the target and the distracters) of the search stimulus. Search is

more accurate and faster with highly salient stimuli than with less salient stimuli. In the search task used in this research, the salience of the stimulus was related to how well the “O” target could be discriminated from “C” distracters, which was related to the size of these search items. Because foveal search performance was used as the baseline performance against which the impact of a simulated scotoma and the subsequent recovery of search performance would be judged, equal stimulus saliency under these two conditions was desirable. This control experiment determined size thresholds for discriminating “O” and “C” at the fovea and at peripheral locations that were then used to determine the stimulus sizes for search with the fovea and with a simulated central scotoma.

The stimuli were full contrast (black on white) letters “O” and “C” of various sizes presented for 200 ms. The C stimulus could have 4 different orientations. The short stimulus duration was used to discourage voluntary eye movements when a stimulus was presented in the visual periphery. Testing was performed at two retinal eccentricities, 0^{o} (foveal) and 5.0° (peripheral). The 5.0° eccentricity was the nominal radius of the simulated scotoma used in the main visual search experiments. Foveal threshold size was measured at 240 cm and the peripheral threshold size was measured at 60 cm. The longer distance for the foveal test was necessitated by the limited spatial resolution of the monitor, the high acuity of foveal vision, and the requirement that the stroke width of the “O” and “C” was 1/5 of the letter height. The subject was asked to keep steady fixation on a fixation target at the center of monitor. For the foveal test, the fixation was the center of four corners of a 0.60° square and the stimulus was presented at the center of

the square. For the peripheral test, the fixation was a 0.57° cross and the stimulus was randomly presented 5.0° eccentrically above, below, left and right from the fixation cross (**Figure2. 6**).

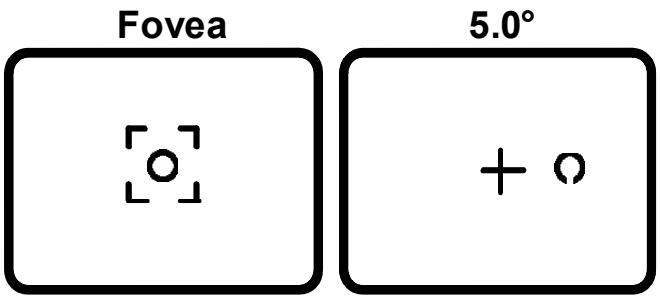

Figure 2.6. **Fovea and 5.0° periphery display screens for Target Threshold test**.

The task was to report whether the stimulus was an O or a C by pressing the left and right arrow keys, respectively. Four stimuli sizes in 5-pixel increments were used to determine a threshold size for discrimination. The minimum stimuli sizes tested were 5 and 10 pixels at the fovea and periphery, respectively There was one practice block of 128 trials, followed by two 128-trial (36 trials per stimulus size) blocks for a total of 256 testing trials per condition. Each block lasted 2-3 minutes.

The data were analyzed off-line to determine the threshold size and the search item size to be used during the main visual search experiments. This was done by fitting a Weibull psychometric function to the percentage correct rates of the four stimulus sizes. The foveal and peripheral discrimination threshold sizes were the sizes that produced a 95% correct discrimination rate. The stimulus sizes for the foveal and peripheral search experiments were 2X the corresponding discrimination threshold sizes. This ensured that the stimulus size was very discriminable and thus would not become the limiting factor for search performance. The data showed some between-subject variations in the required stimulus size.

Because the smallest target size that could be faithfully displayed on the monitor was 5x5 pixels, some adjustments to this criterion were needed. In some subjects, after scaling the foveal test results for the 60cm viewing distance and applying the 2X 95% correct size criterion, the target size was less than 5 pixels. In these cases, the magnification factor was adjusted so that search target size was 5 pixels. The same magnification factor was also used to set the stimulus size for simulated-scotoma search so that equal saliency for these two search conditions could be maintained.

The mean threshold sizes for all subjects to be used at 60cm were 5.75±1.2 pixels (15.1±3.14 arcmin) for foveal and 32.92±6.56 pixels (86.25±17.19 arcmin) for peripheral viewing, respectively. The subject's ranges of target sizes were 5-9 pixels (13.1-23.58 arcmin) and 25-45 pixels (65.5-117.9 arcmin) for the fovea and periphery, respectively.

2.6.2. Foveal Visual Search

This and the following control experiment served 3 purposes. First, they allowed the subjects to be familiarized and become proficient with the visual search task. Secondly, they established a baseline performance measure for each subject. Finally, they were used to compensate for potential variability in search strategies between subjects.

The search stimuli and procedure were similar to those of the main experiment. Although no simulated scotoma was used in this experiment and no gaze contingent display was required, the Eyelink II was used to measure eye move-

ments during fovea search. The calibration and validation procedure, as described in the main experimental section, was repeated prior to each search session.

Originally, the pilot subjects performed the foveal visual search task with the stimulus size determined by the foveal discrimination threshold size test, but with the targets distributed over the same search area as the main search experiment **(Figure 2.7a).**

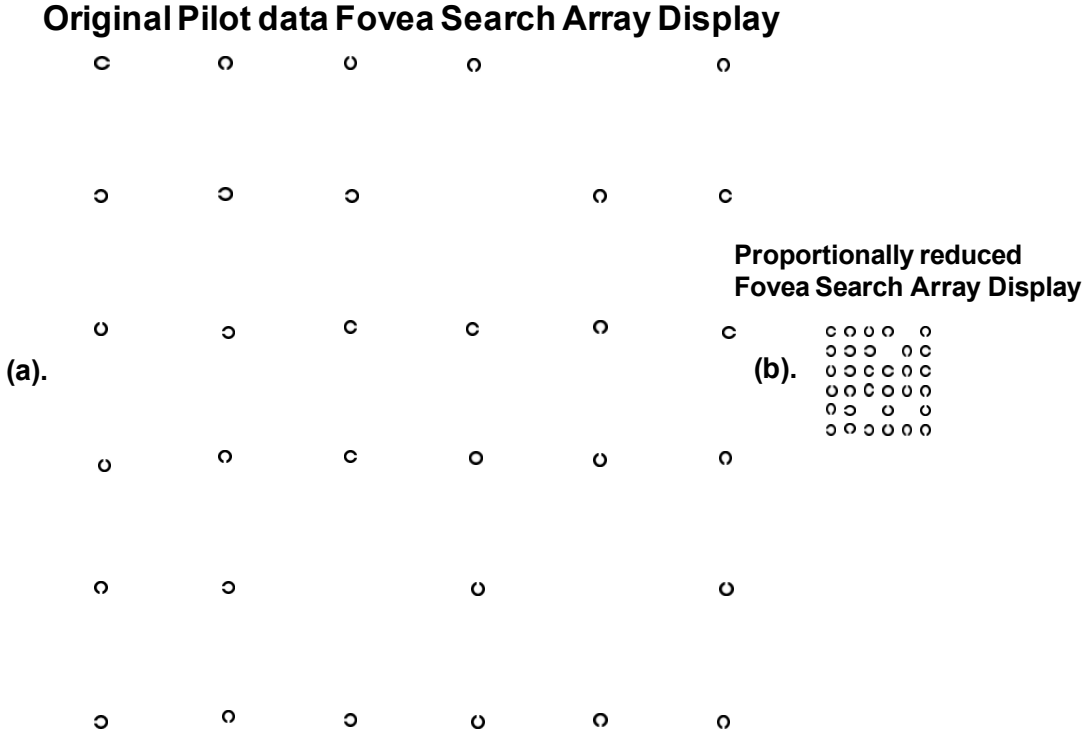

Figure 2.7. Comparison of (a) original pilot data fovea search array display and (b) proportionally reduced fovea search array display.

However, the data showed that the reaction times for foveal search of such a stimulus were slow, sometimes slower than the reaction time obtained when a simulated central scotoma was used. This happened for all subjects. When the RT of foveal search was divided by the RT of scotoma search, the ratio was

greater than 1.0 in most cases and sometimes greater than 2.0. An example is shown in **Figure 2.8a.**

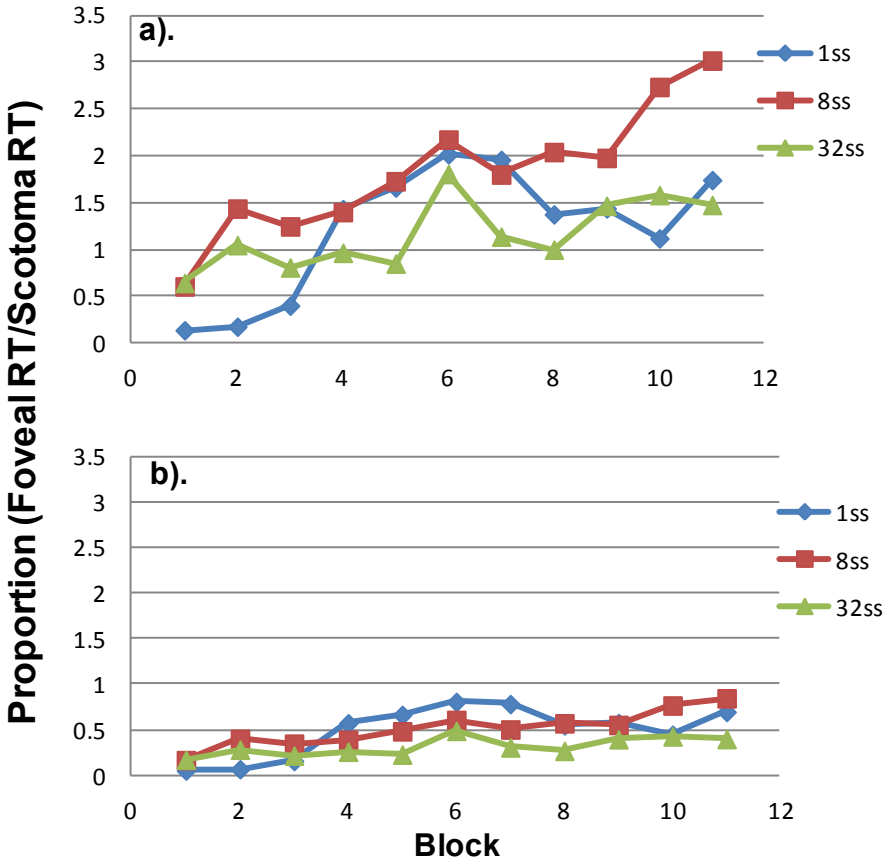

Figure 2.8. Examples of proportion reaction time for one subject.. Scotoma search RT is divided by foveal search RT under two conditions, (a) a full field (20.34°) foveal search using stimulus Figure 2.7a and (b) a scaled field (2.26°) foveal search using stimulus Figure 2.7b.. The three curves in each graph represent results from search set sizes 1, 8 and 32.

The slowness of this foveal search could be explained by the wide spacing between search items in the stimulus shown in **Figure 2.7a** and the rapid decrease of visual acuity from the fovea to the periphery. In the search stimulus shown in **Figure 2.7a**, except for a few search items near the current fixation location, most of the surrounding search items would not be recognizable because

they were too far in the peripheral vision and thus provided little help to guide search eye movements. In comparison, search with a simulated scotoma used peripheral retinal locations, but also used larger search stimuli. Because the acuity falloff beyond 5 deg eccentricity is very gradual, the larger search stimuli might have offered more viable previewing of the surrounding search items at the same inter-item spacing and thus might have resulted in more efficient search.

To produce a more reasonable fovea search control, the search display used for foveal search was scaled down in proportion to the ratio between the foveal and peripheral discrimination threshold sizes so that the smaller foveal search items had the same proportional inter-item spacing as the larger scotoma search items. For example, if the target size for the scotoma and the fovea conditions were determined to be 45 and 5 pixels respectively, the display screen was proportionally reduced by a factor of 9 as seen in **Figure 2.7b**. The search stimulus shown in **Figure.2.7b** allowed more efficient previewing of items that surrounded foveal fixation and resulted in faster search performance. As show in **Figure 2.8b**, the subject's scotoma performance initially was only 10-20% of foveal performance, and improved with practice to approach foveal performance, which is represented by a value of 1.0 in **Figure 2.8b**.

Large inter-subject variance was observed in foveal search. In target-present trials (Hits), the individual subjects' 1 set size reaction times ranged from 451.95 ms to 682.12ms (mean=576.39± 80.59), and the 8 set size condition ranged from 807.54ms to 1302.51ms (mean=1017±174.50). The largest range of search times was seen in the 32 set size condition, 1660.30ms to 3697.56 ms

(mean=2639.70±624.95). In target-absent trials (Correct Rejections), the1 set size range was 523.70 to 776ms (mean=624.24±58.69), the 8 set size ranged from 1395.58 to 3885.93 ms (mean=2125.01±786.49), and the 32 set size times ranged from 4841.06 to 14822.74ms (mean=7812.74±3064.52). These large individual differences in search performance highlighted the importance of normalizing each individual's search results with their foveal data.

2.6.3. Foveal Visual Search 2

The scaled-down fovea search appeared to be appropriate for analyzing search RT, but it might not be appropriate for other search performance measurements. For example, scotoma search was conducted over a larger, 20.34°, area while fovea search was conducted over a much smaller area. Comparison between search saccade amplitudes observed under these two conditions would not be appropriate because an observed difference in saccade amplitude could be the result of different viewing condition (scotoma vs. no scotoma) or the result of different search field size. It was thus determined a more appropriate method for analyzing oculomotor data would be to have the subjects perform a separate fovea control using the search stimulus that would be used in scotoma search. Eye movement data collected from this control experiment was used to normalize eye movement scotoma search eye movement data.

2.7. Data Analysis Plan

The between-group comparison experimental design resulted in 4 study factors, ADAPTATION (11 blocks), SCOTOMA (sharp vs. gradual edge), SETSIZE (1, 8 and 32 items) and RESPONSE (hits vs. correct rejections). The focuses were the adaptation process and the comparison of adaptation processes of the two scotoma groups. The outcome measures included search accuracy, search reaction time (RT), search efficiency (the slope of the RT by Set Size plot), number of fixations during a search trial, saccade amplitude and peak velocity, and the location of the last fixation relative to the search target. A general repeated measures ANOVA was used to analyze the main effects and interactions among the study factors. Additional statistics and treatments were used to quantify special aspects of search performance.

2.7.1. General Analysis

A Mixed-design repeated measures ANOVA with ADAPTATION and SETSIZE as the within-subject variables and SCOTOMA as the between-subjects variable was used to analyze RT, number of fixations, saccade amplitude, and peak velocity. The data analysis scheme is illustrated in **Figure 2.9**. The first hypothesis, that adaptation occurred when practicing with a simulated scotoma, could be tested by the main ADAPTATION effect. The second hypothesis, that performance differed between the two different scotoma profiles, could be tested by the main SCOTOMA effect and the ADAPTATION*SCOTOMA interaction. The impact of factor SETSIZE on the adaptation could be assessed by

its interaction with the other factors. For all analyses, the statistical significance criterion was set at the 0.05 level.

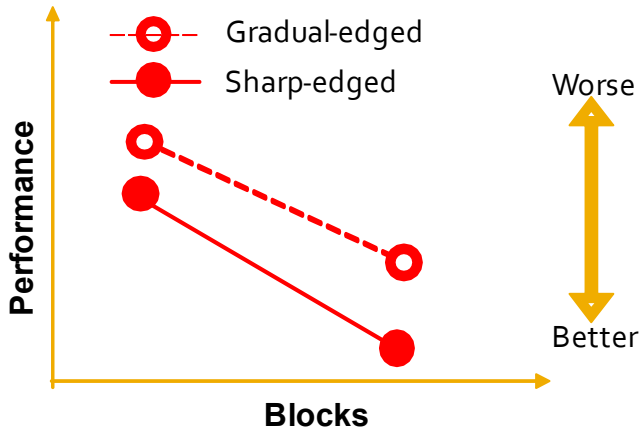

Figure 2.9. Data Analysis Scheme

Prior to the analysis, the following procedures were conducted to prepare the data.

2.7.1.1. Data cleaning.

While the Eyelink eye tracker did a good job in delivering a gaze-contingent display and parsing eye movement data online, there were occasions where unrealistic numbers were recorded. These might be the result of a sudden movement of the head that caused a shift of the headband or the internal error codes of the eye tracker. A set of eye movement filters were applied to clean the eye movement data. Specifically, eye tracker signals with velocities >= 1000 °/ second or amplitudes corresponding to >= 200^{o} were excluded from analysis. Trials with very long blinks (loss of tracking) were labeled as “cheat” trials and were excluded from analysis.

2.7.1.2. Number of practicing blocks

At the onset of the study, the completion of adaptation was determined observing two occurrences of RT reversals for the 32-item set size in target-present trials as seen in **Figure 2.10.**

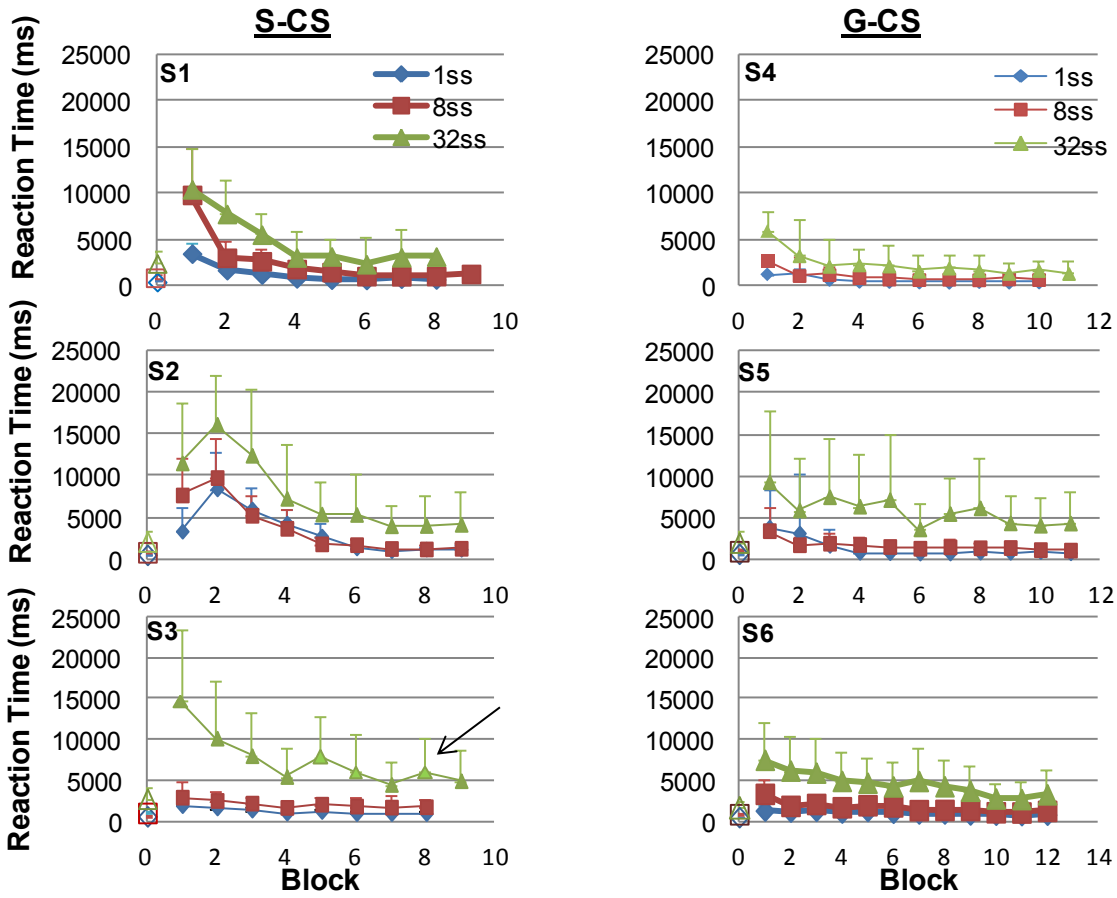

Figure 2.10. Target Present (HITS) pilot data comparison of the sharp edge (S-CS) of subjects 1-3 (S1-S3) and gradual edge (G-CS) of subjects 4-6 (S4-S6). The control times (fovea) are seen at block zero (0). Set sizes of 1 (blue diamonds), 8 (red squares) and 32 (green triangles) are used throughout the experiment. The **arrow** demonstrates an example of two occurrences of RT reversals (S3).

Based on this criterion, the first three subjects of the S-CS group completed adaptation between the 7th-9th block. Two subjects of the G-CS group completed adaptation between the 10th-11th block. Another subject of the G-CS group (S5)

had more reversals but reached a stable performance level by the 11th block. Based on the data from these subjects, a decision was made that all subsequent subjects would perform 11 blocks of training. However, by the time of this decision, it was not possible to get the first few subjects to come back and complete the missing blocks. A statistician was consulted about the possibility of using the data sets that didn't contain 11 blocks. The statistician confirmed that these subjects had sufficiently adapted by the 7th-9th block, and recommended using averages of the data from the final 3 blocks completed of these subjects to make up the missing blocks. Missing data is a common occurrence in longitudinal studies, and multiple remedies have been proposed. One of them is to use existing data to make up missing ones based on the knowledge of the process.

2.7.1.3. Application of control experiment data

Large between-subject variations were observed in foveal search. This was expected because the subjects differed in their search strategy, decision criterion and response time. These individual variations might interfere with between-subject comparison. Control experiments were thus performed to collect baseline fovea search data so that each subject's scotoma search performance could be expressed as the proportion of his/her own fovea search performance. After this manipulation, the data contained less inter-individual variability and was thus more comparable between subjects.

The raw search performance data were prepared for analysis by applying the fovea control data. The scotoma search RT was divided by the foveal

scotoma search time (from Control Experiment 2) to obtain a measurement of the impact of a scotoma on search performance. This ratio (Q) could then be used to compare performance improvement within and between groups. As performance improved, the ratio of scotoma search RT to foveal search RT decreased and approached a value of one.

When eye movement data were analyzed, scotoma saccade data were divided by the corresponding fovea search data conducted with the peripheral target size (Control experiment 3).

2.7.1.4. Normalization

An inspection of the search performance data revealed that most of the data sets were highly skewed toward longer search RT. A Lilliefors' composite goodness-of-fit test for normality was thus performed on all 11 blocks of search adaptation data and the 7 blocks of counterbalance data. The purpose was to detect whether the data satisfied one of the assumptions of ANOVA, namely, the data followed a normal distribution. The Lilliefors' test is designed to test goodness of fit to any normal distribution. In contrast, the usual one-sample Kolmogorov-Smirnov test only tests goodness of fit to a 0-mean normal distribution with a standard deviation of 1.0. The null hypothesis tested was as follows: H_0: data are normally distributed. The outcome measures under study were first tested for significance, and a statistic, K1 was obtained. If significant deviation from a normal distribution was found at the 5% level, a Log_{10} transformation was performed. The Lilliefor's test was then repeated on the transformed data, and an-

other statistic, K2, was obtained. If H_0 for the transformed data could not be rejected, the transformed data was used. If H_0 was again rejected, the statistics K1 and K2 were compared to the normality criterion to determine if the original or the transformed data was closer to normality and thus would be used in analysis. In all blocks of scotoma/fovea (Q) data, transformation was needed in Reaction Time, Number of Fixations and Fixation Duration. Saccadic Amplitudes and Velocities did not need to be transformed in any block of data.

2.7.2. Special Analyses: The search experiment produced large amounts of data (>500,000). While data directly extracted from the experiment, RT, number of fixation, fixation duration, and saccade parameter were analyzed in an overall ANOVA, special measures of search performance were also derived and analyzed.

2.7.2.1. Slopes of the RT vs Set size curves

When the search RT is plotted against the search set size (the number of search items), the slope of the curve is a measure of the additional time needed for each additional search item. This slope is traditionally considered the most important measure of search efficiency. A shallow slope indicates more search items being processed at the same time and the search is thus more “Parallel”. A steep slope indicates items are processed one by one, and the search is thus more “Serial”. The O vs C search used in this study is known to be serial (Dosher, Han et al. 2004). Research on normal perceptual learning of serial search tasks showed

that a learning effect is manifested as a reduction in the slope (automaticity). In this study, the search RTs of 1, 8 and 32 set sizes collected from each search block from each subject were individually fitted with a straight line, and the slopes and the y-intercepts of all blocks of all subjects were analyzed using a repeated measures ANOVA to quantify the slope changes throughout adaptation and between groups.

2.7.2.2. Last fixations in positive trials

The eye position during the last fixation before the subject pressed the response key was collected from all positive (target-present) trials, and the last fixation positions of each subject were compared with the target position on a trial-by-trial basis. The rationale was that the search on a target-present trial should be terminated as soon as the target was detected. This logic suggests that the last fixation carries information about what retinal position was used to see when the target was detected. With a simulated central scotoma, it was possible to relate retinal locations with the spatial position of the target. This is because at the beginning of each trial, the fovea was used to perform a drift correction before the scotoma was turned on. This procedure ensured the search trial started with the fovea directed at the center of the screen, and thus allowed inferences of all other retinal positions to be made throughout the trial, assuming there was no significant position shift of the headband.

The reason for analyzing the individual last fixation distribution instead of group average distributions is that different subjects under different experimental

conditions might have clear clustering of last fixations but in different regions of the search area. Analyzing group average last fixation distributions might obscure the clustering that occurred in the individual data within and between experimental sessions

To analyze the last fixation data, the difference between the x and y positions of the target and the x and y positions of the last fixation (i.e., the projected location of the fovea) were taken. These differences were used to produce x and y scatter plots as seen in **Figure 2.11.**

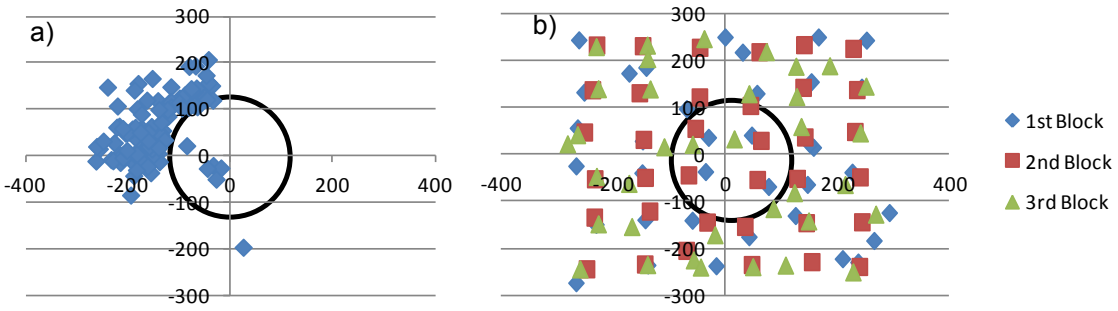

Figure 2.11. Example of two scatter plots with last fixation distributions of (a) the upper left quadrant and (b) random scattering. The center circles represents (approx.) the 10 deg simulated scotoma.

Notice that the fixation position reported by the eye tracker was the position of the fovea, even though direct visual input was deprived from the fovea by the simulated scotoma. Therefore, each symbol on the plot represented the deviation of the anatomic fovea from the target in a positive trial. The origin of the plot, [0 0], represented a condition in which the fovea was directed at the target. A symbol that was displaced from the origin indicated that the fovea was not used to view the target when the response key was pressed and the position of the symbol showed the peripheral retinal location used to view the target. Clus-

tering of last fixations in this plot indicated consistent use of a particular retinal location. The analysis of these scatter plots would reveal if a particular retinal location was consistently used to search and, if so, the position of this retinal location with respect to the fovea.

The clustering of the last-fixation distribution was quantified by analyzing the probabilities of the last fixation falling into the following five areas of the scatter plot. Area 0 was a circle centered at the origin of the plot with a radius of 115 pixels (5.0^{o}). This central area was the same size and location as the simulated scotoma. Areas I, II, III & IV were the four Cartesian quadrants minus Area 0 as seen in **figure 2.12.**

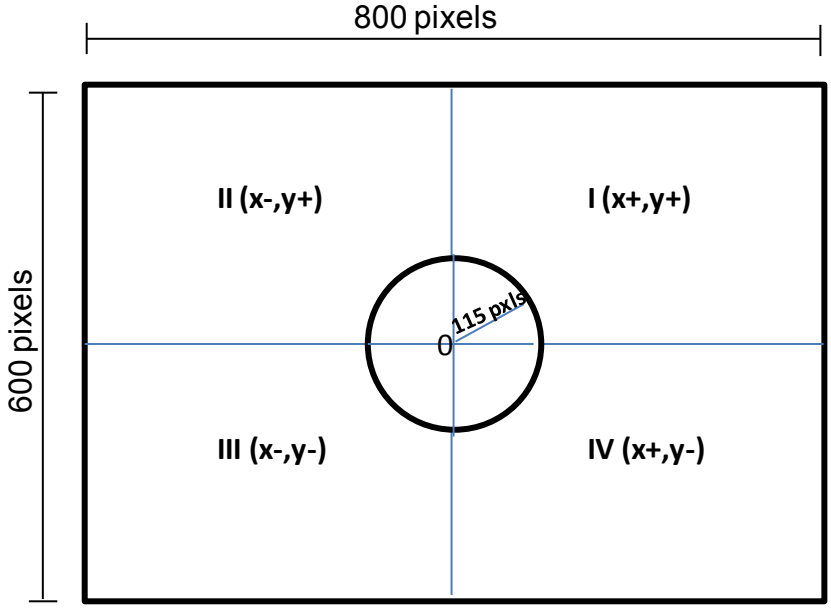

Figure 2.12. Schematic diagram of cartesian coordinate system of potential last fixation plots on 800x600 display monitor.

Because these peripheral areas were larger than Area 0, the last fixation was more likely to fall into these areas if the position of the last fixation was completely random. To facilitate comparison among all 5 areas, the chance that a last

fixation fell into a peripheral area was divided by a factor that reflected the difference in area between the region of the scotoma and the surrounding peripheral areas. The area of the central area (in square pixels) was:

$$\text{Area}_{\text{central}} = \pi \times 115^2 = 41548$$

Each of the peripheral areas was:

$$\text{Area}_{\text{peripheral}} = \frac{\text{Area}_{\text{monitor}} - \text{Area}_{\text{central}}}{\#\ \text{Peripheral Areas}} = \frac{800 \times 600 - 41548}{4} = 109610$$

The normalization factor used was 109610/41548=2.6382. To analyze the last fixation distribution, the numbers of last fixations falling into the 5 areas were tallied, and the numbers for the 4 peripheral areas were divided by 2.6382. This procedure produced 5 last fixation counts, n_0, n_I, n_{II}, n_{III} and n_{IV}. They were the number of last fixations falling into a 41,548 pixel^2 area in the 5 areas.

A one-way ANOVA was then used to test the following hypothesis:

H_0: $n_0 = n_I = n_{II} = n_{III} = n_{IV}$

If H_0 could not be rejected, then the distribution of last fixations did not differ significantly from a random distribution in the 5 areas and no more testing was conducted. If H_0 was rejected, then follow up comparisons were conducted to determine which of the area(s) had a higher concentration of last fixations than others.

2.7.2.3. Fitting the adaptation process

An Omnibus analysis was used to test the statistical significance of the adaptation to a simulated scotoma. A significant ADAPTATION effect confirmed that search performance improved as adaptation progressed. However, this analysis did not provide descriptive information about the process of adaptation, for ex-

ample, how fast the subject adapted to a particular type of scotoma. To obtain such information, curve fitting was conducted on adaptation data that were normalized by foveal search data. Curves of several analytical forms were tried, and a power function in the form of $y=At^{-\tau}$ was selected, where y was a performance measure, for example, normalized RT, t was the practice block, 1 to 11. Free parameters A and τ were the y value at the first block and the time constant. From the equation above, it was determined that the number of blocks required to reduce the initial performance deficit by half was $t_{1/2} = 10^{\frac{\log_{10} 2}{\tau}} = 10^{\frac{0.301}{\tau}}$. The parameter $t_{1/2}$ had a similar meaning as the half-time measure of radioactive material and was independent of the starting level of performance

Finally, adaptation data under certain conditions did not exhibit a definitive performance saturation point within the 11 blocks tested. To estimate the best power function curve fit, it was assumed that search performance would approach an asymptotic value if sufficiently long adaptation was given. To reflect this asymptotic behavior, an asymptotic value of 1.10 (10% above foveal search performance) was assumed to occur at the 22nd (twice the practiced number of blocks). The curve fitting was performed on the data of the 11 practice blocks and

the asymptotic point **(solid and open diamonds in Figure 2.13)**.

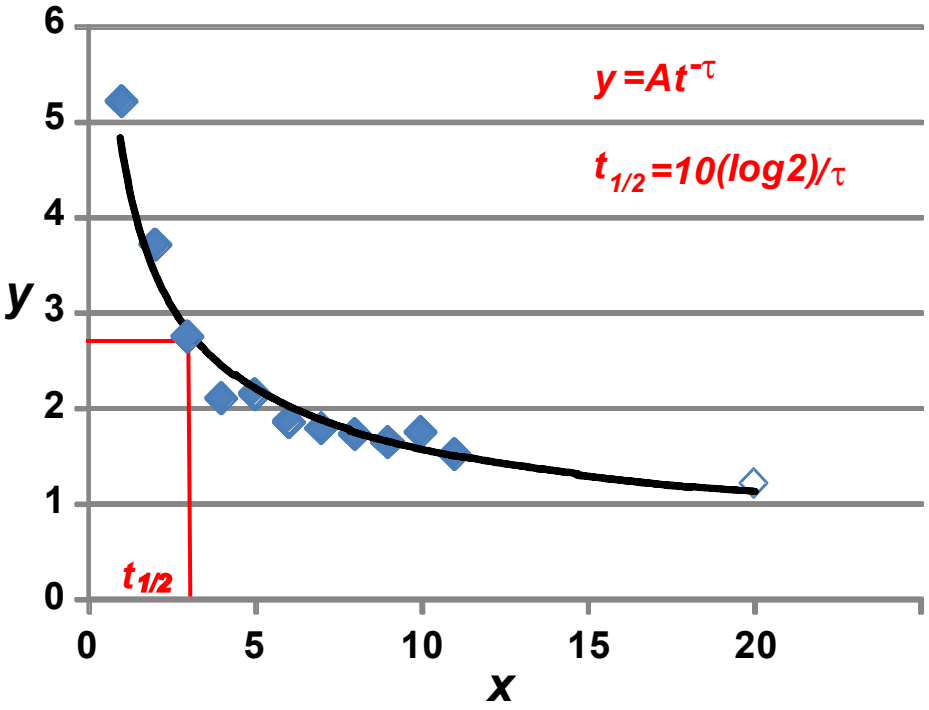

Figure 2.13. Performance measure curve of a power function fitting.

3. RESULTS

3.1. Search Accuracy

A Mixed-design repeated measure ANOVA with BLOCKS as the within-subject variable and SCOTOMA as between-subjects variables was used to analyze the accuracy of search performances in the sharp- and gradual-edged scotoma groups. Both Hit Rates (HR, detecting a target in a target-present trial) and Correct Rejections (CR, reporting no target in a target-absent trial) of the 11 search blocks were evaluated for all 3 set sizes.

At 1 set size, HR were 0.998±0.004 and 0.993±0.004 for S-CS and G-CS groups, respectively, and CR were 0.993±0.002 and 0.996±0.002 for S-CS and

G-CS groups, respectively. There were no significant differences in search accuracy between the two groups ($F(1,10)=1.21$, $p=0.297$ for HR; $F(1,10)=0.738$, $p=0.411$ for CR).

At 8 set size, HR were 0.987±0.003 and 0.986±0.003 for the S-CS and G-CS groups respectively, and CR were 0.996±0.002 and 0.997±0.002 for the S-CS and G-CS groups respectively. The differences between groups were not significant ($F(1,10)=0.066$, $p=0.803$ for HR and $F(1,10)=0.135$, $p=0.721$ for CR).

At 32 set size, HR were 0.957±0.009 and. 0.932±.0.009 for the S-CS and G-CS groups respectively, and CR were 0.999±0.005 vs. 0.990±0.005 for the S-CS and G-CS groups, respectively. The differences between groups were not significant ($F(1.10)=3.88$, $p=0.077$ for HR and $F(1,10)=2.13$, $p=0.175$ for CR).

These results suggested that the subjects could search with great accuracy even with a simulated central scotoma, and there was no indication that different scotoma profiles had resulted in drastically different search accuracy. This was important for data analysis because focus could be placed only on search RT if search accuracy was high and consistent. It is known that speed/accuracy trade-off is often observed in visual search (Salthouse and Hedden 2002). If such a trade-off had occurred, both accuracy and speed would have to be taken into consideration when analyzing search performance. However, trade-off was not observed, and subsequent analyses of search performance were thus focused only on the RTs.

3.2. General Analysis

An Omnibus repeated measures ANOVA was conducted using SPSS 18 to assess the impact of the two types of simulated central scotoma edge profiles, Sharp-CS (S-CS) and Gradual-CS (G-CS), on normal subjects' visual search performance and their adaptation to simulated central field loss. The within-subjects variables were ADAPTATION (11 blocks) and SET SIZE (1, 8, and 32), and the between-subjects variable was SCOTOMA (S-CS vs. G-CS). Five psychophysical and oculomotor outcome measures, Reaction Times (RT), Number of Fixations, Fixation Duration, Saccadic Amplitudes and Saccadic Velocities, were analyzed separately.

These measures were analyzed and were presented in the same manner in the following subsections. Because the focus of the research was the adaptation to a simulated central scotoma and the impact of different scotoma edge profiles, the main effect of the repeated variables (ADAPTATION) and its interactions with other variables were presented and discussed first. This was followed by the analysis of the between-subjects variable, the main effect of SCOTOMA.

As described in the Method section, all outcome measures were converted into the ratio of (scotoma search)/(foveal search) individually and then normalized with a Log_{10} transform if necessary, before entering the analysis. Two foveal search controls (subsections 2.6.2 and 2.6.3) were used for RT and eye-movement measures, respectively. Scotoma search RT (subsection 3.2.1.) was divided by foveal RT using a scaled-down search stimulus, the scaling factor of which was the ratio of the peripheral and foveal recognition thresholds (subsec-

tion 2.6.2). Scotoma search oculomotor measures (Number of Fixations, Fixation Duration, Saccadic Amplitudes and Saccadic Velocities) were divided by corresponding values obtained from a foveal search that used the same search area and the same stimulus size as scotoma search. The Mauchly's test showed that the sphericity hypothesis was rejected ($p<0.0005$) for all variables tested. The Greenhouse-Geisser correction (Qiu, Jin et al. 2007) was thus used to refine the numerator in the degrees of freedom (df), and assess statistical significance.

3.2.1. Reaction Time

As explained in the Method section, RTs collected with a simulated central scotoma were divided by the RTs of the same subject searching with the fovea over a scaled down search stimulus **(Fig 2.7b** in Methods section**)**. The result, referred to hereafter as Q, was the proportional lengthening of scotoma search relative to foveal search. The data was then corrected by a logarithmic transform before being entered in the analysis. Subsequently, RT in this section refers to this proportional Q.

3.2.1.1. Adaptation effect

The main effect of ADAPTATION was highly significant ($F(7.44, 349) = 384.76$, $p<0.0005$) which indicated that significant adaption to the simulated central scotoma occurred in normally-sighted subjects performing visual search tasks regardless of the scotoma edge profile, search set size and search trial type. The interaction ADAPTATION * SCOTOMA was also significant (F(11.43,

349) =17.81, p<0.0005) indicating the adaptation process was significantly different between the S-CS and G-CS groups, as seen in **Figure 3.1.**

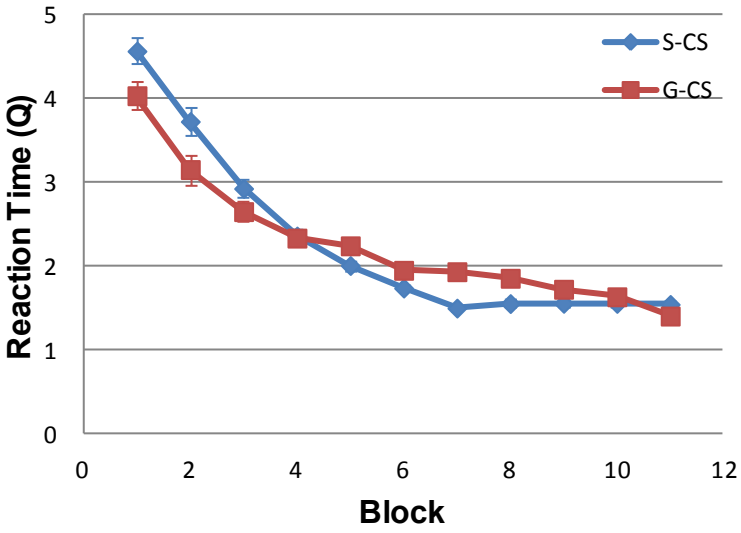

Figure 3.1. Reaction Time adaptation time course for the Sharp-CS (S-CS) and Gradual-CS (G-CS) edge profile groups . Blue diamonds are data points from the S-CS group, and red squares are data points from the G-CS group.

The S-CS group started with a significantly larger RT impairment (F(1,544)=18.44, p=0.0005), underwent a quick RT improvement, and settled down after about 7 blocks. The RT improvement seen in the G-CS group was more gradual and did not show a clear saturation at the 11th block. Over the 11-block adaptation, RT was reduced from 4.57 and 4.04 times of foveal search RT to 1.55 and 1.41 times in the S-CS and G-CS groups, respectively. The interaction of ADAPTATION * SETSIZE was significant (F(16.37, 8909)=2.56, p=0.001) indicating the adaptation process was significantly different among the 3 set siz-

es tested, as seen in **Figure 3.2.**

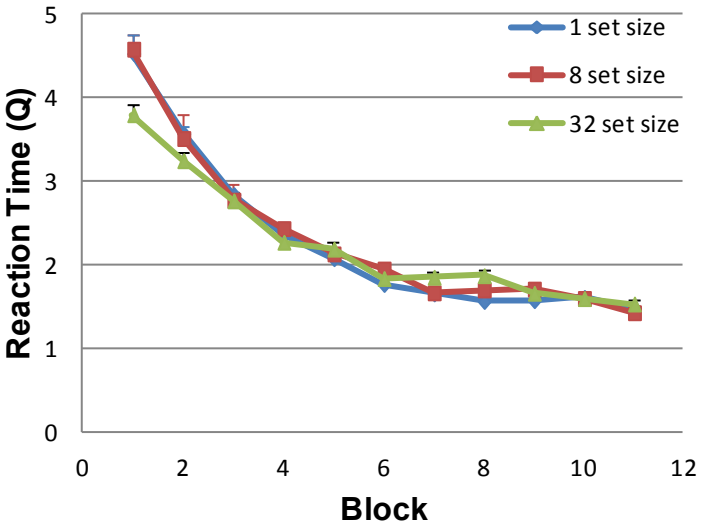

Figure 3.2. Reaction Time adaptation time course for the 3 set size conditions. Blue diamonds,red squares and green triangles are from the 1, 8, and 32 set size conditions, respectively.

Averaged across scotoma type, the improvement in RT for all 3 set sizes saturated at about the 7-9th block, with slight improvements still seen up to the last block in the 8 and 32 set sizes. The 8 set size condition had the largest RT improvement, from 4.58 times of foveal search time to 1.43 times, and the 32 set size the smallest, from 3.80 times of foveal search time to 1.53 times. A pairwise comparison (Bonferroni corrected) showed the adaptation time course was significantly different between the 32 set size and 1 or 8 set size conditions ($p=0.031$; $p=0.0005$, respectively).

The interaction ADAPTATION * SCOTOMA * SETSIZE was significant ($F(16.38, 8909) = 3.70$, $p<0.0005$) suggesting the set size effect was significantly different between the two scotoma groups. Further analysis of the S-CS group (ADAPTATION * SETSIZE), found significant differences in adaptation improve-

ments among the three set sizes (F(15.25, 4362)=3.39, p<0.0005.

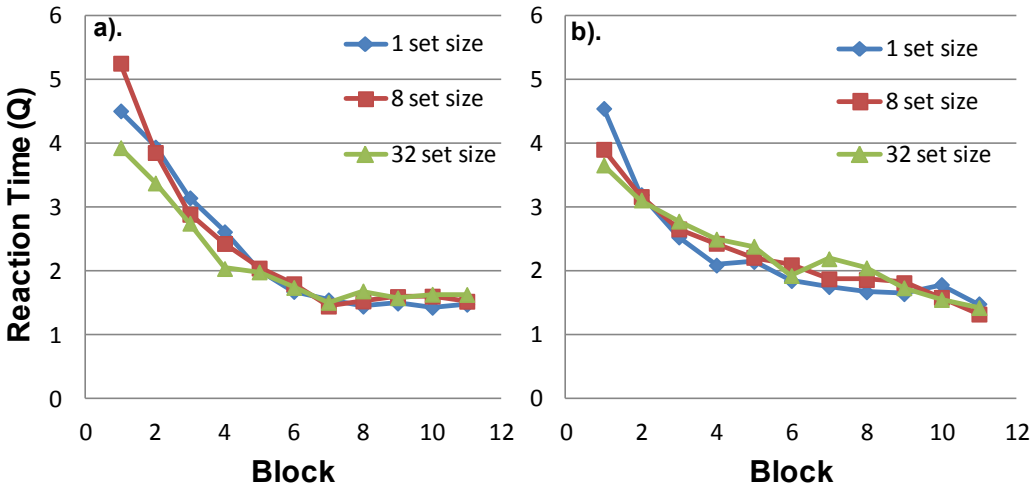

Figure 3.3. Reaction Time set size effect adaptation time course for (a)Sharp-CS and (b)Gradual-CS. Blue diamonds, red squares and green triangles are data points for the 1, 8 and 32 set sizes respectively.

Performance saturation in all set sizes appeared to occur about blocks 7-8, with the 8 set size condition having the largest improvement, 5.26 times of foveal search to 1.53 times (**Figure 3.3a**). In the G-CS group, the ADAPTATION * SETSIZE interaction was also significant (F(16.06, 4144)=2.85, p<0.0005). The 1 set size condition appeared to saturate about block 9 whereas continuous improvement was seen in the other two set sizes. The 1 set size condition had the largest improvement in performance, from 4.55 times of foveal search to 1.48 times as seen in **Figure 3.3b.**

Finally, the main effect (ADAPTATION) was analyzed separately in both scotoma groups to determine if significant adaptation had occurred over the 11-block search training. The trial responses (positive and negative) and set sizes (1, 8 and 32) were analyzed individually, and in all twelve analyses the main effect was highly significant, F=9.53 to 115.36, p<0.0005. This indicated that no

matter the type of response or set size, performance with both scotoma edge profiles exhibited significant adaptation over the 11-block training (see **Appendix D** for all figures)

3.2.1.2. Scotoma effect

The between-subjects variable SCOTOMA was analyzed with the 11 adaptation blocks averaged. The main effect was significant ($F(1, 544) = 4.09$, $p<0.044$), which indicated that the RTs of the two types of scotomas were different regardless the trial type and set size of the stimulus.

3.2.1.3. Halftime adaptation

To quantify the rates of adaptation of the two groups, the RT data were fitted with power functions and the halftime RT improvement ($t_{½}$) was calculated, as specified in the Method section. The grand average of the number of blocks that reduced the initial search RT deficit by half over all subjects, all response types, and all set sizes was 4.96 blocks. The $t_{½}$ were 4.45 and 5.63 blocks for the S-CS and G-CS groups, respectively (regardless of set size and response types). Therefore, the G-CS group adapted more slowly, reaching half of the initial RT at least 1 block longer than the S-CS group (**see APPENDIX E)**

The best-fitting power parameters, τ and $t_{½}$, and the percentage of data variance explained by the curve fitting (R^2) for all permutations of group, set size

and response types were summarized in **Table 3.1.**

Table 3.1. Power function values for both scotoma edge profiles.

Set Size		HITS		Correct Rejections	
		S-CS	G-CS	S-CS	G-CS
1	τ	0.58	0.49	0.36	0.32
	$t_{1/2}$	3.28	4.07	6.79	8.55
	R^2	0.93	0.97	0.92	0.92
8	τ	0.59	0.41	0.41	0.41
	$t_{1/2}$	3.22	5.54	5.40	5.40
	R^2	0.93	0.99	0.93	0.88
32	τ	0.49	0.45	0.31	0.29
	$t_{1/2}$	4.10	4.71	9.16	10.83
	R^2	0.89	0.95	0.82	0.77

$t_{1/2}$=half-time measure of adaptation; R^2=percentage of the data variance explained by the power fitting function.

Among the two scotoma groups, the S-CS group had the shortest $t_{½}$ of 3.22 blocks (8 set size, HITS trials), whereas the longest $t_{½}$ was found in the G-CS edge group (10.83 blocks; 32 set size, CR trials). The high R^2 values indicate that the power function was an excellent fit for most of the RT adaptation functions. In the few cases where the fits were not as good, for example, the correct rejection trials for the G-CS group under 8 and 32 set size conditions, the adaptation functions were closer to straight lines than power function curves. A two-line-segment fit would have described the data of these few cases better than a power function fit and might have resulted in even longer $t_{½}$. However, the two-line-segment fit would not be good for most of conditions.

3.2.1.4. Correlation Analysis

To obtain a global view of the interactions among the 5 search performance outcome measures, an Omnibus trial by trial correlation analyses was performed (**Table 3.2)**. Prior to analyses**,** a Kolmogorov-Smirnov test for normality was conducted and was highly significant ($p<0.0005$) for all variables tested, indicating the data were skewed. The non-parametric Spearman's ρ was thus used to quantify correlations.

Table 3.2. **Total Omnibus correlations (Spearman's Rho)**

	Reaction Time	**Number Fixations**	**Fixation Duration**	**Saccade Amplitude**	**Saccadic Velocity**
Reaction Time		.948**	-.205**	.407**	.407**
Number Fixations			-.466**	.407**	.410**
Fixation Duration				-248**	-.240**
Saccade Amplitude					.826**
Saccadic Velocity					

****** Correlation is significant at the 0.01level (2-tailed).

All correlations were highly significant ($p<0.01$). The strongest correlation was seen between RT and the number of fixations ($\rho=0.948$). This suggested that the number of fixations was probably the underlying mechanism for the observed RT changes. As RT shortened with practice, the number of fixations was reduced. Shorter RT was also associated with longer fixation duration, though the correlation was weaker ($\rho=-0.205$). RT was positively correlated with saccade amplitude ($\rho=0.407$), indicating that shorter RT might be associated with smaller saccades

and thus possibly finer control of eye movement. Finally, RT was positively correlated with saccade velocity (ρ=0.407).

Table 3.3. Group Omnibus correlations (Spearman's Rho)

		Reaction Time	Number Fixations	Fixation Duration	Saccade Amps	Saccadic Velocity
S-CS	Reaction Time		.944**	-.068**	.375**	.398**
	Number Fixations			-.349**	.377**	.387**
	Fixation Duration				-.217**	-.163**
	Saccade Amps					.873**
	Saccadic Velocity					
G-CS	Reaction Time		.953**	-.333**	.459**	.442**
	Number Fixations			-.568**	.457**	.458**
	Fixation Duration				-.305**	-.345**
	Saccade Amps					.777**
	Saccadic Velocity					

** Correlation is significant at the 0.01 level (2-tailed).

Correlation analyses were also performed for the S-CS and G-CS groups separately (**Table 3.3).** Again, all correlations were highly significant ($p<0.01$). The highest correlations observed in both groups were between RT and number of fixations (ρ=0.944 and 0.953 for the S-CS and G-CS groups, respectively). The variable that correlated least with RT and showed the largest differences between the two groups was Fixation Duration (ρ=-0.068 and -0.333 for S-CS and

G-CS, respectively). A Fisher's r to z transformation was performed to test the significance of the difference between the two ρ's of the two group (Kendall and Stuart 1973; Press, Vettering et al. 1992). A significant difference was found ($z = 20.14$, $p < 0.0005$, two-tailed), which indicated that the correlation between RT and fixation duration was stronger in the G-CS group than in the S-CS group.

The significance of these trial-by-trial correlations may be inflated by including the large number of trials from each subject. An examination of correlations on a session-by-session basis was performed and similar results were obtained **(**see **Appendix F).** The session-by-session analysis indicates that the trial-by-trial correlations were not artifacts.

Finally, because of the very high correlations between RT and number of fixations, a full analysis of the number of fixations would be redundant to the RT analysis. However, the change of the number of fixations was likely to be the underlying mechanism for the observed initial impact and subsequent adaptation to a simulated scotoma, and will be further elaborated in the Discussion section.

3.2.2. Fixation Duration

3.2.2.1. Adaptation effect

The main effect (ADAPTATION) was significant, $F(8.41, 4574) = 22.65$, $p < 0.0005$, which indicated that shortening of fixation duration occurred during practice regardless of scotoma edge profile, set sizes or response types. The interaction ADAPTATION * SCOTOMA was significant ($F(8.41, 4574) = 6.88$, $p < 0.0005$) indicating that fixation duration underwent different changes in the two

groups during adaptation (**Figure 3.4).**

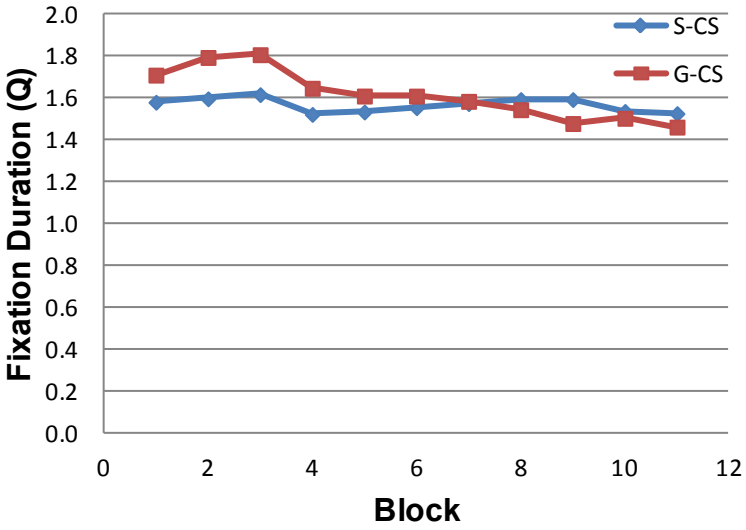

Figure 3.4. Fixation Duration adaptation time course for the Sharp-CS (S-CS) and Gradual-CS (G-CS) edge profile groups. Blue diamonds are data points from the S-CS group, and red squares are data points from the G-CS group.

It appeared that fixation duration hardly changed throughout the adaptation in the S-CS group, but underwent a steady reduction after the first three practice blocks in the G-CS group. Fixation Duration reduced from 1.57 and 1.71 times of foveal fixation duration to 1.53 and 1.46 times in the S- CS and G-CS groups, respectively.

The ADAPTATION * SET SIZE interaction was significant ($F(16.14, 8781)=6.12$, $P<0.0005$). While fixation duration was in general shortened with adaptation to scotoma, different set sizes appeared to have different time cours-

es **(Figure 3.5)**

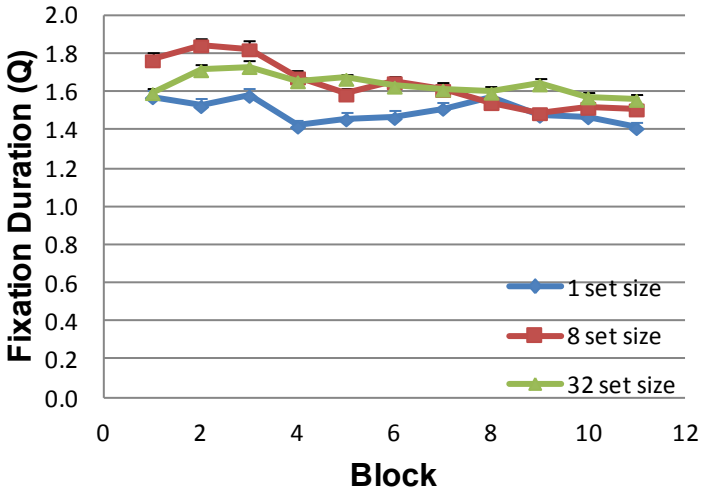

Figure 3.5. Fixation Duration adaptation time course for the 3 set size conditions. Blue diamonds, red squares and green triangles are from the 1, 8, and 32 set size conditions, respectively.

There was hardly any change in fixation duration when there was only 1 search item. Some reduction occurred after 3 blocks of practice with 8 and 32 set sizes. The largest fixation duration change was found in the 8 set size condition, from 1.75 times foveal fixation duration to 1.51 times**.**

The interaction ADAPTATION * SCOTOMA * SETSIZE was significant ($F(16.14, 8781) = 3.96$, $p<0.0005$), suggesting that fixation duration adaptation changes among the three set sizes were significantly different between the two scotoma edge profiles. Further analysis (ADAPTATION * SETSIZE) in the S-CS group comparing fixation durations at different set sizes was significant (F 14.07, 4025) =8.12, $p<0.0005$).

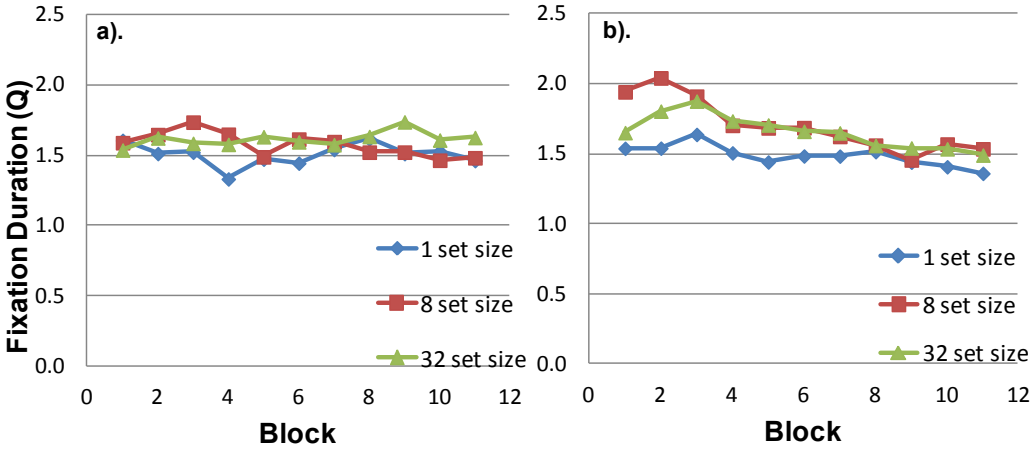

Figure 3.6. Fixation Duration set size effect adaptation time course for (a) Sharp-CS and (b) Gradual-CS. Blue diamonds, red squares and green triangles are data points for the 1, 8 and 32 set sizes respectively.

In all three set size conditions, fixation duration exhibited small changes during adaptation, with equally large changes in performances in the 1 and 8 set size conditions, 1.59 times of foveal fixation duration to 1.45 times (**Figure 3.6a**). In the G-CS group, ADAPTATION * SET SIZE was also significant ($F(16.11, 4157) = 3.01$, $p<0.0005$)**.** There was no definitive saturation point observed in any of the 3 set sizes**,** with the largest change in the adaptation process seen in the 8 set size condition, from 1.94 times of foveal fixation duration to 1.53 times, as seen in **Figure 3.6b.**

3.2.2.2. Scotoma effect

The SCOTOMA main effect was not significant ($F(1, 544) = 1.33$, $p=0.249$). Averaging over the large adaptation changes might have concealed the effect of scotoma on fixation duration.

3.2.3. Saccade Amplitudes

3.2.3.1. Adaptation effect

The main effect (ADAPTATION) was significant, $F(9.15, 5002) = 70.88$, $p<0.0005$, indicating that saccade amplitude was significantly shortened during adaption to a central scotoma, regardless of the scotoma edge profile, set size or response. The interaction ADAPTATION * SCOTOMA was significant, $F(9.15, 5002) = 12.26$, $p<0.0005$. While the saccade amplitude was getting shorter steadily with practice for the S-CS group, it did not appear to change systematically for the G-CS group, except in the first two blocks (**Figure 3.7).**

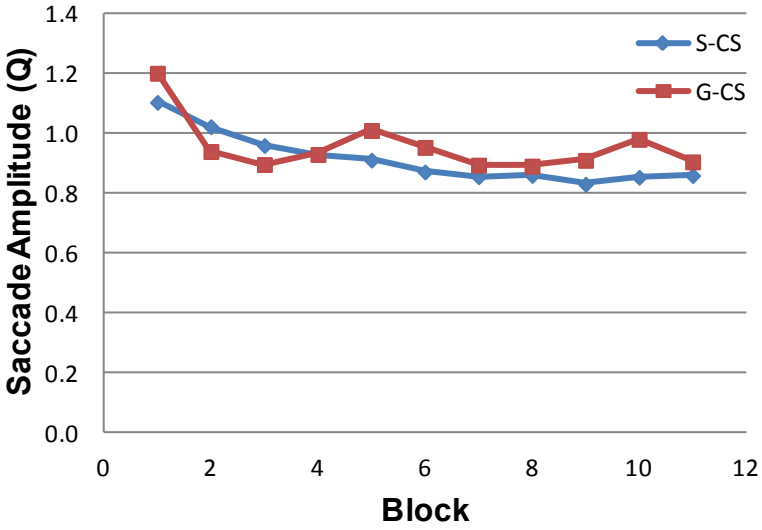

Figure 3.7. Saccade Amplitude adaptation time course for the Sharp-CS (S-CS) and Gradual-CS (G-CS) edge profile groups. Blue diamonds are data points from the S-CS group, and red squares are data points from the G-CS group.

The ADAPTATION * SETSIZE interaction was significant, ($F(14.31,7784)=6.16$, $p<0.0005$). The smaller set sizes appeared to undergo larger reduction than larger set sizes (1.15 to 0.80 times of foveal saccade ampli-

tudes for 1 set size and 1.17 to 0.99 times for 32 set sizes) (**Figure 3.8).**

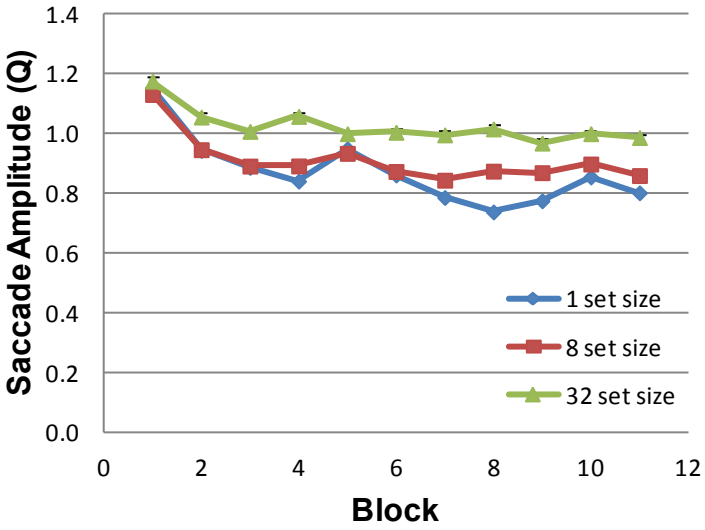

Figure 3.8. Saccade Amplitude adaptation time course for the 3 set size conditions. Blue diamonds, red squares and green triangles are from the 1, 8, and 32 set size conditions, respectively.

The interactions of ADAPTATION * SCOTOMA * SETSIZE were significant, $F(14.33, 7784) = 6.77$, $p<0.0005$. In the S-CS group, the three set sizes started with different saccade amplitudes and smaller set sizes appeared to undergo faster shortening with practice. In comparison, saccade amplitude of the G-CS group did not appear to show significant changes throughout the adapta-

tion, with the exception of probably the first two blocks (**Figure 3.9a).**

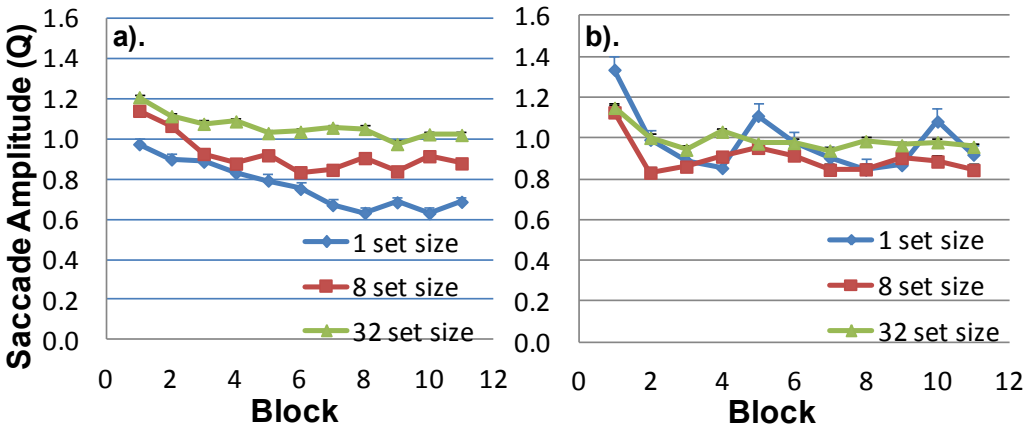

Figure 3.9. Saccade Amplitude size effect adaptation time course for (a) Sharp-CS and (b) Gradual-CS . Blue diamonds, red squares and green triangles are data points for the 1, 8 and 32 set sizes respectively.

The interaction ADAPTATION * SET SIZE, in the S-CS group was significant ($F(13.68, 3911) = 8.60$, $p<0.0005$). Performance saturation in all three set sizes occurred about block 6-9 as seen in **Figure 3.9a.** The largest performance change was seen in the 1 set size condition, 0.96 times foveal performance to 0.69 times. In the G-CS condition, the interaction ADAPTATION * SETSIZE was also significant between the set sizes ($F(13.19, 3402) = 5.26$, $p< 0.0005$). Compared to the S-CS group, performance saturation in all 3 set sizes took fewer blocks of trials to occur, occurring about block 2-4. However more oscillations were seen in the 1 set size condition than in the other two set size conditions as seen in **Figure 3.9b.** As seen in the S-CS group, the largest improvement was also in the 1 set size condition, from 1.33 times foveal performance to 0.91 times.

3.2.3.2. Scotoma effect

The main effects of SCOTOMA **(**F(1, 544) =3.96, p=0.047) was significant, with the S-CS group and 1 set size condition having the smallest average saccade amplitudes over the 11 blocks. In general, scotoma search saccade amplitude started slightly larger or equal to foveal search saccade amplitude, and either quickly approached and remained at the foveal search values, or became shorter than foveal search values with practice.

3.2.4. Saccadic Velocities

3.2.4.1. Adaptation effect

The main effect (ADAPTATION) was significant, F(9.26, 5040) = 84.12, p<0.0005, indicating that saccadic velocities (SV) significantly changed during adaption regardless of scotoma edge profile, set size or response. The interaction ADAPTATION*SCOTOMA was significant (F(9.26, 5040) =6.54, p<0.0005) indicating that during the adaptation process the saccadic velocity changes in the S-CS and G-CS groups were significantly different as seen in **Figure 3.10.**

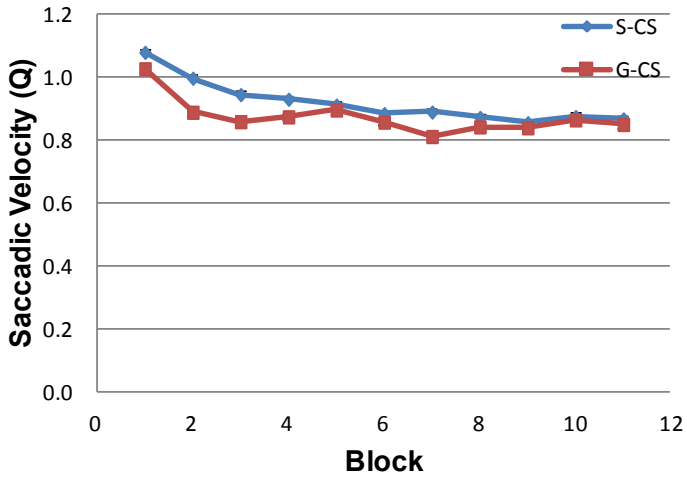

Figure 3.10. Saccadic Velocity adaptation time course for the Sharp-CS (S-CS) and Gradual-CS (G-CS) edge profile groups. Blue diamonds are data points from the S-CS group, and red squares are data points from the G-CS group.

By the second block of adaptation, both groups' saccadic velocity performance was smaller than the foveal search performance. However, as also seen in saccadic amplitudes, the G-CS group performance oscillated more during the 11 blocks of adaptation. The changes in performance between the scotoma edge profiles were similar, with the the S-CS group having a slightly larger change in performance, from 1.08 times of foveal performance to 0.87 times.

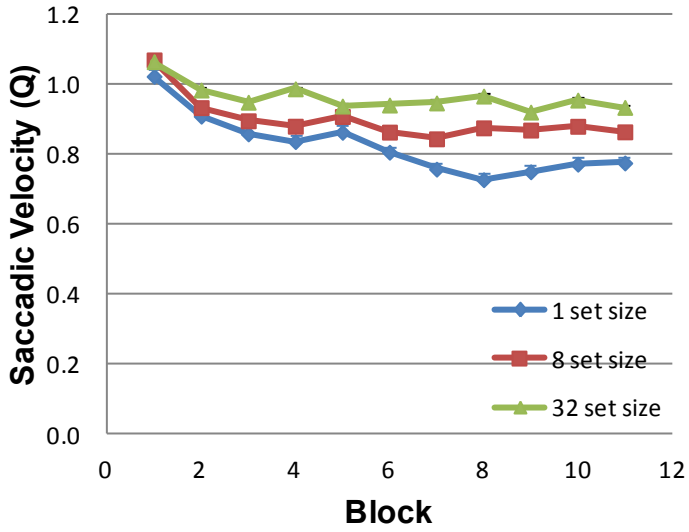

Figure 3.11.Saccadic Velocity adaptation time course for the 3 set size conditions. Blue diamonds, red squares and green triangles are from the 1, 8, and 32 set size conditions, respectively.

The ADAPTATION * SET SIZE interaction was significant ($F(15.40,8378)=9.40$, $p<0.0005$) indicating that during adaptation the saccadic velocities among the 3 set size conditions were significantly different as seen in **Figure 3.11.** The 8 and 32 set size appeared to saturate about block 4, whereas the 1 set size saturated about block eight. The 1 set size condition had the largest decrease in velocity performance,1.02 times of foveal saccadic velocity to 0.76 times, and the 32 set size condition had the least decrease,1.07 times the foveal saccadic velocity to 0.94 times**.**

The interaction of ADAPTATION * SCOTOMA * SETSIZE was significant, $F(15.40, 8378) = 4.44$, $p<0.0005$, indicating the set size performances were significantly different between the scotoma edge profile groups during saccadic velocity changes. Further analysis in the S-CS group indicated ADAPTATION * SET SIZE was significant between the set sizes, ($F(13.11, 3750) =9.18$,

p<0.0005). Performance saturation in the 8 and 32 set sizes occurred about block 6, whereas in the 1 set size condition saturation was seen about block 8 **(Figure 3.12a)**.

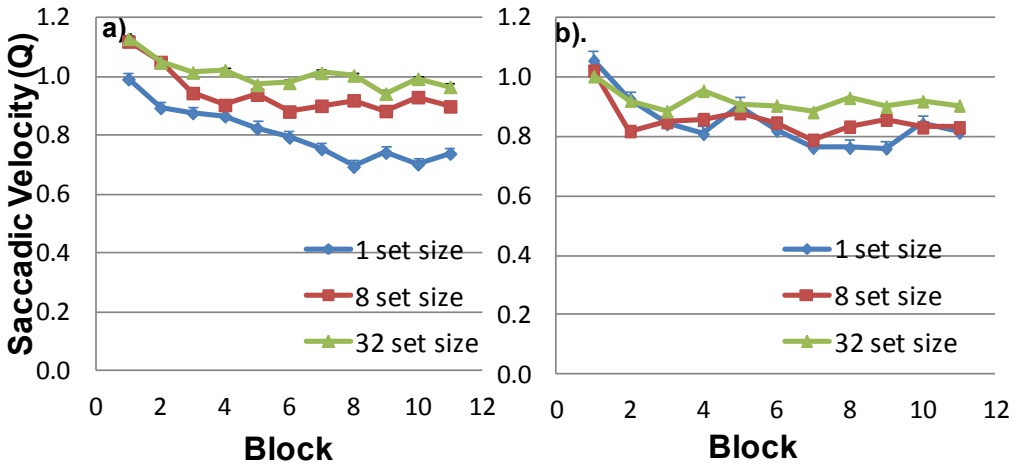

Figure 3.12. Set size effect adaptation timecourse for (a) Sharp-CS and (b) Gradual-CS. Blue diamonds, red squares and green triangles are data points for the 1,8 and 32 set sizes respectively.

The largest saccadic velocity performance change was seen in the 1 set size condition, from 0.99 times foveal performance to 0.73 times. In the G-CS condition, ADAPTATION * SET SIZE was also significant between the set sizes ($F(15.24, 3932)=5.41$ $p< 0.0005$). Performance saturation in all three set size conditions occurred about blocks 2-4 as seen in **Figure 3.12b.** As seen in the S-CS group, the largest improvement was also in the 1 set size condition, 1.05 times foveal velocity to 0.81 times.

3.2.4.2. Scotoma effect

The main effect of SCOTOMA, $F(1, 544) = 19.91, p < 0.0005$, was significant, with the G-CS group and 1 set size condition having the slowest saccadic velocity averages over the 11 blocks.

In general, saccade velocity for scotoma search was slightly faster than or equal to that of foveal search when the subject was first exposed to the scotoma. Adaptation to the scotoma resulted in saccade velocity that was slower than foveal search velocity. This might be related to the smaller saccade amplitude observed after adaptation, because the saccade amplitude and velocity were highly correlated (0.826, **Table 3.2).**

3.2.5. General Analysis Summary

In all outcome measures analyzed (Reaction Time, Fixation Duration, Saccadic Amplitude, and Saccadic Velocity), the ADAPTATION main effects were statistically significant. This indicated that regardless of scotoma types, set sizes, or response types, significant performance changes had occurred during the 11-block adaptation to the visual search tasks.

The interactions involving RT as the outcome measure were significant, which indicated that the stimulus and response factors, such as the scotoma types, set sizes and response types, all profoundly affected the process of adaptation. In particular, the significant ADAPATATION*SCOTOMA interaction showed that different types of scotoma profiles might result in a different time course of adaptation.

The oculomotor outcome measure that correlated best with the psychophysical outcome measure (RT) was the number of fixations. This was true and to the same magnitude for both scotoma edge profiles. This suggested that the change in the number fixations made in a search trial could account for the majority of the initial impact of a simulated scotoma and the subsequent recovery of search performance. Fixation duration, on the other hand, only weakly (but significantly**)** correlates with RT. Saccade parameters also correlated with RT, indicating possible search strategy changes.

3.3. Special Analyses

The following special analyses further addressed various perceptual, attentional and oculomotor behaviors during adaptation to simulated central scotomas.

3.3.1. Search efficiency

Search efficiency is typically quantified by the slope of the curve in a RT vs. set size plot. This slope represents the additional time needed to process each additional item in the search stimulus. A repeated measures ANOVA was performed to assess the impact of the 11-block search training and the two simulated central scotoma edge profiles on the slope of the line fitted to the data obtained at 1, 8 and 32 set sizes. The within-subjects variables were ADAPTATION (11 blocks) and RESPONSE (hit and CR), and the between-subjects variable was SCOTOMA (S-SC and G-CS). Linear regression was first performed on individual data to obtain the slopes (β) and the y-intercepts (α) of the best fitting

lines. Then β and α were entered in the analysis separately. The Mauchly test of sphericity was significant ($p<0.05$) in all analyses except the slopes ADAPTATION * RESPONSE interaction ($p=0.064$). If sphericity was significant, the Greenhouse –Geisser statistic was used in the analyses.

3.3.2.1 Slopes (β): Adaptation effect

The within subject main effect of ADAPTATION was significant ($F(4.07, 40.79) =9.46$, $p<0.005$), indicating that the slope became shallower with practice with a simulated central scotoma. In the visual search literature, this tendency of decreasing RT/Set Size slope is known as automaticity (Schneider and Shriffin 1977). The interaction ADAPTATION * RESPONSE was significant ($F(10,100)=2.55$, $p=0.009$), indicating different slope adaptation change time

courses for positive and negative trials (**Figure 3.13)**.

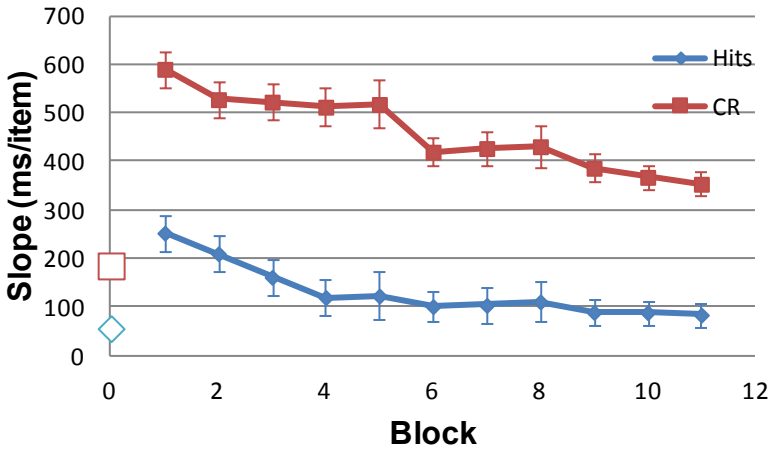

Figure 3.13. Slope adaptation time course for the two response conditions. Blue diamonds and red squares are data points from the Hits (target present) and Correction Rejection (target absent) trials, respectively.. The open blue diamond and red square (Block 0) represent the foveal slopes for the Hits and CRs, respectively.

.

The interactions ADAPTATION * SCOTOMA, and ADAPTATION * SCOTOMA * RESPONSE were not significant,($F(4.08,40.79)= 1.41$, $p=0.256$; $F(3.59, 35.88)= 1.09$, $p=0.374$, respectively), indicating that automaticity followed a similar time course with different scotoma profiles for the different response types.

3.3.2.2. Slopes (β): Scotoma effect

The SCOTOMA main between-subject effect was not significant ($F(1,10)=.029$, $p=0.869$), indicating that, when averaged, the overall RT/Set Size slopes were not different between the two scotoma groups.

3.3.2.3. Y-intercepts (α): Adaptation effect

The ADAPATION main effect was significant ($F(2.43, 24.32) = 5.57$, $p=0.007$), indicating the vertical position of the best fitting lines was significantly lowered with practice regardless of scotoma edge profile type or trial type. The interactions ADAPTATION * SCOTOMA, ADAPTATION* RESPONSE and ADAPTATION * SCOTOMA * RESPONSE were not significant,($F(2.43, 24.32) = .077$, $p=0.952$; $F(3.22, 32.25)=0.586$, $p=0.641$ and $F(3.22,32.25)=1.08$, $p=0.378$, respectively), indicating the process of the best fitting lines moving toward the foveal performance was not affected by scotoma edge profiles or response types.

3.3.2.4. Y-intercepts (α): Scotoma effect

The main effect of SCOTOMA was not significant, ($F(1, 10) = .858$, $p=0.376$), indicating when all 11 adaptation blocks were averaged, the mean y-intercepts of the two scotoma types and the two response types were similar.

3.3.2.5. Search Efficiency Summary

Significant search efficiency changes, regardless of scotoma edge profile or response trial type, were observed. There were shown as decreasing slopes and y-intercepts of the RT vs Set Size curves toward the foveal search curve dur-

ing the 11 blocks of adaptation (**Figure 3.14).**

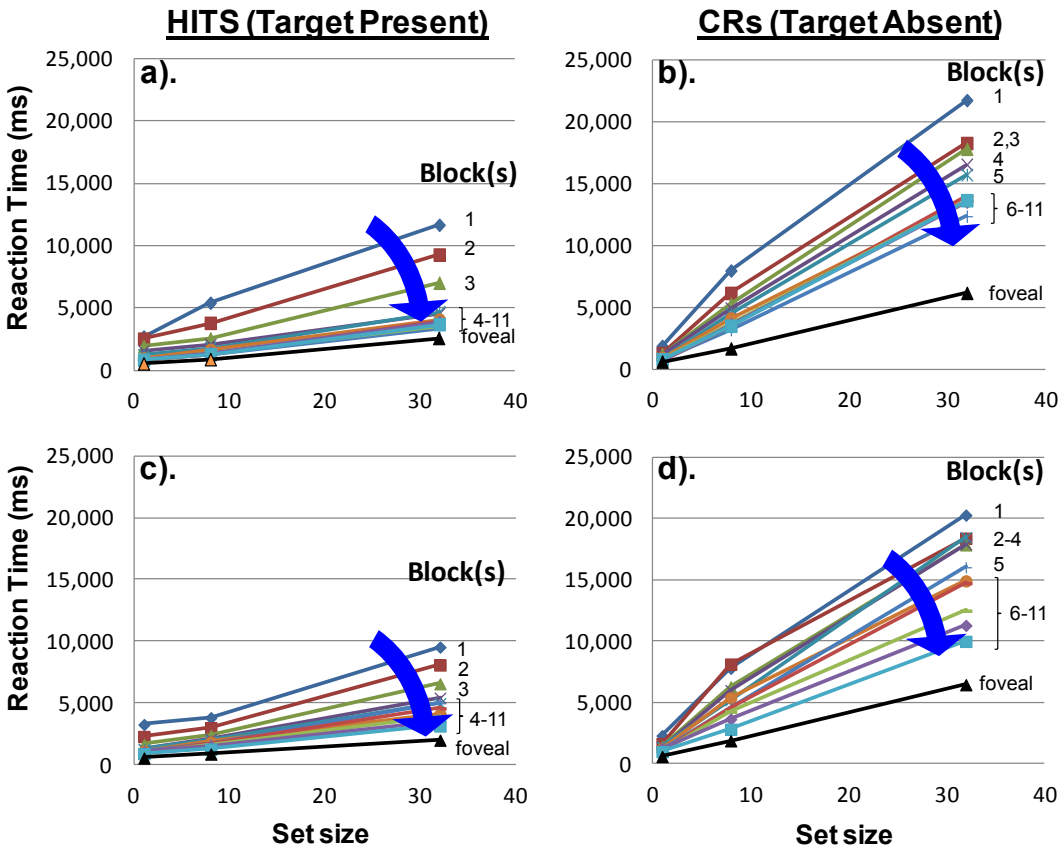

Figure 3.14. RT x Set Size search efficiency slopes of the 11 blocks of adaptation. Top figures are the S-CS group (a) HITS and (b) CRs, whereas bottom figures are the G-CS group (c) HITS and (d) CRs.

3.3.3. Last Fixation

The last fixations of subjects from each scotoma group were analyzed in correct target-present trials (hits). The purpose was to determine the retinal location each subject used when the search target was found, assuming that the subject pressed the response key immediately after the target was detected. As explained in the Methods section, the last fixation positions relative to the target positions in each search session were summarized in a scatter plot. The entire area

of this scatter plot was divided into 5 areas, one central and 4 peripheral. The numbers of last fixations falling into each of these areas were tallied and scaled to make them comparable. A one-way ANOVA was then performed on the proportions of last fixations falling into these 5 areas for each experimental session. The null hypothesis was that the probability of the last fixation falling in any one of the 5 areas was equal. If H_0 could not be rejected, evidence existed that last fixations were randomly distributed over the entire search field. If the H_0 was rejected, the distribution was not random and clustering of last fixations occurred in one or more of the area. For these distributions, planned comparisons (contrasts) were conducted to determine which specific area or a combination of areas had a significantly higher proportion of last fixations.

This analysis was applied to the distributions of last fixations in all 3 set sizes (1, 8, 32) for each subject in the first 3 and last 3 blocks of trials. Consequently, the numbers of subjects in each group whose last fixation distributions allowed rejection of the null hypothesis were reported.

3.3.3.1. Initial Blocks (one-way ANOVA)

The three set size conditions were analyzed separately (**Table 3.4a**).

Table 3.4. One-way ANOVA between-area analysis of (a) Initial and (b) Final Blocks in each set size. Numbers and percentages represent statistical significance (<0.05) seen in each group.

a.)

Group \ Set Size	**1 set size**	**8 set size**	**32 set size**
S-CS	3 (50%)	5 (83%)	6 (100%)
G-CS	3 (50%)	2 (33%)	2 (33%)

b.)

Group \ Set Size	**1 set size**	**8 set size**	**32 set size**
S-CS	6 (100%)	6 (100%)	6 (100%)
G-CS	6 (100%)	5 (83%)	4 (67%)

In the 1 set size condition, H_0 was rejected in three subjects (50%) in each of the S-CS and G-CS groups ($F(4,14)=4.66$ to 92.74, $p=0.022$ to <0.0005). In the 8 set size condition, H_0 was rejected in five subjects (83%) in the S-CS group ($F(4,14)=8.95$ to 261.76, $p=0.005$ to <0.0005) and in two subjects (33%) in the G-CS group ($F(4, 14) =6.47$ to 9.55, $p=0.008$ to 0.002). Finally, in the 32 set size condition, H_0 was rejected in all six subjects in the S-CS group ($F(4, 14) =9.50$ to 52.78, $p=0.002$ to <0.0005) and only in two subjects (33%) in the G-CS group ($F(4, 14) =8.74$ to 20.48, $p=0.003$ to <0.0005). This suggested that when first exposed to a simulated scotoma, last fixation distributions were not random in more members of the S-CS group than in members of the G-CS group. Last fixation distributions also tended to cluster more in the S-CS group with increasing set size (see **APPENDIX G** for all subjects' plots).

3.3.3.2 Final Blocks (one-way ANOVA)

As in the initial block, the 3 set size conditions were analyzed separately (**Table 3.4b**). In the 1 set size condition, H_0 was rejected in all subjects in both the S-CS and G-CS groups (F(4, 14)= 6.76 to 80.08,p=0.007 to <0.0005). In the 8 set size condition, H_0 was rejected in all subjects in the S-CS group (F(4, 14) 9.82 to 230.35, p=0.002 to < 0 0005) and in five subjects (83%) in the G-CS group (F(4,14)=11.36 to 64.56, p=0.001 to<0.0005). Finally, in the 32 set size condition, H_0 was rejected in all subjects in the S-CS group (F(4, 14)= 8.07 to 46.32 ,p=0.004 to <0.0005) and in four subjects (67%) in the G-CS group (F(4, 14)=6.61 to 54.07, p=0.007 to <0.0005). This result suggests that a greater number of subjects had last fixation distributions that were not random after practicing with a simulated scotoma, and that the S-CS group had more subjects with clustered last fixation distributions than the G-CS group. Further analyses on these subjects were conducted to determine the cluster patterns.

3.3.3.3. Planned Comparisons (Contrasts)

Planned comparisons (contrasts) were performed only on distributions that were not random as identified by the one-way ANOVA. At minimum, one level of contrast was performed in all cases:

(a) Central 10.0 deg area (0) vs four peripheral areas (I, II, III and IV).

H_0: Central area (0) = Areas I, II, III, IV

(b). Four peripheral areas divided into 2 hemispheres: Superior vs Inferior hemifield and Left vs Right hemifield.

H_0 (1): Areas I & II (Superior) = Areas III & IV (Inferior)

H_0 (2): Areas II & III (Left) = Areas I & IV (Right)

If(a) indicated a significantly higher central area concentration of last fixations, and (b) did not indicate any significant difference among hemifields no further analysis was performed as this indicated a distribution with high concentration of last fixations in the central area.

If (a) indicated a significantly lower central area concentration of last fixations, then hemifield(s) and quadrant analyses were performed to determine if there was a significantly higher last fixation concentration in a hemifield or a quadrant.

If (a) indicated a significantly higher central area concentration of last fixations, and (b) also indicated difference among hemifield(s), then further quadrant analyses were performed. If a quadrant was found to have significantly higher concentration of last fixation than others, a final contrast was conducted between this quadrant and the central area.

Table 3.5.Initial Blocks last fixation distributions in the 3 set sizes of the S-CS and G-CS groups.

Set Size		1 SET SIZE			8 SET SIZE			32 SET SIZE		
Area / Group/subj		Center	Quadrant	RD	Center	Quadrant	RD	Center	Quadrant	RD
S-CS	1	X			X			X		
	2	X			X			X		
	3			X	X	II		X		
	4	X			X			X		
	5			X			X	X		
	6			X	X			X		
G-CS	7			X			X			X
	8		I& II (Sup)			I&II (Sup)			II	
	9			X			X	X		
	10	X	II			II				X
	11	X	III				X			X
	12			X			X			X

RD =Random Distribution

3.3.3.4 Initial Blocks

Results of the contrast analyses on the initial block were summarized in **Table 3.5.** In the 1 set size condition, three subjects in the S-CS group had significantly higher last fixation concentration in the center (t(10)=4.28 to 19.25, p=0.002 to <0.0005)**.** The remaining 3 subjects had a random distribution of last fixations, as identified by a non-significant one-way ANOVA. In the G-CS group, higher last fixation concentration was found in one subject in the superior hemifield (t(10)=5.52, p=<0.0005), one subject in quadrant II (t(10)=-3.65, p=0.004), and one subject in the center and quadrant III (t(10)=3.00 to 3.40,

p=0.013 to 0.007). The other three subjects had random distributions, as identified by non-significant one-way ANOVA.

In the 8 set size condition, four of the six subjects in the S-CS group had significantly higher last fixation concentration in the center ($t(10)=6.34$ to 32.33, $p<0.0005$). One subject had a higher last fixation concentration in both the center and quadrant II ($t(10)=3.22$ to 3.55, $p=0.009$ to 0.005). The other subject had random distribution, as identified by a non-significant one-way ANOVA. In the G-CS group, a significantly higher number of last fixations was found for one subject in the superior hemifield ($t(10)$ 3.54, $p= 0.005$) and for another subject in quadrant II ($t(10)=-2.74$, $p=0.021$). The remaining four subjects had random distributions.

Finally, in the 32 set size condition, all subjects in the S-CS group had significantly higher last-fixation concentration in the center ($t(10)=5.40$ to 14.52, $p<0.0005$). In the G-CS group, a higher concentration was found in one subject in the center ($t(10)=5.91, p<0.0005$) and in one subject in quadrant II ($t(10)=5.80$ $p<0.0005$). The remaining four subjects had random distributions.

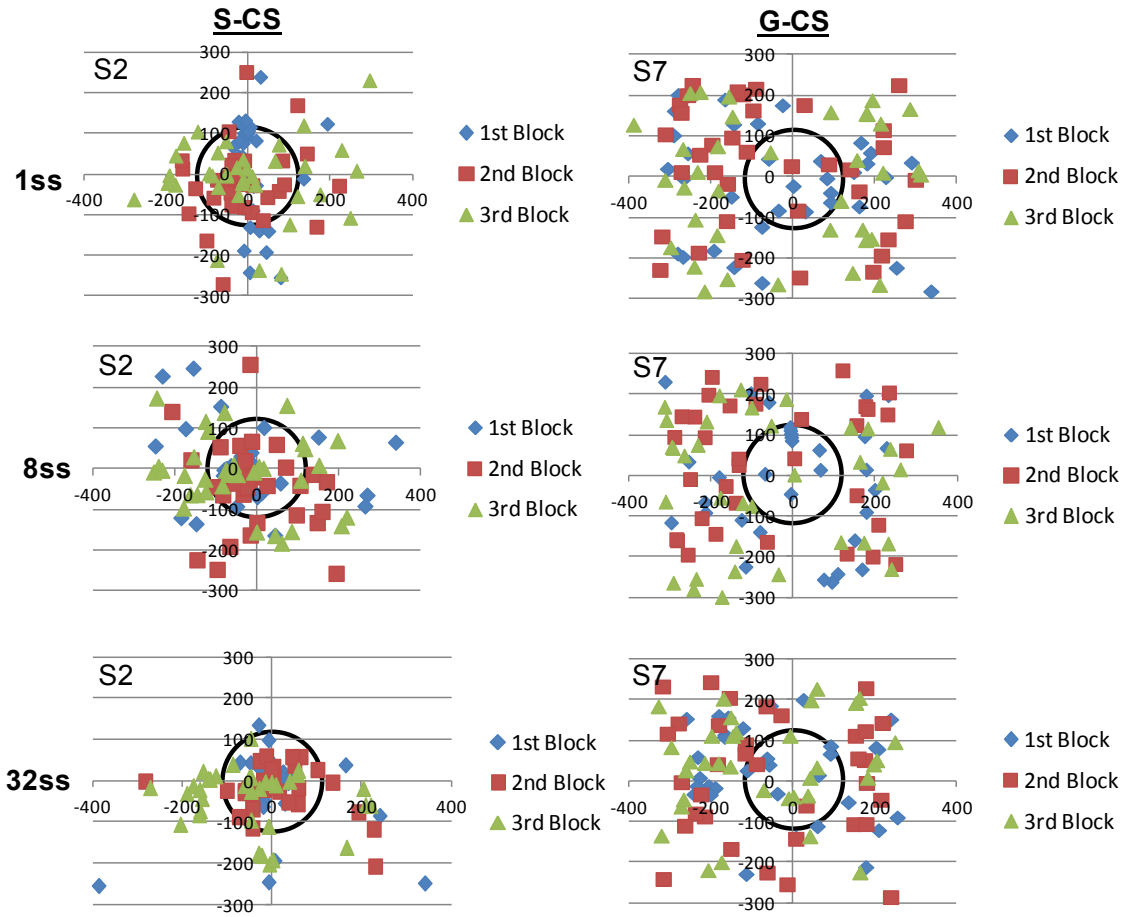

Figure 3.15. Representative last fixation examples from Subject 2 (Lt column:S-CS) and Subject 7 (Rt column:G-CS) in the Initial blocks stages. The plots are from each set size condition (1, 8, 32 set sizes). The blue diamond,red square, and green triangle represent the 1st,2nd, and 3rd blocks of adaptation, respectively.

In summary**,** in all 3 set size conditions **(Figure 3.15),** the area that had the highest last fixation concentration was the center (Area 0) in the S-CS group, indicating that a large portion of last fixations landed within a 10 degree diameter circular area around the target. Because the fixation was also the center of the simulated scotoma, this result indicated that there was a tendency for the subjects of the S-CS group to move the fovea toward the target when the presence

of the target was reported. In other words, these subjects tended to “foveate” the target. As the set size increased, the tendency of foveating the target increased. However, in the G-CS group, last fixations were mostly randomly distributed across the search field.

A Chi Square (2x2 table) independent test (Fisher’s Exact test) was performed on each set size to determine if the predominantly center distribution seen in the S-CS was significantly different from the distribution of the G-CS group. The difference was not significant in the 1 set size condition ($p=0.182$), was approaching significance in the 8 set size condition ($p=0.061$) and was significant in the 32 set size condition ($p=0.014$). Therefore, different search behaviors appeared to be involved in the two groups when first exposed to a simulated scotoma.

Table 3.6. Final Blocks last fixation distributions in the 3 set sizes of the S-CS and G-CS groups.

Set Size		1 SET SIZE			8 SET SIZE			32 SET SIZE		
Area / Group/subj		Center	Quadrant	RD	Center	Quadrant	RD	Center	Quadrant	RD
S-CS	1		II			II			II	
	2	X			X	II & III		X	III	
	3		II		X	II			II	
	4	X			X			X		
	5		I		X			X		
	6		II			II			II	
G-CS	7		I & II (Sup)			II			II	
	8		I			I			I & II (Sup)	
	9		IV				X			X
	10		II			II			II	
	11		III&IV (Inf)		X				III	
	12		II			I & II (Sup)				X

RD =Random Distribution

3.3.3.5. Final Blocks

Results of the contrast analyses of the final blocks were summarized in **Table 3.6.** In the 1 set size condition, two subjects in the S-CS group had a significantly higher distribution concentration in the center, ($t(10) = 8.25$ to 8.37 $p<0.0005$), and three subjects had significantly more last fixations in quadrant II; ($t(10) = 3.65$ to 7.88, $p=0.004$ to <0.0005). One subject (S5) had quadrant I significance, ($t(10) = 4.34$, $t=0.001$). In the G-CS group, one subject (S7) had a superior hemifield distribution, ($t(10)= 8.28$, $p<0.0005$, and one (S11) had an inferior hemifield distribution ($t(10)=-4.98$, $p=0.001$). Two subjects had quadrant II signifi-

cance; (t(10)=4.16 to 13.09, p=0.002 to <0.0005. Subject 8 had a quadrant I distribution, (t(10)=3.29, p=.008), and Subject 9 had a quadrant IV distribution, (t(10)=7.37, p=0.005).

In the 8 set size condition, two subjects in the S-CS group had a center distribution, (t(10)=5.92 to 13.94, p<0.0005. Subject 2 had a center and left hemifield distribution, (t(10)=5.04 to 5.87, p<0.0005). Subject 3 had a center and quadrant II distribution, (t(10)=3.64 to 6.04, p=0.005 to <0.0005). Two subjects (S1 and S6) had a quadrant (II) distribution, (t(10)=13.15 to 23.62, p<0.0005. In the G-CS group, one subject (S11) had a center distribution, (t(10)=3.04, p=0.012. One subject (S12) had a superior hemifield distribution, (t(10)=2.41, p=0.036), and two subjects had a quadrant II distribution, (t(10)=-3.02 to -6.13, p=0.009 to <0.0005). Subject 8 had a quadrant I distribution, (t(10)=3.10, p=0.011), and Subject 9 had a random distribution (RD) as indentified by the non-significant one way ANOVA.

Finally, in the 32 set size condition, two subjects in the S-CS condition still had a predominantly center distribution, (t(10) =5.33 to 8.01, p<0.0005). One subject (S2) had a center and quadrant III distribution, (t(10) =-2.67 to 5.62, p=0.024 to <0.0005). Three subjects had a quadrant II distribution, (t (10)=-13.67 to -5.86, p<0.0005).

In the G-CS condition, one subject (S8) had a superior hemifield distribution, (t(10)=11.70, p<0.0005), two subjects had a quadrant II distribution, (t(10)=4.10 to 6.87, p<0.0005), and one subject (S11) had a quadrant III distribution(t(10)=-7.51, p<0.0005). Two subjects had random distributions.

In summary, clustering of last fixations became more prevalent in the last blocks of search adaptation as seen in **Figure 3.16.** The Fisher's Exact test was used to compare incidence of clustered distributions in the two groups and no significant difference was found at any set size.

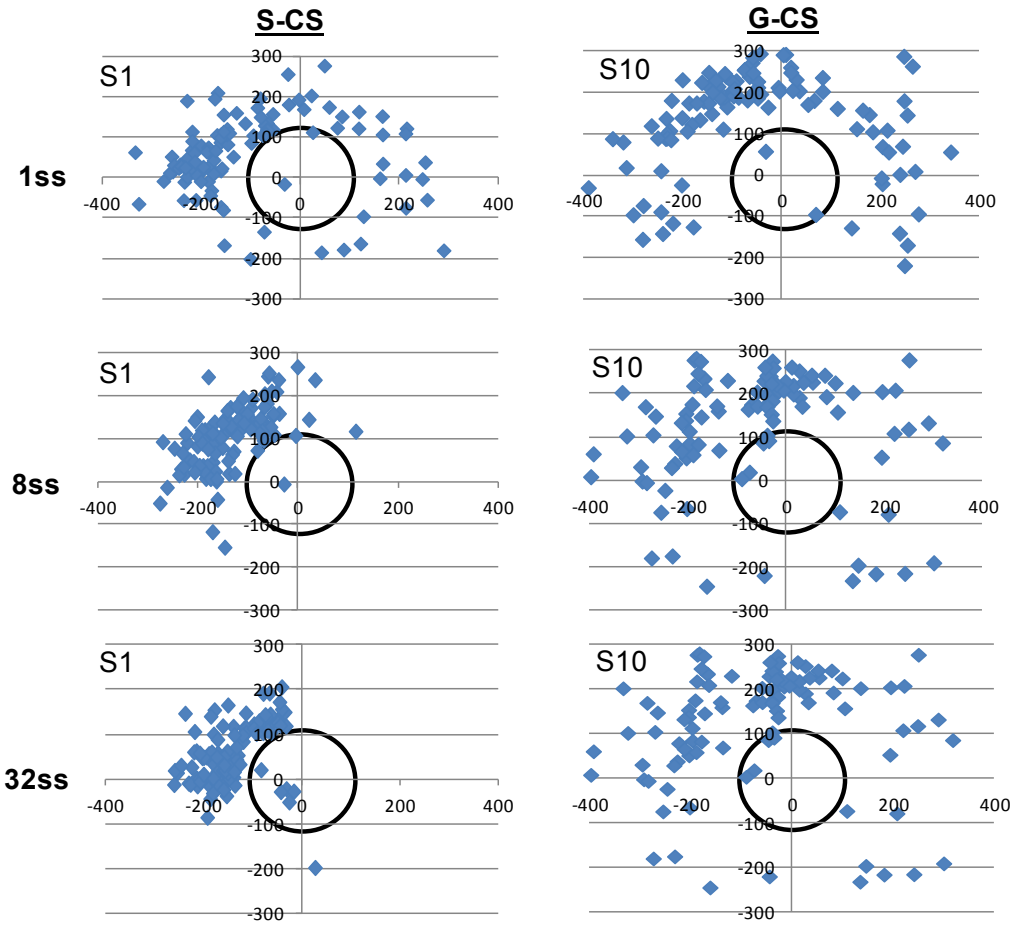

Figure 3.16. Representative last fixation examples from Subject 1 (Lt column: S-CS) and Subject 10 (Rt column: G-CS) in the final block stages. The plots are from each set size condition (1, 8, 32 set sizes). The blue diamonds represent the final 3 blocks of adaptation.

3.3.3.6. Last Fixation Summary

When first exposed to a simulated central scotoma, subjects of the S-CS group showed a strong tendency to foveate the target, as signified by a high concentration in a central area corresponding to the size of the simulated scotoma, even though the target would fall into the scotoma and thus would not be visible. Subjects of the G-CS group appeared initially to place the last fixation randomly across the search field. After practicing search with a simulated scotoma, the central concentration of last fixations in the S-CS group was largely replaced by high concentrations in peripheral areas. High concentrations in the peripheral areas also became prevalent in the G-CS group. However, the clustering of last fixations in association with adaptation was less tight in the G-CS than in the S-CS group. This was shown as more cases of hemifield fixation distributions in the G-CS group than in the S-CS group. It is also obvious from **table 3.7** that 43-49% of all last fixations of S-CS group fell in one quadrant (Area II), whereas the highest concentration of last fixation in any one area was not higher than 36% in the G-CS group. A high concentration of last fixations in a localized area indicates the consistent use of a retinal region when the target in the search stimulus was detected. Larger set sizes appeared to have stronger influence on the tendency of last fixation clustering. The most prevalent area for last fixations to cluster in both scotoma edge profiles was the superior left field quadrant (Area II) as seen

in **Table 3.7**.

Table 3.7. Last fixation concentrations of the two scotoma edge profiles (S-CS, G-CS) broken down, by the five areas under study and the 3 set sizes.

	Set Size	Block(s)	Areas				
			0	I	II	III	IV
S-CS	1	First	0.33	0.17	0.23	0.13	0.15
		Last	**0.13**	**0.16**	**0.43**	**0.16**	**0.12**
	8	First	0.38	0.13	0.24	0.12	0.13
		Last	**0.20**	**0.12**	**0.49**	**0.12**	**0.08**
	32	First	0.45	0.11	0.20	0.12	0.11
		Last	**0.20**	**0.10**	**0.49**	**0.16**	**0.05**
G-CS	1	First	0.14	0.20	0.27	0.20	0.18
		Last	**0.04**	**0.23**	**0.31**	**0.17**	**0.24**
	8	First	0.08	0.23	0.28	0.22	0.18
		Last	**0.07**	**0.24**	**0.32**	**0.20**	**0.16**
	32	First	0.15	0.21	0.27	0.22	0.15
		Last	**0.07**	**0.21**	**0.36**	**0.22**	**0.14**

3.4. Counterbalance Trials

After completing the 11-block search practice, five subjects from each group (N=10) continued the experiment and performed 7 additional search blocks using the opposing scotoma (18 blocks total). The purpose of this counterbalancing arm of the study was to observe if any of the adaptation to a simulated scotoma could be transferred to a scotoma of a different profile, and to determine if the transfer depended on the type of the adapted scotoma profile. In this analy-

sis, the group that practiced search with a sharp-edged scotoma in the first 11 blocks and then practiced with a gradual-edged scotoma in the subsequent 7 blocks was referred to as Group 1. The group that practiced the gradual-edged scotoma first and the sharp-edged scotoma second was referred to as Group 2. A repeated measures ANOVA was conducted on the 7 blocks of counterbalance data, with ADAPTATION as the within-subjects variable and GROUP (1 and 2) as the between-subjects variable. The primary outcome of measure was Reaction Time. The Mauchly's test for normality was rejected ($p<0.0005$), and the Greenhouse-Geisser correction was used in assessing statistical significance.

3.4.1. Adaptation & Scotoma effects

The main effect of ADAPTATION was significant in the counterbalanced scotoma conditions ($F(5.72,2817)=47.96$, $p<0.0005$). The interaction of ADAPTATION * SCOTOMA interaction was also significant ($F(5.72, 2817) =11.23$, $p<0.0005$). The between-subjects main effect of GROUP was highly significant ($F(1,493)=436.21$,$p<0.0005$). Therefore, after switching to a different type of scotoma, the search performance of both groups had improved, but through different time courses.

3.4.2. Transfer of Training effects

A two-sample t-test and a paired- t-test were conducted to evaluate the transfer of the training effect between scotoma types in the two groups. In both Groups 1 and 2, transfer was compared in two ways: a comparison of final block

of exposure to the first scotoma profile (block 11) to the first block of the second scotoma profile (block 12) within the same group using paired t-test, and a comparison of the first exposure to the first scotoma profile of one group (block 1) with the first exposure to the second scotoma profile of the opposing group (block 12) using a two-sample t-test. The first comparison determined whether the performance level achieved at the end of the first phase of adaptation was altered when first exposed to a different scotoma profile, and in what way. The second comparison addressed the issue of if there was a transfer, how complete it was.

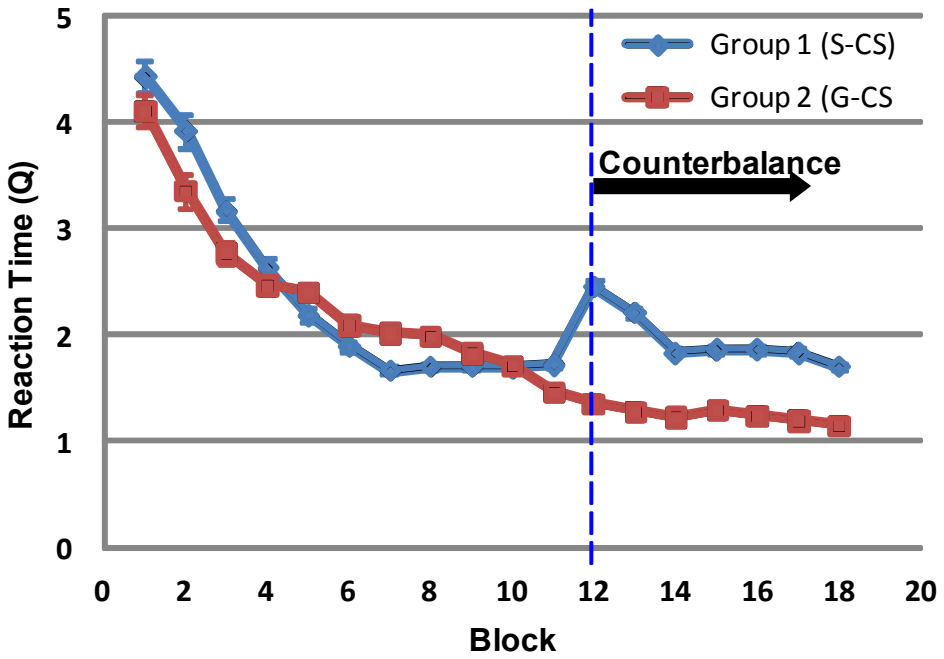

Figure 3.17. Mean RT (Q) for Group 1 (blue diamonds) and Group 2 (red squares). **Group 1** practiced search using a sharp-edged scotoma from block 1 to 11 and using a gradual-edged scotoma from block 12 to 18. **Group 2** practiced in the opposite order

In Group 1 (initially adapted to S-CS, blue diamonds in **Figure 3.17),** there was a significant difference between RTs of the last block of the sharp-edged scotoma (block 11) and the first block of the gradual-edged scotoma

(block 12) ($t(4)=-5.87, p<0.004$). The sign of this difference indicated that the first exposure to the gradual-edged scotoma significantly lengthened search RT, from 1.72 times to 2.45 times of foveal search RT. Therefore, whatever skills the subjects learned from using the sharp-edged scotoma were not completely transferred to searching with the gradual-edged scotoma. If nothing group 1 subjects learned from the sharp-edged scotoma were transferred to the gradual-edged scotoma, there would not have been a significant difference between their first exposure to the gradual-edged scotoma (Group 1's block 12) and Group 2's first exposure to the gradual-edged scotoma (Group 2's block 1). A two-sample t-test between these two blocks was used to test this conjecture, and a significant difference ($t(8)=2.72$, $p<0.027$) was found. The sign of the difference suggested that the RT of Group 1's first exposure to the gradual-edged scotoma was significantly shorter than the RT of Group 2's first exposure to the gradual-edged scotoma, 2.45 vs.4.12 times of foveal search RT. When the results of these two tests were combined, it was concluded that a substantial amount of Group 1's adaptation to the sharp-edged scotoma was transferred to searching with the gradual-edged scotoma, although this transfer was not complete. It also is worth noticing that the lengthening of RT at the first exposure to the gradual-edge scotoma diminished quickly with continued practice with the gradual-edged scotoma. Only two blocks of practice with the new, gradual-edged scotoma (block 14), the RT had recovered to the level prior to the switch of scotoma type and did not change with further practice.

In Group 2 (initially adapted to G-CS, red squares **in Figure 3.17),** there was no significant difference between RTs of the last block of the gradual-edged scotoma (block 11) and the first block of the sharp-edged scotoma (block 12) ($t(4)=2.61$, $p<0.060$). The first block of search with the sharp-edged scotoma slightly shortened the search RT established at the last block of search with the gradual-edge scotoma (1.37 vs. 1.47 times foveal search RT). Therefore, the skills learned from dealing with a gradual-edged scotoma were completely transferred to a sharp-edged scotoma, The RT kept improving at a slow pace for at least two more blocks of practice with the sharp-edged scotoma before settling at 1.15 times foveal search RT. A significant difference between Group 2's first exposure to the sharp-edged scotoma (block 12) and Group 1's first exposure to the sharp-edged scotoma (block 1) was found ($t(4.24)=6.36$, $p<0.003$). This large difference, from 4.44 to 1.37 times of foveal search RT, further confirms that the shorter RT observed in the 12^{th} block of Group 2 was not because the sharp-edged scotoma was an easier task but because the skills learned from previous practice on simulated scotoma, though a different kind, was applied.

Finally, comparing mean RTs of blocks 16, 17 and 18 between Groups 1 and 2 showed a significant difference ($F(1,494))=246$, $p<0.0005$), indicating a difference in the final asymptotic RTs after 18 blocks of practice (**Fig 3.17)** It appeared that in Group 2, the switching from the gradual-edged to the sharp-edged scotoma continued the slow but steady improvement while in Group 1, the practice with a new (gradual-edged) scotoma only maintained the level of performance established at the end of the first phase of adaptation. There was a pos-

sibility that the two groups could have ended at the same level of performance, had they practiced for 11 blocks after switching to a new type of scotoma. This possibility was not explored.

3.4.3. Adaptation Transfer Summary

Significant transfer of a practice effect occurred for both types of scotoma profiles. However, the transfer was more complete when a gradual-edged scotoma was the first one practiced.

4. DISCUSSION

The purpose of this study was to achieve a better understanding about how individuals with central scotomas may adapt to their condition by letting normally-sighted subjects practice visual search tasks with a simulated scotoma.

4.1. Initial Impact of a Simulated Scotoma

Initial exposure to the simulated central scotoma drastically increased search RT and resulted in highly disorganized eye movements. Search RT rose

to 4.30 times of foveal search RT (**Figure 4.1**).

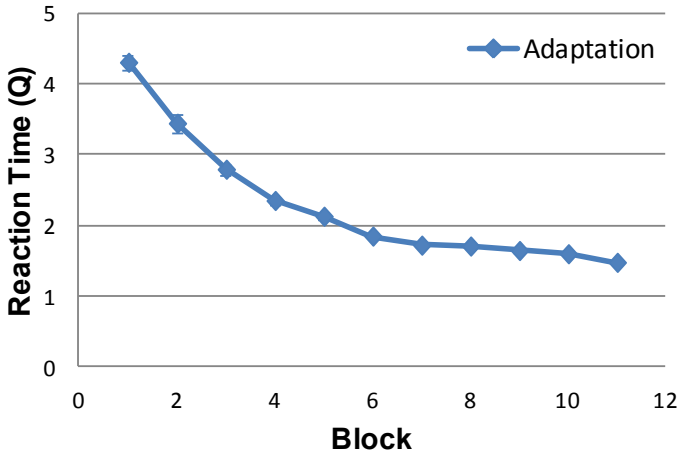

Figure 4.1. Reaction Time adaptation time course. Blue diamonds are data points from both the Sharp-CS and Gradual-CS groups,regardless of set size or trial response.

Search also became less efficient. The RT vs. set size lines had a much steeper slope when subjects viewed with an artificial scotoma **(Figure 3.13),** indicating a lot more time was spent for each additional item. Corresponding to the increased RT, there was a large increase in the number of fixations and saccades **(Figure 4.2).**

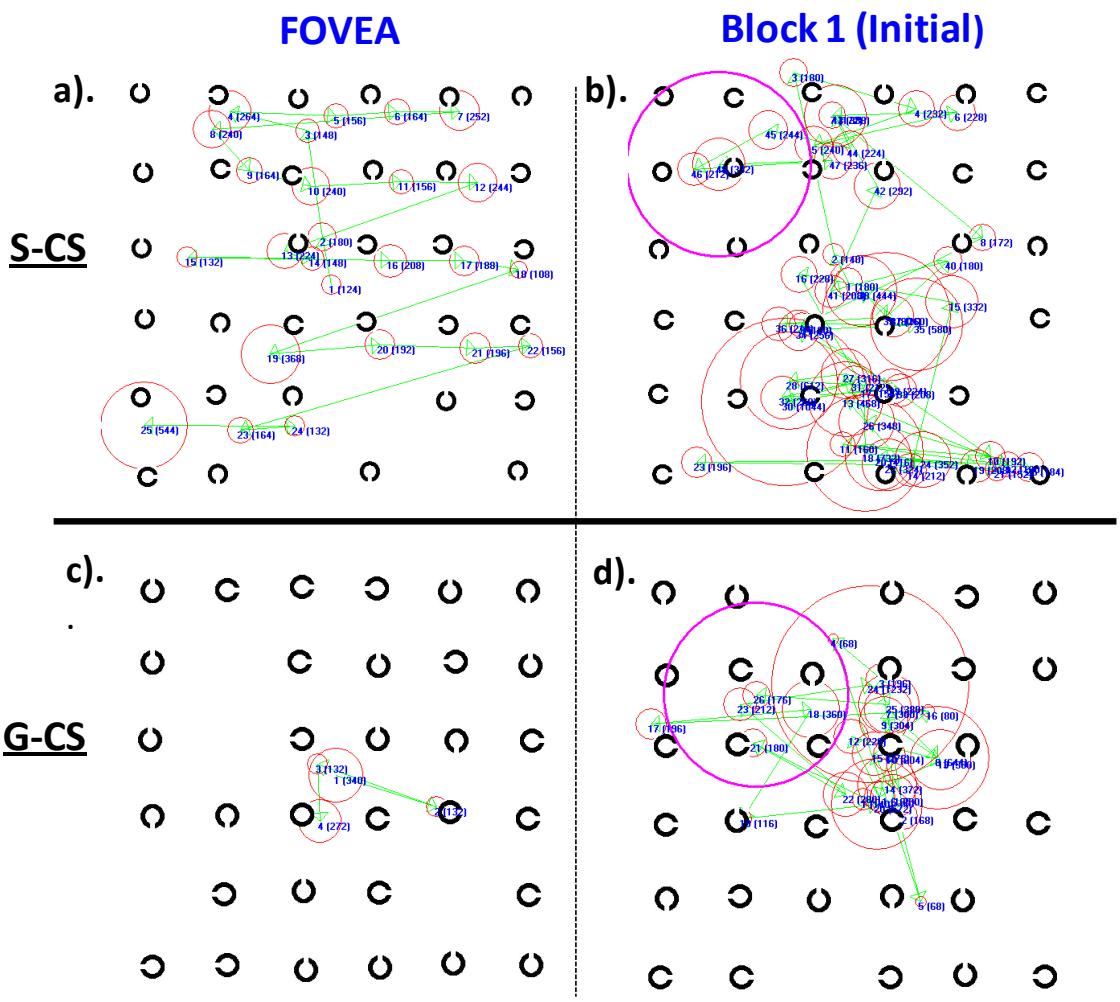

Figure 4.2. Representative scan paths of a foveal (control) and Initial (Block 1) trial from the 32 set size condition for both the Sharp-CS (top row: S-CS) and Gradual-CS (bottom row: G-CS) groups. The green lines and purple circles represent saccades and fixation areas, respectively. The larger the purple circle, the longer the fixation duration.

As shown in Figures 4.2 (b) and (d), when first exposed to a simulated central scotoma, the search scanpath was chaotic. The subjects did not show an organized, purposeful path that led to the target or went through all search items. Instead, some search items were visited more than once, and there were many regressions (one saccade leaving one location and the next saccade coming back). Other initial changes in eye movements included increased fixation duration and larger saccade amplitudes. Normal visual search is made of a visually guided

eye movement sequence that optimizes the task-relevant information with each saccade until the search goal is achieved (Najemnik and Geisler 2005). The key to this process is a fovea-centered sensitivity map that reevaluates potential increases in useful information with each successive move and takes the one that offers the best gain. The presence of a simulated scotoma, and probably a real scotoma too, doesn't prevent peripheral preview of the search items, but it does interrupt the normal search routine in a way that the fovea-centered reevaluation of information in the field is no longer valid. A saccade that would have increased useful information could actually result in less information. As having been demonstrated in other studies (Whittaker, Budd et al. 1988; White and Bedell 1990), subjects retained the fovea-centered oculomotor behavior for many years of the onset of central scotoma, even though it only made the intended object invisible. This was seen in the S-CS group where the subjects tended to move the fovea, which was at the center of the simulated scotoma, to the search target when they reported finding it **(Fig 3.14).**

4.2. Adaptation to a Simulated Scotoma

A significant adaptation to the simulated scotoma was found after 11 blocks of search practice (~1800 trials). A large reduction of search RT, from 4.30 to ~1.5 times of foveal search RT, was observed. This reduction was mainly due to the reduction of number of fixations and saccades made during search. This was because the search RT was highly correlated with the number of fixations. There was also a significant reduction of fixation duration, but the magni-

tude of this reduction could only account for a small portion of the RT reduction observed. After training, fixation duration settled down at about 50% longer than that of the foveal search condition. Fixation duration reflects the demand for both processing the visual information under the current fixation and planning the next saccade. Because search had to be done with a peripheral retinal location with a simulated scotoma, the observed longer fixation duration might be associated with searching with a peripheral instead of foveal retinal location. An eccentricity effect (Carrasco, Evert et al. 1995) was found in normal foveal search, where a more peripherally located target took longer to be found. This eccentricity effect appeared to be attention deployment in origin as manipulating visual factors such as crowding and cortical scaling had little effect (Wolfe, O'Neill et al. 1998). Saccades initiated from a peripheral location are also known to have longer latencies. Whittaker, Cummings and Swieson (1991) measure saccades from 18 patients with central field loss and found that their initiation latencies were 25% longer than the saccades of normal controls (402 ms vs. 298 ms). The slowness in both attention deployment and saccade initiation might have contributed to the longer fixation duration observed in simulated central scotoma. The current research cannot distinguish the contributions of these two factors because it is difficult to determine the initiation latencies of a sequence of voluntary saccades among search items that are all visible at the same time.

At the end of the 11 blocks of training, the scotoma search saccade amplitude was in most conditions smaller than that of foveal search (0.6-1.0 times), and saccade velocity also became slower than that of foveal search. It has been

well established that “saccades without a fovea” are slower (Whittaker, Cummings et al. 1991). While the smaller amplitude and slower velocity was expected from the saccade “main sequence” (Bahill, Clark et al. 1975), there is no simple explanation why practice reduced saccade velocity or amplitude and why saccades with a simulated scotoma, which were initially equal to or slightly larger and faster than foveal search saccades, became smaller and slower. In our search task, each trial usually contained a large number of saccades, some were larger, moving between different regions of the search area, and some were smaller, bracketing around one search item. It is possible that the saccade amplitude and velocity changes reported here reflect a change in the relative proportions of large and small saccades through practicing search with a simulated scotoma. Future analysis of saccade amplitude and velocity distributions may reveal the true nature of oculomotor adaptation to a simulated central scotoma.

An interesting finding is the consistent use of a peripheral retinal location near the border of the simulated scotoma, usually within the upper left quadrant (superior left visual field), to detect the target (**Figure 3.15 and Table 3.6**). Because the simulated scotoma was symmetrically placed around the fovea, all retinal locations around the edge of the scotoma had similar visual acuity and contrast sensitivity, and thus were equally qualified to detect the target. However, instead of adopting a strategy that all retinal locations around the scotoma edge were used opportunistically, according to whichever was closest to the target, most subjects appeared to prefer using one retinal location consistently. This strategy may not always be the most efficient. For example, if the target hap-

pened to be on the opposite edge of the scotoma from the chosen retinal location, instead of reporting it right away, the subject had move the eye to aid the chosen retinal location to the target, and risk losing it on the way. One possible motivation for, or constraint to such a strategy, is the limited processing capacity of the human visual system. One filter that keeps the amount of incoming information manageable is the fovea/periphery functional division. Another filter is focal attention, which typically limits the processing to a small area in space at any time. When the fovea filter is disabled by a simulated or a real scotoma, the selectivity of focal attention becomes vitally important. Apparently, the subjects learned to use one retinal area/location because monitoring many locations around the scotoma was not possible or comfortable.

4.3. Visual Search with and without a Simulated Scotoma

Oculomotor behavior and learning effects in visual search have been extensively studied during normal foveal search to understand the underlying neural and cognitive processes and the impact of normal aging. For example, a high correlation between search RT and the number of fixations has been found in parallel and serial search (Zelinsky and Sheinberg 1997; Scialfa, Jenkins et al. 2000). In serial search, the last fixation endpoints were less than 2° from the target, indicating foveation of the target at the end of the sequence of search eye movements (Zelinsky and Sheinberg, 1997). Fixation duration was found to be uncorrelated with search trial type (target-present and absent) or search set size, supporting a “variable number model” of search (Treisman and Gormican

1988; Cave and Wolfe 1990), which proposed that roughly the same number of search items were processed at each search location (spot light size changing inversely with set size). When normal subjects practice serial search tasks, both overall search RT and search efficiency (the slopes of the RT x set size lines) improves (Anandam and Scialfa 1999; Scialfa, Jenkins et al. 2000); this improvement is accompanied by a reduction of the number of saccades (fixations) but no change of fixation duration (Scialfa, Jenkins et al. 2000).

While these findings bear similarity to some of findings in search with a simulated scotoma and thus provide a context for the current study, there are dramatic conceptual and quantitative differences between search with and without foveal visual inputs. First, in most of the studies of normal foveal search, eye movement is considered another form of attention deployment, an overt attention shift compared to a covert one that cannot be observed directly. In fact, the serial and parallel search tasks studied could be done without eye movements with better or only slightly reduced performance if the targets are sufficiently discriminable (Klein and Farrell 1989; Zelinsky and Sheinberg 1997). Eye movements were considered to play “little role” in parallel and serial search (Klein & Farrell, 1989) and using saccades “was actually counterproductive to the instruction to answer as quickly as possible” (Zelinsky & Sheinberg, 1997). “The use of eye movements might simply reflect a default strategy by which people naturally search their environments.” (Zelinsky & Sheinberg, 1997). In comparison, in searching with a simulated central scotoma, and probably with a real one too, eye movements become a necessity, because in most situations, there is no prior

knowledge whether some search items fall into the scotoma, and eye movements are needed to uncover them. This is true even if the subject has perfectly adopted a PRL and has completely transferred oculomotor control to that location. Second, training in normal foveal search resulted in a meager 20-30% improvement in search RT, reflecting a refinement of an already highly-efficient process (Anandam and Scialfa 1999; Scialfa, Jenkins et al. 2000). Mechanisms that contribute to this learning effect include priority learning (attention being attracted to a target and staying away from distracters), response learning (automatization of stimulus-response mapping) and more efficient use of stimulus features (excluding items with features that are irrelevant to search tasks, for example, not searching any green item if the task is to find a red vertical bar)(Fisk, Hertzog et al. 1994; Scialfa, Jenkins et al. 2000). In comparison, a 200-300% improvement of RT was observed when practicing search with a simulated scotoma, indicating a gross change of search behavior. Phenomenally, a much more organized search scanpath (**Figure 4.3)**

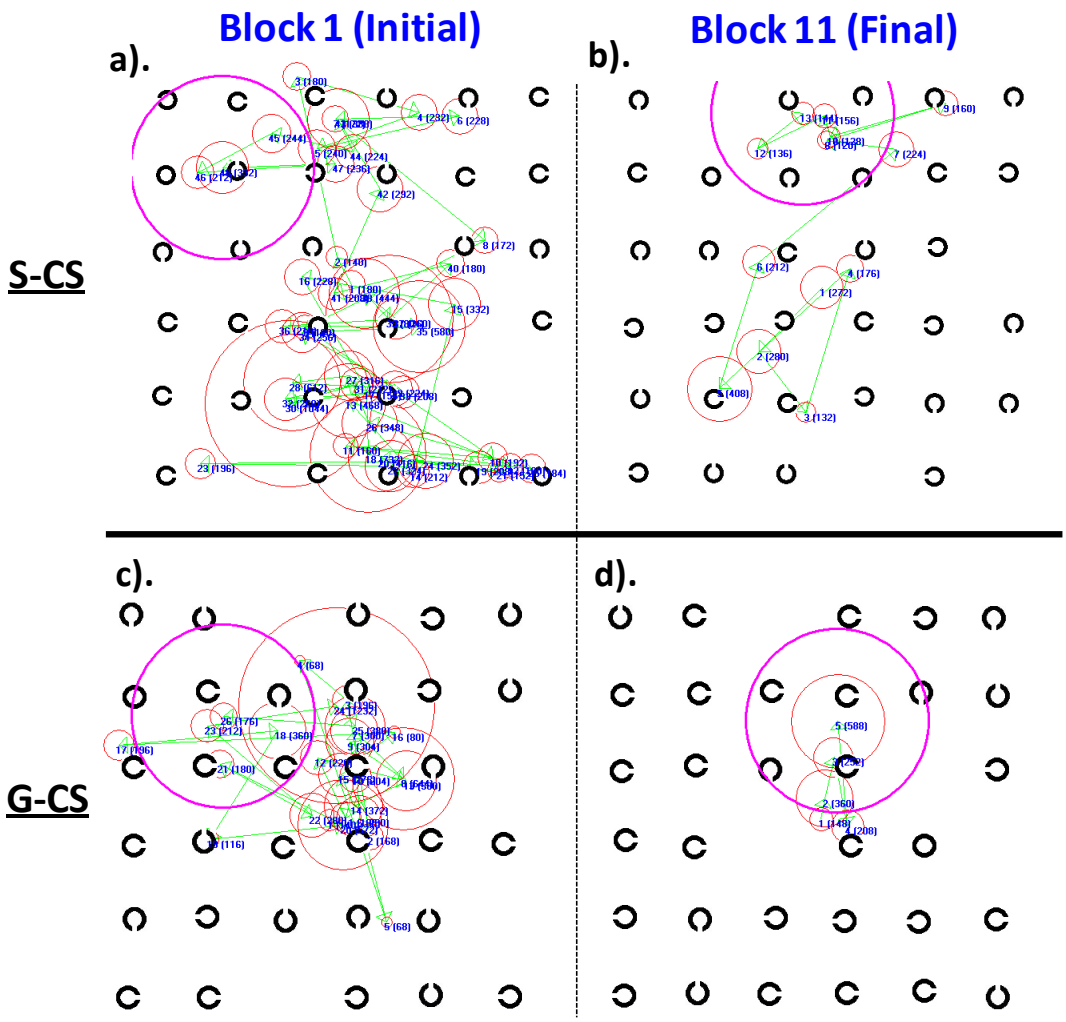

Figure 4.3. Representative scan paths changes from initial (Block 1) and final (Block 11) blocks in the 32 set size condition for both the Sharp-CS (top row: S-CS) and Gradual-CS (bottom row :G-CS) groups. The green lines and purple circles represent saccades and fixation areas, respectively. The larger the purple circle, the longer the fixation duration.

and a tendency to consistently use one retinal location near the border of the simulated scotoma appear to be responsible for the observed RT improvement. The contributions of the search learning mechanisms mentioned above become insignificant here. The paramount goal is to form a new search routine that is likely to involve modifying the existing, fovea-based visual, perceptual and oculomotor mechanisms and their coordination. Further studies of patients with

real scotomas may lead to a better understanding of how they may change their behavior to accommodate to the loss of central vision.

4.4. Effects of the Profiles of the Simulated Scotoma

The two scotoma profiles tested, a sharp-edged (S-CS) and a gradual-edged (G-CS), had significantly different initial impacts on visual search and on subsequent adaptation. The S-CS appeared to have caused more pronounced initial slowing down of search, compared to G-CS, but the adaptation to a S-CS appeared to be faster and the improvement of search performance saturated earlier than the G-CS, reaching half of the improvement from the initial RT in 4.45 and training blocks instead of 5.63 blocks. By the final block of training, both groups had ~1.5 times longer search times than foveal performance. The S-CS group demonstrated a clear saturation level of search performance (Figure 3.1). However, the G-CS group had continuous improvement throughout. The sensible question to ask is, had the training continued, how close the G-CS group could approach to the foveal performance. Further research is needed to provide the answer.

There were significant differences between the two types of scotoma in terms of fixation duration and saccade parameters, but the magnitudes of the differences were small. A major difference in oculomotor behaviors between the two scotomas was the retinal location used in search. This was quantified by the last fixation location before a response was made to indicate finding the search target. As shown in **Figure 3.14 and Table 3.5,** when first exposed to a simulat-

ed central scotoma, subjects with S-CS had a strong tendency to place the last fixation, which was the fovea and thus the center of the simulated scotoma, on the target when they reported seeing the target, even though this act actually obscured the target from view. In contrast, the last fixations for subjects with G-CS tended to scatter randomly. At the end of the 11-blocks of training, subjects with both types of scotoma showed a tendency to use one peripheral retinal area more consistently. However, there was a difference in the degree of concentration of final fixation locations between the two scotoma types. The last fixations of the S-CS subjects were mostly confined in one quadrant, but those of the G-CS subjects were spread over a larger area. Finally, when subjects who initially practiced with the S-CS switched to the G-CS after they finished the first 11-blocks of search, they searched more slowly and took a couple of blocks of training to regain the search performance level they had reached after practice with the S-CS scotoma. When subjects who initially practiced with the G-CS made the switch to the S-CS, they retained all their training gains and made slightly more improvement with the S-CS. In general, it seemed that coping with a G-CS was harder than with a S-CS. This difference is likely to be caused by the more precise information about the location and spatial extent of the S-CS, which was available when the sharp edge of the scotoma cut through the search-array features. Subjects with a G-CS were aware of the existence of a field defect, but there was less salient information about where the center was and how far it extended, because the scotoma gradually faded into the background.

Although there is no such a thing as a scotoma with perfectly sharp edge in real retinal diseases, there is a degree of difference in transition from absolute scotoma to relatively intact retina. End-stage wet AMD leaves disciform scars in the retina with an absolute scotoma on one side of the scar and relatively intact retina on the other. On fundus photos, these scars are shown as clearly demarcated regions**.** Stargardts disease, a type of juvenile macular degeneration, also tends to produce a sharp transition from absolute scotoma to relatively normal vision **(Figure 4.4)**.

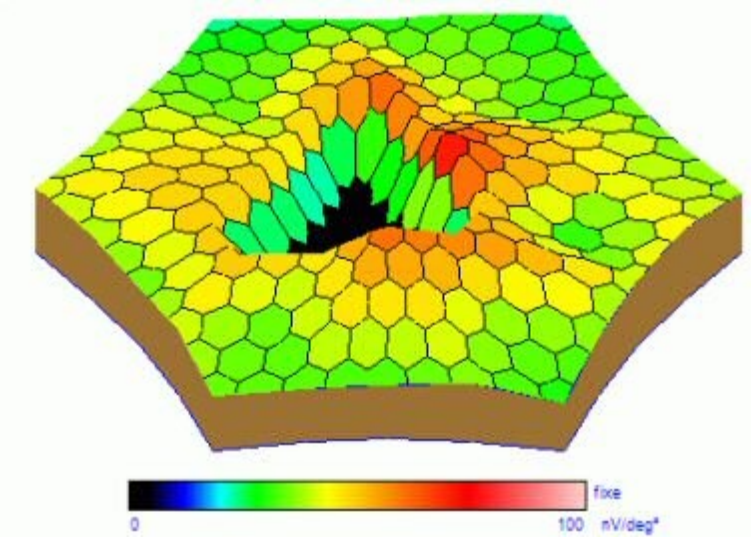

Figure 4.4 A multifocal ERG from a Stargardts patient. The colors reflect the response density distribution across the stimulated area..

As seen in Figure 4.4 (Charlier) , the area of highest peak ERG intensity (in red) is near the border of the absolute scotoma, with a sharp drop-off into the central scotoma. In dry AMD, the attenuation of the RPE and the degeneration of the photoreceptors progress slowly and continuously. An absolute scotoma may thus be surrounded by relative scotomata where visual function is impaired to various degrees but not completely abolished. The observed difference between

S-CS and G-CS may help to understand the different functional impacts and adaptation to real scotomas of different profiles. A change of scotoma profile may also be possible in real patients, especially with the anti-VEGF treatment, which reduces fluid leakage in the retina and reduces swelling. Visual function may improve soon after treatment and depth of the scotoma reduces. The different adaptation courses observed in this study may also help to understand patients' adaptation to AMD treatment.

4.5. Simulated vs. Real Scotoma

Simulation is a common method used to study the visual system's response to certain ways of information deprivation. Positive lenses are added to simulate refractive errors, and diffusers are added to simulate cataracts**.** Films with smudges mounted on glass frames are a typically way to educate the public how various retinal diseases may affect vision. Gaze-contingent display provides a more precise way to simulate what happens "in" the eye, as the simulated field defects move with the eye. Several studies have used this technology to study the effect of field loss in reading and search, but no previous study considered adaptation to the simulated scotoma or the effect of scotoma profile. From this point of view, this research has broadened the scope of simulation research in low vision.

It has been recognized that a gaze contingent display can only simulate one aspect of field loss, namely depriving visual input to certain part of the retina. The disease that causes the field defect may also affect or modify other parts of

the neural system and other components of visual processing. Realizing this limitation helps to evaluate the implication of simulation research findings, to relate them to real disease and to inspire new studies. For example, Schuett et al (Schuett, Kentridge et al. 2009).found the adaptation to a simulated homonymous hemianopia occurred much more quickly than what is seen in the real hemianopia population. Similarly, in this study, consistent use of a peripheral retinal location for detecting the search target was found within 11 blocks of search training. In patients with real central scotomas, such a change of oculomotor behavior may take months (Crossland, Culham et al. 2005) or even years (White and Bedell 1990) to accomplish. A study of monkeys adapting to bilateral ablation of the fovea (Heinen and Skavenski 1992) showed fast adaptation of fixation control, however much slower, and incomplete, adaptation of saccades.

One possible reason for the observed faster adaptation with a simulated scotoma is that the trained PRL could be task-specific. It could be a skill that was learned specifically for the purpose of searching with a central scotoma. Low vision patients, on the other hand, must learn to establish a PRL for multiple tasks. It is also possible that if patients with central scotoma had visual search training, they would have acquired a PRL at a faster pace. We would not know the answer until we know whether the trained PRL in normal subject with a simulated scotoma can be used in other tasks, for example, reading with a simulated scotoma and whether patients with real central scotoma can acquire a PRL faster if they go through the search training.

4.6. Visual Search Training

Visual search is a goal-driven task, finding the larger square or the letter "O" as fast as you can, that leaves how to achieve the goal to the subject to figure out. This kind of task may find use in low vision rehabilitation, because the patient is usually the most qualified person to find the best way to complete a vision task. In a series of studies of visual search training in low vision patients, Kuyk, Fuhr and Liu (Liu, Kuyk et al. 2007) used a simple, feature search task (finding a larger square target among smaller square distracters) to train low vision patients with a wide variety of visual impairments. They found that patients with severe visual impairment could do such a search task with great accuracy, and that these patients could learn to perform the search task faster. More importantly, after 5 sessions of search training, the patients showed a significant decrease of obstacle contacts on an obstacle course, compared to a control group that did not have search training. However, the search task used in these studies appeared to be too simple. The total amount of search RT improvement was only 10-20% before it saturated. Consequently, the impact on the mobility task was also relatively small. In comparison, in this study the search RT improvement observed when normal subjects practicing with a simulated central scotoma was 200-300%. The search task used in this study was much more demanding than the feature search task used by Kuyk, Fuhr and Liu. Specifically, the search task used in this study needed a lot more covert and overt attention deployment, as indicated by steep slopes of the foveal search RT vs. set size curves (~ 60 and 160 ms/item for positive trials and negative trials, respectively).

Although set size interacted significantly with practice, the practical difference between the 1, 8 and 32 set sizes in their effect on search performance improvement was small (**Figure. 3.2**). Therefore, training with 1, 8 or 32 items is likely to be equally efficient. Because a search of 32 items takes much longer than search for 1 item, an efficient search training protocol should use smaller set sizes. Trial type (target-present and target-absent) also interacted significantly with practice but the two trial types produced similar proportional RT improvement at the end. Because target-present trials typically take half of the time of target-absent trials in a difficulty search task, an efficient search training protocol should include more target-present trials. It is speculated that if such a training protocol is used in low vision patients, a larger improvements in search performance and more substantial improvement in vision related daily activities may be achieved.

4.7. Conclusion

Central scotomas are initially detrimental to visual search performance. Adaptation to a simulated central scotoma during search does occur, however those individuals with a relative, or gradual, scotoma edge border may adapt more slowly in a search task. This may be related to their difficulty of designating a specific area on the retina (PRL) to substitute for their diseased fovea. However, with search training, it may be possible to alleviate some of the search deficiencies seen initially in patients with central scotomas. Improving oculomotor skills such as eye movement control can potentially lead to improvements in per-

forming active daily living tasks because having central vision loss is not just a loss of visual function, but also a loss of functional vision.

4.8. Limitations and Future Studies

There are several limitations with the present study. First, only one type of scotoma can be simulated to the two eyes in gaze-contingent display. In reality, macular degeneration patients usually have different retinal damage in the two eyes. The simulation method, at least the version used in this research, cannot be used to study the interaction of different visual impairment in the two eyes. Second, subjects only have a "scotoma" during testing sessions; the rest of the time they are using their foveas in the normal way. The simulation study may capture some of the initial impact of the onset of a scotoma and the strategies to adapt to the condition, but to what degree these finding may resemble the experience of patients with real scotomas requires further research.

A future study, besides the visual search training as previously discussed, can focus on some of the limitations of simulation research. By mapping (with visual fields) the real scotomas of low vision subjects, and incorporating these scotomas in the field of different normal subjects, we can look for common factors and disagreements using functional vision tasks. This type of study can attempt to validate the simulation methodology.

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APPENDIX A

CHIN REST vs BITE BAR

Successful simulation of a central scotoma depended on accurate monitoring of gaze position on the display screen, which was a combination of head position and eye position in the head. Although the Eyelink provided a head camera to monitor head position, it was unclear whether a more stringent head stabilization method, a dental imprint (bite-bar) was necessary had any advantage over a more subject-friendly chin-rest. Fixation stabilities with a bite-bar and a chin rest were compared.

A. Methods

A.1. Subjects: Six subjects with normal vision and no oculomotor abnormalities participated in this experiment.

A.2. Stimulus and Procedure: Subjects were seated comfortably at 60 cm distance in front of a 21” color monitor. The Eyelink II tracker was worn throughout the procedure. Prior to testing, a calibration and validation procedure was performed (**see Methods 2.5.4**) to ensure accurate eye tracking. Each trial started with the yellow drift control dot (**Figure 2.5)** at the center of the screen. The subject was instructed to fixate in the center of the dot before pressing the spacebar

to start the stimulus display. The stimulus was a cross (subtending 58 arcmin) that was presented at one of the 9 positions of a 3x3 virtual grid subtending 20x20 deg and stayed there for 10 seconds. The subject was instructed to move his/her eyes to the cross and to kept fixation at the center of the cross until it disappeared. When the cross disappeared, the drift correct dot reappeared at the center of the screen for the test of the fixation at the next location. Eye position data was collected and analyzed offline. Each subject performed the task with one head stabilization device (bite-bar or chin rest) first, and then with the other device. The order of device use was randomized among subjects. One practice trial was performed to familiarize the subjects with the task. Testing lasted 20-30 minutes.

A.3. Analysis: A repeated measures ANOVA was performed with DEVICE as the within subject variable and the outcome measure was fixation stability. Bivariate Contour Ellipse Area **(**BCEA**)** values were calculated from the fixation distribution ($arcmin^2$) that encompassed 68% (1 SD) of fixations from the center of the crosses.

A.4. Results: There was not significant main DEVICE effect ($F(1.24,65.74)=1.19$, $p=0.291$). The results (**Table A.1)** suggested the fixation stability between the usage of the bite-bar and chin rest were similar.

Table A.1. Average log BCEA for both eyes in the six subjects tested.

Subject	AVE log_Left_BCEA Chin rest	AVE log_Right_BCEA Chin Rest	AVE log_Left_BCEA Bite Bar	AVE log_Right_BCEA Bite Bar
1	3.85	3.79	3.92	3.83
2	3.74	3.76	3.83	3.75
3	3.97	4.07	3.90	3.98
4	4.04	4.34	3.64	3.72
5	4.14	4.20	4.16	4.21
6	3.59	3.67	3.58	3.58

APPENDIX B

CONTRAST ATTENUATION TESTING

Prior to beginning the study, a contrast attenuation test was performed to assess the effects of reduced stimuli contrast on search performance. A concern with the Gradual-edged scotoma (G-CS) was that the extension of the edges outside the 10 deg Sharp-edged scotoma confine made the gradual-edged scotoma appear larger (**Figure 2.2**), and the comparison between the two scotoma types was really a comparison between two scotoma of different size. It was recognized that the effect of the gradual edges was not to make the search stimulus disappear but was to attenuated its contrast slightly. The search stimulus outside of the 10 deg half height of the gradual-edge scotoma still had quite high contrast (>50%). The question was whether this contrast attenuation affected search performance. The dependency of search RT on stimulus contrast was thus conducted.

B. Methods

B.1. Subjects: Three experienced observers (including the author) participated in this experiment. All subjects had normal visual acuity, and no oculomotor abnormalities.

B.2. Stimulus, Task and Procedure: The search stimulus used in the simulated scotoma search experiment was used with one exception. The search items had four contrast levels: 1.0, 0.5, 0.25, and 0.10. A simulated, 10-deg sharp-edged scotoma was used throughout the testing (**see Methods section 2.5.1.)**. The subject performed the same task of finding an "O" target among "C" distractors. The testing procedure was similar to that used in the simulated scotoma search experiment. Only the 32 set size was tested. Each subject performed 8 search sessions, two for each of the four contrast levels. One practice search session with item contrast at 0.55 contrast was performed prior to the test. The testing lasted 1- 2 hours with breaks encouraged after every 2^{nd}—3^{rd} session.

B.3. Analysis: Repeated measures ANOVAs were performed separately on performance accuracy and reaction time. The within-subject variable in both analyses was CONTRAST(4).

B.4. Results: For accuracy, in both the target present and absent trials the main effect (CONTRAST) was not significant,($F(3,15)=.505$, $p=0.684$; $F(3,15)=1.0$, $p=0.420$).

For Reaction Time, the main effect (CONTRAST) was significant, ($F(3,543)=11.34$, $p=0.005$). A post-hoc comparison (Bonferroni corrected) was made among the 4 contrasts, and no significance was found among contrasts 1.0, 0.5 and 0.25 ($p=0.831$ and 0.273). The 0.1 contrast was significantly different from the 1.0 contrast ($p=0.001$).

Both accuracy and reaction time results **(see Table B.1)** suggested that contrast attenuation caused by the gradual edges outside of the 10 deg half height diameter was not strong enough to affect search performance, even though the gradual-edged scotoma did appear slightly larger than the sharp-edged scotoma. Any significant difference found between the two scotoma groups thus was not caused by the difference in the effective sizes of the scotomas but by the difference in the profiles of the edges.

Table B.1. Contrast Attenuation results

Subject	Contrast	Ave Hit Rate	Ave HITRT	Ave CR Rate	Ave CRRT
1	1.0	0.74	3341ms	0.97	7221ms
	0.5	0.82	3457ms	0.97	7172ms
	0.25	0.81	3240ms	1	6744ms
	0.10	0.81	4549ms	1	8403ms
2	1.0	0.99	2148ms	1	7927ms
	0.5	0.96	1903ms	1	8130ms
	0.25	0.97	2460ms	1	9158ms
	0.10	0.97	2877ms	1	9823ms
3	1.0	0.89	2026ms	1	4391ms
	0.5	0.94	1740ms	1	4248ms
	0.25	0.93	2936ms	1	6839ms
	0.10	0.90	2788ms	1	5859ms

APPENDIX C

VERGENCE EYE MOVEMENTS

In this study, subjects performed the search task binocularly. While the eye tracker tracked the movements of both eyes, only one eye's gaze position was used to draw the simulated scotoma (left eye if left eye or both eye gaze data was available, otherwise right eye). A concern with drawing a simulated central scotoma with one eye's gaze was the possibility that the visual axes of the two eyes might not always intersect on the plane of the display screen. Because the simulated central scotoma had a limited size (115 pixel or 5 deg radius), if the two eyes of the subject converged in front or behind the plane of the screen, one eye's gaze would deviate from the center of the simulated scotoma and search items might be viewed more foveally in that eye than intended. This error in vergence posture might be happening more often during search with a simulated central scotoma because the foveal inputs to the two eyes were deprived. The purpose of the following analysis was to assess the fluctuation vergence posture during search with a simulated scotoma.

Methods: Approximately 10% of all data (1944 trials) were pseudo-randomly from each subject for vergence analysis. The data consisted of one session (54 trials) from each of the 3 set size conditions (1, 8 and 32). Sessions from the be-

ginning, middle and end of the 11 blocks were randomly selected and analyzed. For each search experimental session, the Eyelink II stored in an ASCII file a set of gaze position data every 2 ms. Each set of gaze position data contained the Horizontal (X) and Vertical (Y) positions of the left and right eye on the screen. A Matlab program was developed to extract all gaze position data from each search trial from the onset of the search stimulus to the moment when the response key was pressed. The offsets in the X and Y direction between the two eyes' positions were computed.

Results: The proportions of the two eyes' offset smaller than or equal to 25, 50 and 100 pixels were calculated. Because the gaze position data were produced at a uniform interval of 2 ms, the proportions above also indicated the proportion of time when the two eyes had offsets on the screen that were smaller than or equal to 25, 50 and 100 pixels. The **Table C.1** below summarized the mean proportions of X and Y eye gaze position offsets. In the horizontal and vertical directions, the two eyes' gaze positions on the screen did not deviate from each other for more than 25 pixels (1.09°) in 92.8% and 95.3% of the time, respectively. In the horizontal and vertical directions, the two eyes' gaze positions on the screen did not deviate from each other for more than 50 pixels (2.18°) 99.1% and 98.5% of the time, respectively. Finally, in both the horizontal and vertical gaze offset, the two eyes' gaze positions on the screen did not deviate from each other for more than 100 pixels (4.36°) in 99.8% of the time.

Summary: Occasionally, the two eyes' gaze positions might separate by a distance that allowed one eye to look at the border or even outside the border of the simulated scotoma drawn around the center of the other eye's gaze position. However, in our simulated scotoma condition (115 pixel radius), the chance for such vergence posture to occur was no more than 0.002% of the time. It was thus concluded that although the vergence posture of the two eyes varied during search with a simulated scotoma, both eyes' foveal view was substantially blocked by the simulated scotoma drawn around the center of one eye's gaze position.

Table C.1. Horizontal and Vertical eye gaze position offsets

Pixels on screen	Horizontal position (X)	Vertical position (Y)
25	0.927564865	0.952535135
50	0.991208108	0.985413514
100	0.998172973	0.998094595

APPENDIX D

RT (Q) RESPONSE/SET SIZE FIGURES

All RT Q figures for each scotoma group (S-CS, G-CS) are presented.

The left and right columns are the positive and negative trials, respectively.

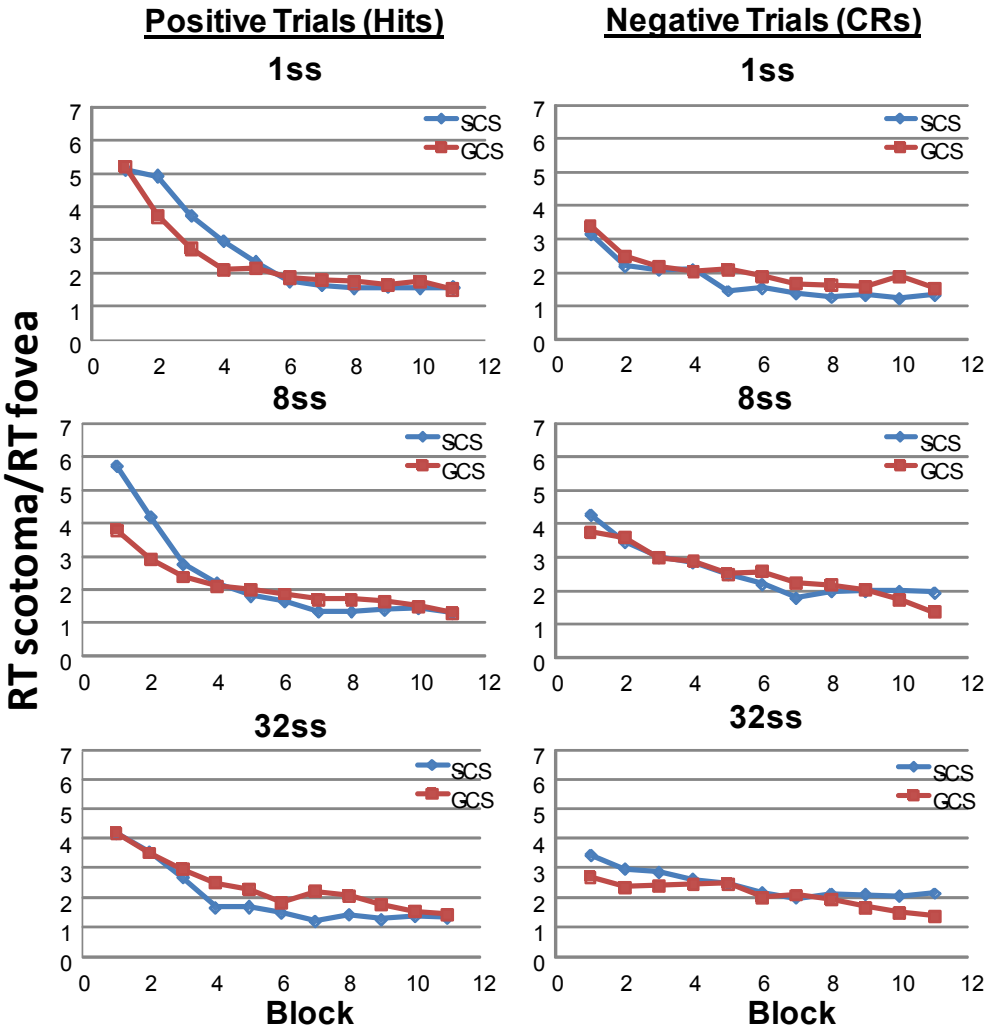

Figure D.1. All RT Q plots for both types of response trials (Positive and Negative) and three set sizes (1, 8, and 32). Blue diamonds and red squares are data points for the S-CS and G-CS scotoma groups, respectively.

APPENDIX E

HALFTIME ADAPTATION AT DIFFERENT ASYMPTOTE LEVELS

As mentioned in Section 2.7.2.3, an asymptote level, 1.1 time of fovea search RT at block 22, was chosen to fit a power function curve through adaptation data. A potential concern was that the results could be influenced by the choice of this asymptotic level. If the asymptote levels were set to different values, this could potentially affect the value of $t_{1/2}$ and thus change the differences seen between the S-CS and G-CS groups. The sensitivity of the $t_{1/2}$ value to the choice of the asymptotic value was thus evaluated.

METHODS: Six different asymptote values, 1.1, 1.2, 1.3, 1.4 1.5 and 1.6, were use at block 22 to calculate $t_{1/2}$ values using the procedure specified in section 2.7.2.3. The means, standard deviations', maximum and minimum values of the six asymptote values for each condition were computed.

RESULTS: The $t_{1/2}$ value in general was not sensitive to the choice of the asymptotic value (**Tables E.1 and E.2)**. This was indicated by the small standard deviations and the small differences between the maximum and minimum $t_{1/2}$ values. The G-CS 32 set size correct rejection had the largest standard devia-

tion, however it had the poorest fit (R^2 = ~ 0.7). This was because the adaptation curve was roughly a straight line.

SUMMARY: The choice of the asymptote level did not appear to influence the $t_{1/2}$ values. Therefore, the $t_{1/2}$ values and discussions in Sections 3.2.1.3 and 4.4 were valid.

Table E.1. Sharp-edge CS (S-CS) HT Adaptation data for 5 asymptote values

	S-CS 1ss HIT	S-CS 8ss HIT	S-CS 32ss HIT	S-CS 1ss CR	S-CS 8ss CR	S-CS 32ss CR
Mean	3.72	2.88	3.77	6.51	6.71	16.08
StDev	0.06	0.03	0.08	0.42	0.29	1.76
Max	3.79	2.92	3.88	7.10	7.11	18.59
Min	3.65	2.84	3.66	5.98	6.33	13.91

Table E.2. Gradual-edge CS (G-CS) HT Adaptation data for 5 asymptote values

	G-CS 1ss HIT	G-CS 8ss HIT	G-CS 32ss HIT	G-CS 1ss CR	G-CS 8ss CR	G-CS 32ss CR
Mean	3.74	5.90	5.71	9.65	8.60	25.05
StDev	0.07	0.27	0.21	0.84	0.48	4.32
Max	3.83	6.27	5.99	10.85	9.28	31.45
Min	3.65	5.56	5.44	8.59	7.98	19.89

HT=Halftime

APPENDIX F

CORRELATION TABLES

A session-by-session Omnibus correlation analysis was performed among the 5 search performance outcome measures (**Table F.1)**. In contrast to the trial-by-trial analyses (Section 3.2.1.4), the session-by-session analyses takes the average of the 54 trials of each search session, which in turn reduces the degree of freedom in the analyses by a factor of 54.

Table F.1. **Total Omnibus correlations (Sessions)**

	Reaction Time	**Number Fixations**	**Fixation Duration**	**Saccade Amplitude**	**Saccadic Velocity**
Reaction Time		.778**	-.099*	.291**	.425**
Number Fixations			-.485**	.416**	.350**
Fixation Duration				-235**	-.084
Saccade Amplitude					.746**
Saccadic Velocity					

** Correlation is significant at the 0.01level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed).

Prior to analyses, a Kolmogorov-Smirnov (K-S) test for normality was conducted. Reaction Time and Number of Fixations were significantly deviated from normal distribution ($p<0.0005$), but Fixation Duration, Saccade Amplitude and Saccadic

Velocity were not (p=0.721; p=0.444; p= 0.577, respectively). The more conservative non-parametric Spearman's ρ was used to quantify correlations. As was seen in the trial-by-trial correlation analyses (**3.2.1.3**), the strongest correlation seen with the primary outcome measure (RT) was number of fixations, and the weakest correlation was fixation duration.

Correlation analyses were also performed for the S-CS and G-CS groups separately (**Table F.2).**

Table F.2. Group Omnibus correlations (Sessions)

		Reaction Time	Number Fixations	Fixation Duration	Saccade Amps	Saccadic Velocity
S-CS	Reaction Time		.972**	-.052	.307**	.370**
	Number Fixations			-.251**	.326**	.365**
	Fixation Duration				-.170*	-.066
	Saccade Amps					.876**
	Saccadic Velocity					
G-CS	Reaction Time		.617**	-.132	.277**	.520**
	Number Fixations			-.666**	.609**	.474**
	Fixation Duration				-.458**	-.259**
	Saccade Amps					.562**
	Saccadic Velocity					

** Correlation is significant at the 0.01level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed).
.

The highest correlations observed in both groups were between RT and number of fixations (ρ=0.972 and 0.617 for the S-CS and G-CS groups, respectively). The variable that correlated least with RT and showed the largest differences between the two groups was Fixation Duration (ρ=-0.052 and -0.132 for S-CS and G-CS, respectively).

APPENDIX G

LAST FIXATION PLOTS FOR ALL SUBJECTS

All last fixation plots are presented in order of the set sizes 1, 8 and 32, respectively. To facilitate optimal comparison of the performances of the two scotoma groups, plots of the initial and final blocks of adaptation were put side by side on the same page starting on the following pages.

1 set size

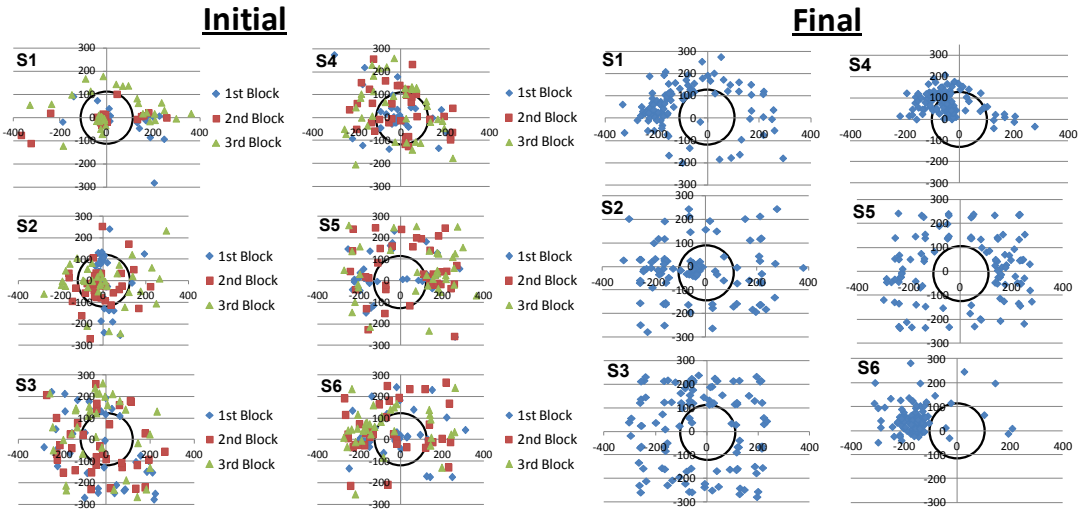

Figure G.1. One set size last fixation from the Sharp-CS group (S1-S6) in the Initial and final blocks stages. The blue diamond, red square, and green triangle represent the 1st,2nd, and 3rd blocks of adaptation, respectively in the initial blocks. Blue diamonds represent the last 3 blocks of adaption in the final blocks

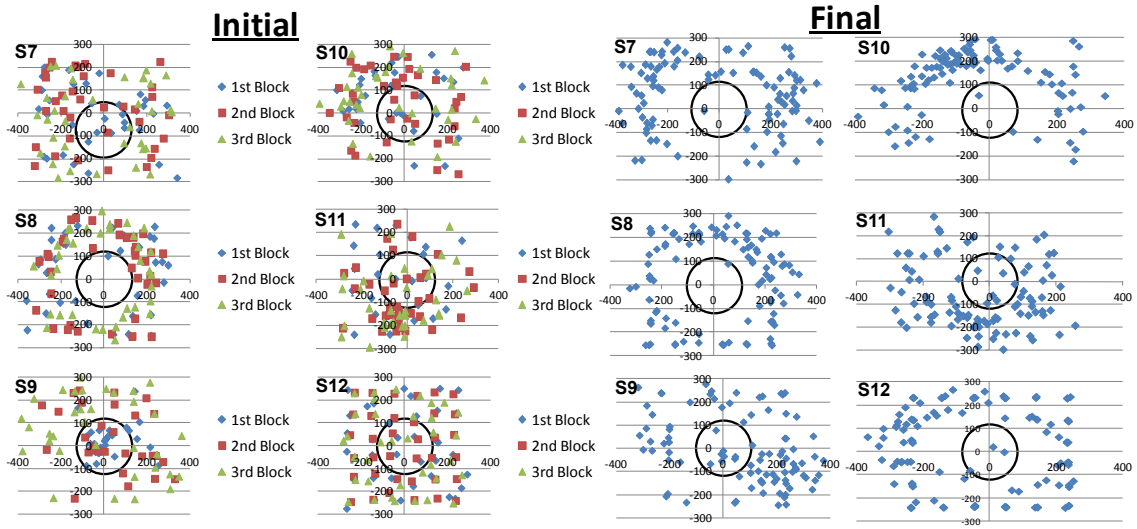

Figure G.2. One set size last fixation from the Gradual-CS group (S7-S12) in the Initial and final blocks stages. The blue diamond, red square, and green triangle represent the 1st,2nd, and 3rd blocks of adaptation, respectively in the initial blocks. Blue diamonds represent the last 3 blocks of adaption in the final blocks

8 set size

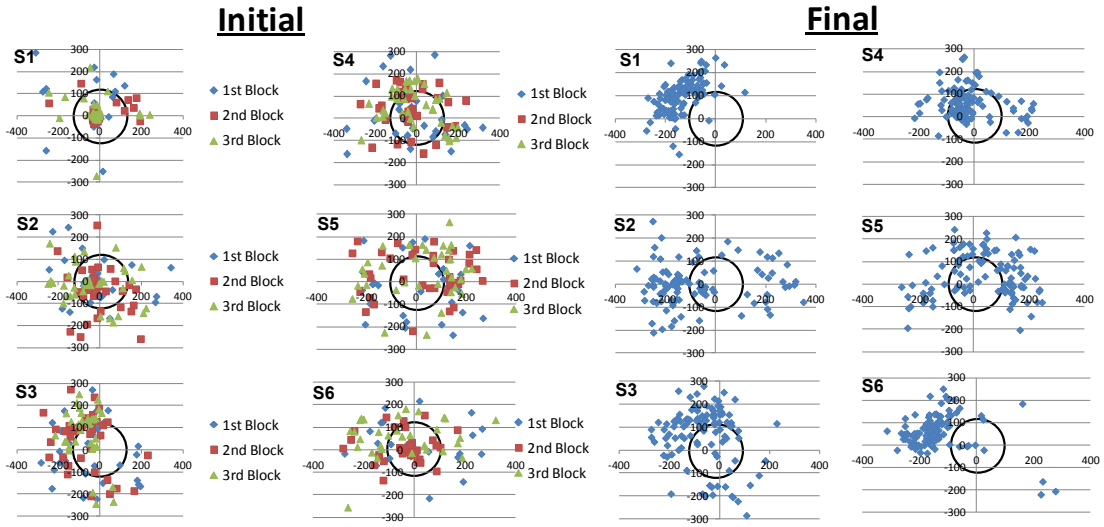

Figure G.3. Eight set size last fixation from the Sharp-CS group (S1-S6) in the Initial and final blocks stages. The blue diamond, red square, and green triangle represent the 1st,2nd, and 3rd blocks of adaptation, respectively in the initial blocks. Blue diamonds represent the last 3 blocks of adaption in the final blocks

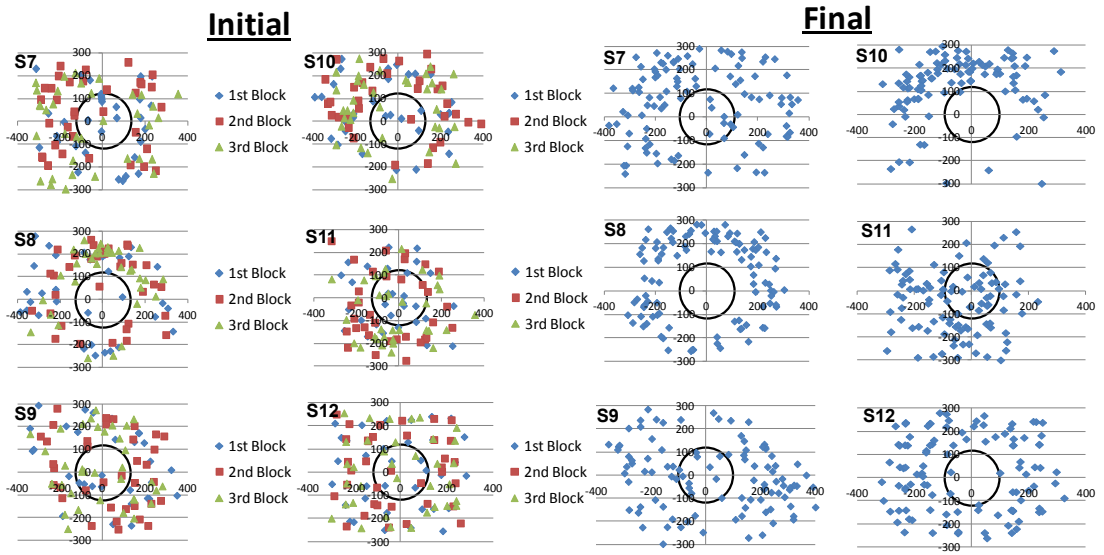

Figure G.4. Eight set size last fixation from the Gradual-CS group (S7-S12) in the Initial and final blocks stages. The blue diamond, red square, and green triangle represent the 1st,2nd, and 3rd blocks of adaptation, respectively in the initial blocks. Blue diamonds represent the last 3 blocks of adaption in the final blocks

32 set size

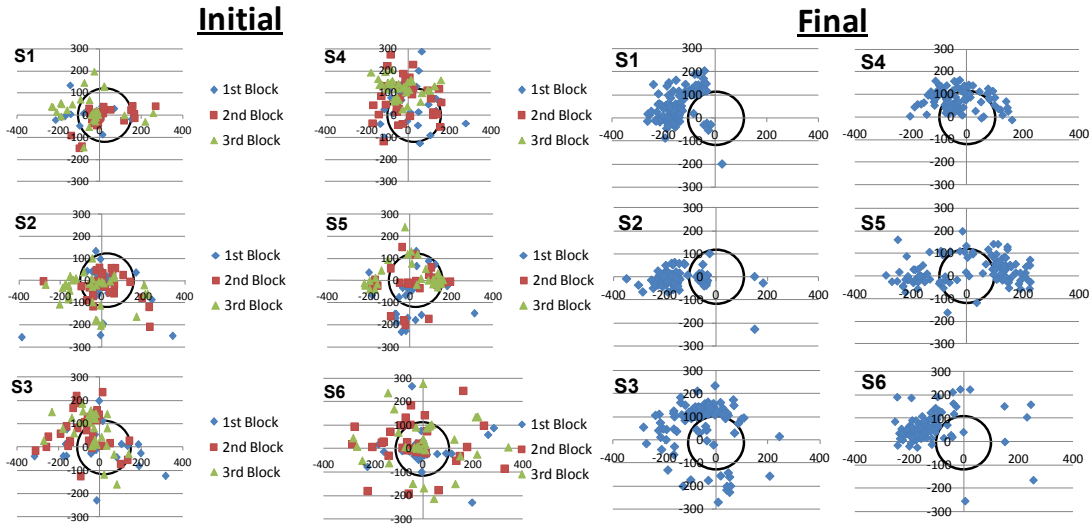

Figure G.5. Thirty-two set size last fixation from the Sharp-CS group (S1-S6) in the Initial and final blocks stages. The blue diamond, red square, and green triangle represent the 1st,2nd, and 3rd blocks of adaptation, respectively in the initial blocks. Blue diamonds represent the last 3 blocks of adaption in the final blocks

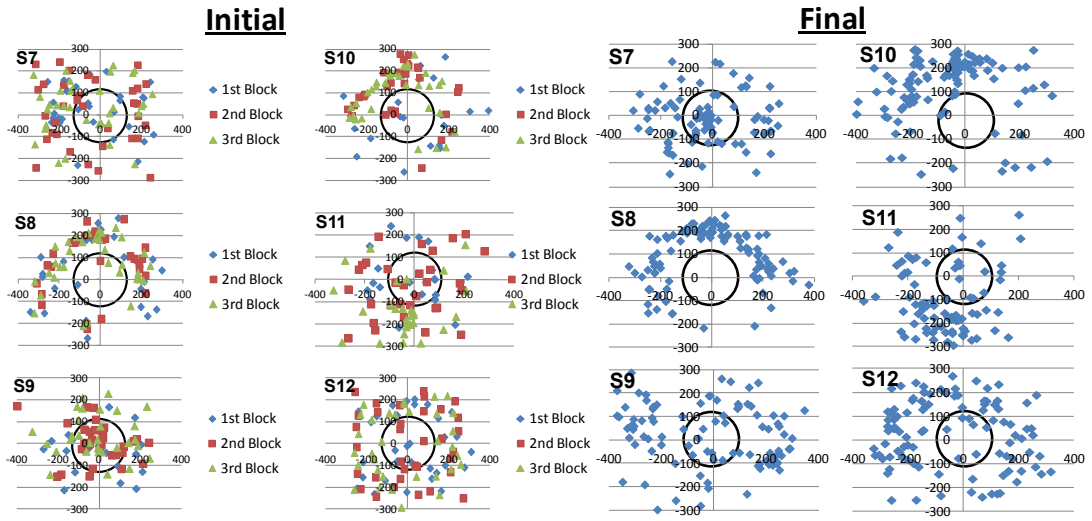

Figure G.6. Thirty-two set size last fixation from the Gradual-CS group (S7-S12) in the Initial and final blocks stages. The blue diamond, red square, and green triangle represent the 1st,2nd, and 3rd blocks of adaptation, respectively in the initial blocks. Blue diamonds represent the last 3 blocks of adaption in the final blocks

UAB THE UNIVERSITY OF ALABAMA AT BIRMINGHAM

Institutional Review Board for Human Use

Form 4: IRB Approval Form
Identification and Certification of Research
Projects Involving Human Subjects

UAB's Institutional Review Boards for Human Use (IRBs) have an approved Federalwide Assurance with the Office for Human Research Protections (OHRP). The Assurance number is FWA00005960 and it expires on January 24, 2017. The UAB IRBs are also in compliance with 21 CFR Parts 50 and 56.

Principal Investigator: WALSH, DAVID V

Co-Investigator(s):

Protocol Number: **E120228003**

Protocol Title: *Adaptation to a Simulated Central Scotoma in Visual Search Tasks*

The above project was reviewed on 3/20/12. The review was conducted in accordance with UAB's Assurance of Compliance approved by the Department of Health and Human Services. This project qualifies as an exemption as defined in 45CF46.101, paragraph 4.

This project received EXEMPT review.

IRB Approval Date: 3/20/12

Date IRB Approval Issued: 3/20/12

Cari Oliver
Assistant Director, Office of the
Institutional Review Board for Human
Use (IRB)

Investigators please note:

IRB approval is given for one year unless otherwise noted. For projects subject to annual review research activities may not continue past the one year anniversary of the IRB approval date.

Any modifications in the study methodology, protocol and/or consent form must be submitted for review and approval to the IRB prior to implementation.

Adverse Events and/or unanticipated risks to subjects or others at UAB or other participating institutions must be reported promptly to the IRB.

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