Mobile Perimeter

by

Ilona Wong

A thesis submitted in conformity with the requirements
for the degree of Master of Applied Science
Graduate Department of Electrical and Computer Engineering
University of Toronto

Abstract

Mobile Perimeter

Ilona Wong
Master of Applied Science
Graduate Department of Electrical and Computer Engineering
University of Toronto
2016

We developed a novel perimeter that is implemented on a low-cost tablet that can be used by patients at home and/or to screen for visual field defects in areas of the world in which access to expensive medical instrumentation and hospitals is limited. To perform visual field tests on a standard tablet in an uncontrolled environment, we have developed methods that are able to test the entire visual field and extend the limited dynamic contrast range. Furthermore, we have developed methods that automatically adjust the testing procedure (i.e. change the intensity of the stimuli) when the ambient light in the room changes and automatically compensate for relative movements between the subject and the display so that patients will not have to use chin-rest during the test. We obtained comparable results to the Humphrey Field Analyzer (the industry standard) when testing on control groups and patients with glaucoma.

Acknowledgements

I would like to thank my supervisors, Jonathan Rose and Moshe Eizenman, for all their knowledge, assistance and guidance. I would also like to thank Dr. Graham Trope for his clinical input and help with all the studies involved. Thank you also to Susan Umail for helping recruit patients, Behzad Amoozgar for testing all our control subjects on the Humphrey Field Analyzer on his birthday, and Melissa Wong for helping coordinate patients for the study.

Thank you to the Vision Science Research Program and the Glaucoma Society of Canada for their support of this research.

Thanks to the people in my graduate group, Braiden Brousseau, Daniel DiMatteo, Jason Luu, Alex Rodionov, and Henry Wong for all their help and insights. Thanks to all my friends for their support. And thank you especially to my parents and my family for their constant love, support and encouragement.

Contents

List of Tables

List of Figures

Chapter 1

Introduction and Background

Glaucoma, one of the leading causes of blindness in the world, is a disease that first affects a person's peripheral visual field [1]. Visual field testing, or perimetry, is of fundamental importance in the diagnosis of glaucoma. It is difficult to detect glaucoma without proper visual field testing instrumentation, and by the time the symptoms show up, there is a high risk of permanent lost of vision. The human brain's ability to extrapolate and fill in the missing parts from the image seen make the detection of peripheral visual field loss harder. Large parts of a person's vision can be lost before the disease is noticed by the person suffering from glaucoma. Ophthalmologists estimate that there are currently 3 million people in the United States with glaucoma, half of which are undiagnosed. Currently, visual fields are tested by specialized and expensive instruments in controlled environments and under the supervision of trained technical staff. This is not feasible in many parts of the world.

The purpose of this thesis is to develop a portable perimeter that can be used by patients at home and/or screen for visual field defects in areas of the world in which access to expensive medical instrumentation and hospitals is limited. We believe that the many sensors and the computing power available on standard mobile devices, such as tablets and smartphones, can support the development of a *portable* perimeter that will not require any extra specialized hardware. Successful development of a portable perimeter could revolutionize the ability to detect and monitor visual field loss in patients with glaucoma.

This chapter will provide necessary background on the process of perimetry, existing

strategies, and will outline the goals of this project.

1.1 Perimetry

Perimetry is a systematic process that tests the visual field. The visual field refers to the area in which objects can be detected while the eye is fixating on a point. The boundary limit of this field is normally 60° superiorly, 75° inferiorly, 100° temporally, and 60° nasally as illustrated in Figure 1.1.

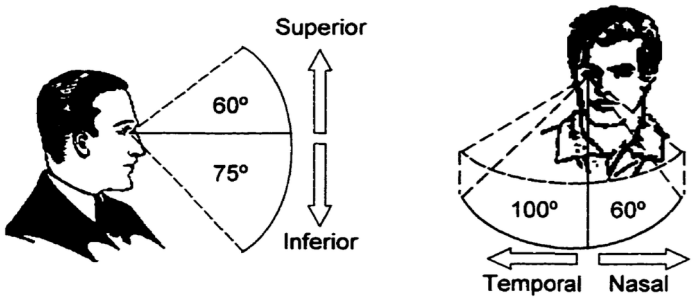


Figure 1.1: Visual field boundary, picture taken from [2]

Perimetry tests the visual field by measuring the eye's ability to perceive stimuli at different points in the field. More precisely, this is the capacity to perceive differences in luminance. Luminance is a measure of the luminous intensity per unit area travelling in a specific direction. In the case of perimetry, stimuli are presented on a surface and the luminance is the light per unit area that is reflected from the screen into the eye. Luminance can be measured in candela per square meter (cd/m^2) or in apostlibs (asb) ($1\ cd/m^2 = \pi$ asb).

The probability of a person detecting stimuli at each point in the visual field can be defined by a frequency-of-seeing curve. A visual field test finds the point at which there is a 50% chance of perceiving the stimulus. The contrast difference between the luminance of the stimulus and the background at this 50% point is called the visual threshold or differential light sensitivity. The frequency-of-seeing curve, seen in Figure 1.2, shows the probability of perception relative to the stimulus intensity. There is a very high chance of seeing the stimulus at a specific point if it is bright enough and a very low chance of perception when the intensity is very low, illustrated by the flattening of the curve on the extremes of the x-axis, representing the intensity of the stimulus. However, the curve between the ability and inability to perceive a stimulus is quite steep, and the range of

intensities for a trained observer at which they may or may not perceive the stimulus spans roughly 3 dB [3].

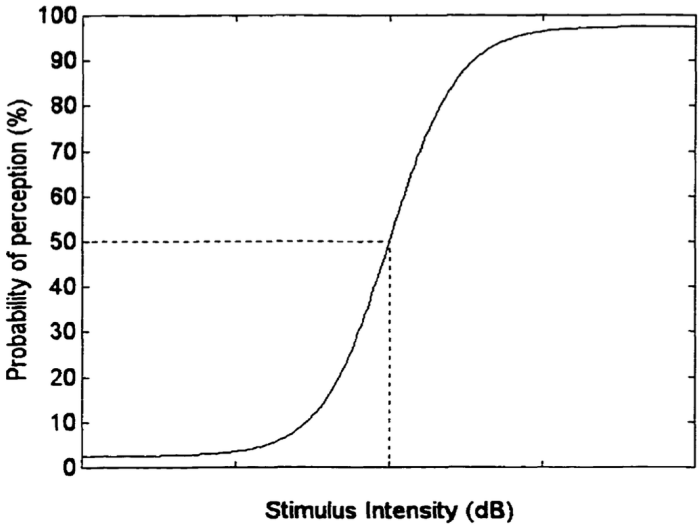


Figure 1.2: Frequency-of-seeing curve, picture taken from [2]

It should be noted that the thresholds vary with ambient light. The visual field tests generally measure these thresholds in mesopic (low lighting conditions) or photopic (bright lighting conditions) levels of light, meaning there is at least some level of background lighting. When in complete darkness, the threshold is known as the absolute threshold.

The human eye perceives differences in light intensities as ratios, as described in the Weber-Fechner fraction (Equation 1.1. To find the measure of contrast, also known as the differential light sensitivity S or the contrast ratio, the background luminance L_b is subtracted from the stimulus luminance L and is divided by the background luminance. This law only applies in the mesopic (0.001 - 3 cd/m^2) and photopic illumination levels (10 - 10^8 cd/m^2).

$$S = \frac{L - L_b}{L_b} \tag{1.1}$$

When reporting results in perimetry, the differential light sensitivity is expressed in an attenuation scale in decibels. The maximum stimulus intensity of the standard perimeter (Humphrey Field Analyzer) is represented by 0 dB, with larger numbers dimmer intensities. A 0 dB threshold would represent complete vision loss as the subject was unable

to see a 0 dB stimulus. The area of the visual field in which a patient has loss of vision is called a scotoma.

1.1.1 Examination Strategies

The two most common strategies for visual field testing include kinetic and static perimetry. Both require measuring the differential light sensitivity of the field, but they do it in different ways. As hinted at by their names, kinetic perimetry involves the movement of the stimulus point, in static perimetry, the stimulus is not moving. We will only be focusing on static perimetry as it is the standard used in the diagnosis and monitoring of glaucoma.

Static perimetry determines the differential light sensitivity at specific locations in the visual field as seen in Figure 1.3. The specific arrangement of points is called the 24-2 test for the right eye. The test for the left eye is the mirror image of this figure. The points are spaced 6° apart and points as far as 27° from the centre are tested. The darkened spots in the figure are where the physiological blind spot is located for the average person. This is where the optic nerve is attached to the retina, and thus there are no rods or cones to detect the light falling at that point on the eye, causing a blind spot. At each of these points, the intensity of the stimuli finds the differential light sensitivity threshold by testing higher and lower levels of intensities until it approaches the actual threshold. A damaged visual field is one in which the differential light sensitivities are lower than the age-corrected values of a normal and healthy eye.

One of the simplest algorithms to perform static perimetry is the 4:2 double-staircase strategy. An initial stimulus is presented to the patient, and if it is seen, the intensity is decreased by 4 dB until it can no longer be seen. Then it is increased in 2 dB steps until the user can see it again. If the user does not see the initial stimulus, the intensity is increased in 4 dB steps until it can be seen, and then decreased by 2 dB until it cant be seen. The final intensity recorded as seen is the differential light sensitivity.

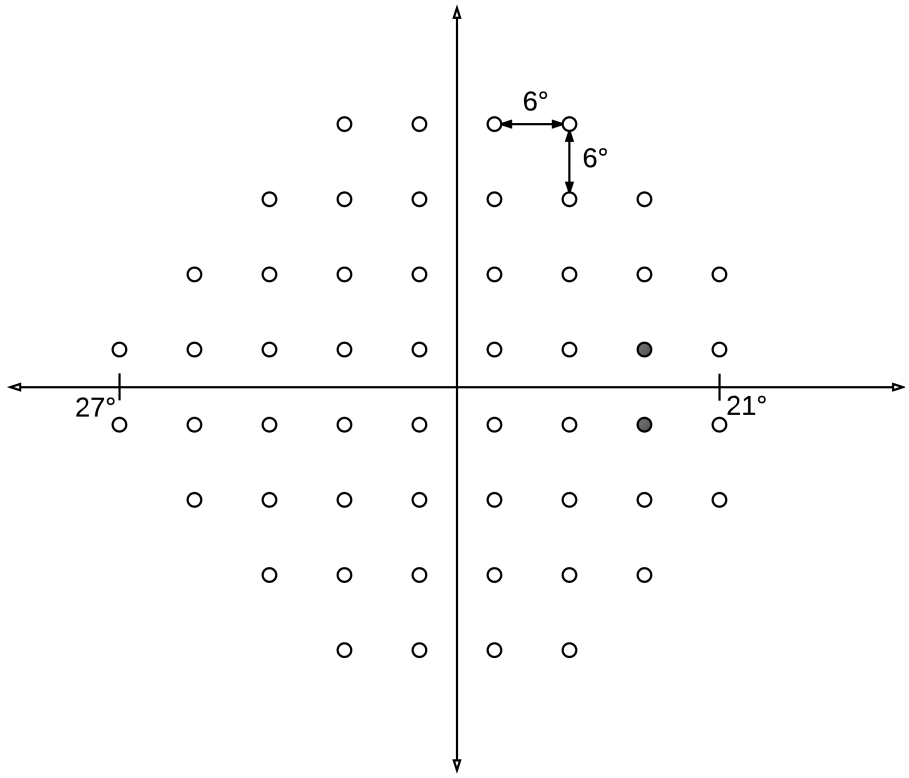


Figure 1.3: 24-2 Test

1.2 Humphrey Field Analyzer

The Humphrey Field Analyzer (HFA) is an automated perimeter that uses static perimetry and is the perimeter of choice at most hospitals in North America. Ophthalmologists mainly use the results from this test to diagnose and plan treatment and surgery for patients with glaucoma. This is an industry standard and if we want doctors to care about a mobile version of this test, the mobile perimeter will have to support the HFA as closely as possible. This section describes the major properties of this test that will have bearing on the design of the mobile perimeter.

1.2.1 Physical Setup

In the HFA's setup, seen in Figure 1.4, the subject sits and rests his/her head on a chinrest and faces a white hemispheric bowl of 30 cm radius that envelopes their visual field. The subject is told to take off any glasses they may be wearing and the proper lens compensation is placed in front of their eye. The lens compensation is either taken from

the subject's prescribed reading glasses or calculated based on their age and the distance (30 cm). The subject wears an eye patch on the eye not being tested and is told to fixate on a point in the middle of the bowl that is coloured an amber shade. When they see flashing stimuli in their peripheral vision, the subject is required (through prior verbal instruction) to press a button..

The important details here that a mobile perimeter will have to imitate or accomodate for are the fixed position of the subject, requiring their head to be still on chin-rest, the fixed environmental lighting of the setup, and a method to give feedback to the test when a stimuli is seen.

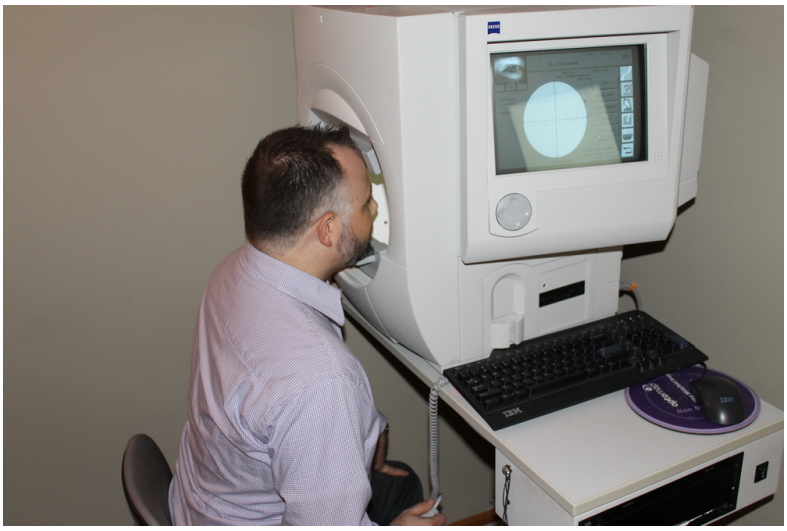


Figure 1.4: Humphrey Field Analyzer, picture taken from [4]

1.2.2 Display

The Humphrey Field Analyzer uses a white bowl with a uniform background illumination of 31.5 asb (apostlibs, unit of luminance) or 10 cd/m^2 (luminance). The HFA projects light onto the background illumination, and the maximum light that can be projected is 10,000 asb. It uses an attenuation scale of 0 to 50 dB (0 being the brightest). The test is done in a room with dim lighting so that the background illumination is provided mainly by the perimeter. As a result, the perimeter can control the contrast ratio of their stimuli.

Recall from Section 1.1 that the contrast ratio depends on the ratio of background and stimulus luminance. Luminance perceived by the eye is dependent on the size of the

stimulus. A larger stimulus size results in a larger effective intensity perceived by the subject as the sizes get larger. This is because the larger stimulus sizes physically project a larger area onto the retina. Quadrupling the area of the stimulus is psychophysically equivalent to increasing the intensity by 5 dB [5]. Goldmann stimulus sizes are standard stimulus sizes used for visual field tests. They specify the diameter of the stimulus in terms of degrees. These diameters are shown in Table 1.1. Each size stimulus quadruples the area of the one before it. The length of time can also effect the luminance perceived; the longer the stimulus is displayed, the brighter it is perceived. The standard stimuli on the Humphrey Field Analyzer are projected for 200 ms and are a Goldmann stimulus size III. The HFA is capable of varying the stimulus size from I to V.

Table 1.1: Standard Goldmann stimulus sizes

Goldmann Notation	**Stimulus diameter (°)**	**Stimulus area at 30 cm distance (mm^2)**
0	0.05	0.0625
I	0.11	0.25
II	0.22	1
III	0.43	4
IV	0.86	16
V	1.72	64

The HFA uses an attenuation scale of 0 to 50 dB to represent the range of intensities that can be displayed on the dome. 0 dB is the brightest intensity, where 10,000 asb is projected onto the 31.5 asb bowl (resulting in a stimulus intensity of 10,000 + 31.5 asb, and a background of 31.5 asb), giving a differential light sensitivity of 317.5, as calculated by Weber's law, seen in Equation 1.2.

$$\begin{aligned} S &= \frac{L - L_b}{L_b} \\ 317.5 &= \frac{(10000 + 31.5) - 31.5}{31.5} \end{aligned} \tag{1.2}$$

To convert it to the attenuation scale, the HFA uses Equation 1.3, which is designed to set the 10,031.5 asb stimulus to be the 0 db level. As you can see, the 10,000 asb projected onto the dome is represented as 0 dB. Table 1.2 shows the entire attenuation scale.

$$\begin{aligned} S_{dB} &= 25 - 10log(S) \\ 0dB &= 25 - 10log(317.5) \end{aligned} \tag{1.3}$$

Table 1.2: HFA Attenuation Scale

HFA Attenuation (dB)	**Projected Stimulus Intensity (asb)**	**HFA Attenuation (dB)**	**Projected Stimulus Intensity (asb)**
0	10000	26	25
1	7912	27	20
2	6285	28	16
3	4992	29	13
4	3966	30	10.0
5	3150	31	7.9
6	2502	32	6.3
7	1988	33	5.0
8	1579	34	4.0
9	1254	35	3.2
10	996	36	2.5
11	791	37	2.0
12	629	38	1.6
13	499	39	1.3
14	397	40	1.0
15	315	41	0.79
16	250	42	0.63
17	199	43	0.50
18	158	44	0.40
19	125	45	0.32
20	100	46	0.25
21	79	47	0.20
22	63	48	0.16
23	50	49	0.13
24	40	50	0.10
25	32		

The mobile perimeter will have to be able to support an attenuation scale that sufficiently tests the visual field, as well as be able to account for changes in the background illumination to produce the proper differential light sensitivity.

1.2.3 Visual Field Test

The standard perimetry test on the HFA uses the 24-2 visual field assessment, as seen previously in Figure 1.3. The test takes approximately 4 - 7 minutes. It can also handle many other variations, some which can test a larger visual field and others a more dense central visual field. The HFA uses the Swedish Interactive Thresholding Algorithm, in place of the slower 4:2 double staircase algorithm mentioned in Section 1.1.1, and can find the thresholds in a short amount of time through knowing the expected thresholds based on the subject's age and the surrounding threshold values [6]. This algorithm reduces the amount of time required for a test by about 50%, which helps to reduce patient fatigue and increase the reliability of the test.

The HFA is also able to detect fixation losses, false positive and false negatives. Fixation loss refers to when a subject moves their fixation from the amber dot in the middle of the hemispheric bowl. To test for this, the HFA projects a stimulus onto the subject's blind spot, and if the subject presses the button indicating they have seen it, it means their eyes have strayed off the fixation point. False positives represent the times a patient presses the button when no stimulus is presented. False negatives represent the times a patient does not see a brighter stimulus at a point where a dimmer stimulus was previously seen.

The mobile perimeter will, at minimum, need to be able to test all the points in the visual field while not causing significant fatigue for the subject.

1.3 Existing Applications

In this section, various visual field testing applications are discussed and examined.

1.3.1 Damato Multifixation Campimeter

The Damato Multifixation Campimeter is a novel algorithm developed by Damato [7] to test the visual field by using a moving fixation point. An online version of this also exists at [8]. Instead of having the subject fixate continuously on one point, subjects are instructed to fixate on one point while moving the mouse to a second (stimulus)

point whenever they see it in their field of view. They then fixate on the new point and repeat the process with every new point that they see. This technique does not require continuous long fixations on a central target and at the same time raises the probability that the subject is fixating on the proper point on the screen when the peripheral point appears.

One of the drawbacks of this method is the time it takes to complete the test increases dramatically as the fixation point needs to move for every single point that is being tested and the test requires active effort on the part of the subject. To mitigate this problem, this test only differentiates between three intensity levels. Another drawback is their method of determining the intensity of the stimulus. There is a manual calibration step where the subject is told to identify the lightest shade of gray they can see on the screen. In addition, the test requires the subject to position themselves manually. The test displays two dots, and tells the subject to focus on one dot to adjust their position until the other dot cannot be seen. The test itself involves significant amounts of eye and hand movement, so the original position of the subject will invariably be lost during the test, resulting in inaccurate test results.

1.3.2 Eyes Age

Eyes Age is a desktop application [9] that displays a rotating expanding and shrinking circle in the middle of the screen that the user fixates on, and flashes small crosses that expand until the user sees it and hits the spacebar. The expansion of these crosses fluctuates and some expand faster than others. These methods seem to be used to help the subject fixate and concentrate on the test, as well as test for reliability. A slowly expanding cross would not be seen as quickly and if a subject were to press before it has expanded to a reasonable size, the test would know the subject is unreliable.

However, there are many drawbacks to this test. First, this test also requires manual calibration. The subject is required to enter their screen's size as well as how far they are from the screen. The test does not take into account movement during the test and assumes a constant distance between the subject and the screen for the entire duration. In addition, the test does not tell the subject where to position their head in the plane parallel to the screen, which would lead to unreliable test results. This test also does not use varying intensity levels or any kind of attenuation scale.

1.3.3 Vutest

Vutest is an online visual field test [10] in which the subject focuses on a cross and multiple circular stimuli of varying sizes appear on the screen at once. The test then asks the subject how many stimuli they saw in a multiple choice format. The user clicks on the answer and if they missed a stimulus, the test will display all of them again and have the user click on the ones they saw. If the user answered more stimuli than there were, the test will warn them to be more careful. The cross fixation point moves across the screen as the test progresses. This method is able to speed up the test by testing multiple locations on the visual field at once, but the overhead of asking the user the number of dots seen could cause a longer and more tedious test for some users. This method also employs the moving fixation point to cover more of the visual field.

Some drawbacks to this test is manual calibration for both the screen and the subject's position, and potential frustration with their visual test methodology. Vutest asks the subject to measure the size of their computer screen and move 1.5 times away from the screen. Again, this test also assumes the user will stay in the same spot for the whole test while answering questions, and does not know where the user is positioned in the plane parallel to the screen. Vutest also requires the user to calibrate their screen by doing a contrast test and comparing various shades of gray with each other. This test would also likely frustrate users who have glaucoma as they are being shown the stimuli that they missed.

1.3.4 Peek

A UK group called Peek is working on a comprehensive eye exam that can be performed on a smartphone [11]. They do not currently support visual field tests but their goal and premise is similar to this thesis. Their aim is to lower the cost of diagnosis and treatment for use in developing nations for a variety of eye diseases by reducing the cost of expensive eye equipment through creating a method of testing using a mobile device. Their main test involves using a clip-on camera adapter that can take images of the back of the eye and diagnose cataracts, glaucoma and other diseases by sending these pictures to ophthalmologists for independent remote grading. This could potentially prevent many cases of blindness if caught early enough for intervention. From Peek's study [12], they found that nonclinical photographers were able to acquire optic nerve images at

a standard comparable to images taken using a desktop retinal camera operated by an ophthalmic assistant.

1.4 Research Goals

The goal of this thesis is to be able to perform visual field tests on a standard tablet in an uncontrolled environment. The specific goals are as follows:

1. Develop methods for a visual field test on a mobile device.
2. Develop methods that use the sensors of the device to compensate for changes in ambient light and head position.
3. Evaluate the results for control groups and patients and compare against the industry standard.
4. Compare the reliability and accuracy of the mobile perimeter to the standard clinical perimeter (HFA).

1.5 Thesis Overview

Chapter 2 discusses the methods used to improve the restricted field-of-view and the limited dynamic contrast ratios of screens on mobile devices. It also discusses the methods used to compensate for varying ambient light and subject head movements, allowing for testing in a variety of environments. Chapter 3 contains detailed descriptions of the experiments that were carried out to compare the mobile perimeter to the HFA, as well as the methods of analyses that are used to evaluate the mobile perimeter. Chapter 4 presents the data from a series of studies with healthy subjects and compares their results to the HFA. Chapter 5 presents the data from a study with glaucoma patients and compares their results to the HFA. Chapter 6 provides conclusions and outlines potential future work.

Chapter 2

Mobile Perimetry

Existing automated perimeters, such as the Humphrey Field Analyzer [6] or the Octopus [13], require carefully managed environmental protocols. Patients have to maintain fixed head positions by means of a chinrest on the perimeter, while fixating on a central fixation target for long time periods (roughly five to ten minutes per eye). The ambient light of the environment also needs to be controlled, requiring dedicated facilities such as hospitals or eye clinics. This is problematic in developing countries where mobile devices are more accessible than dedicated equipment. A perimeter implemented on a mobile device would provide a low-cost solution that is portable and can be used by anyone with a mobile device, as well as being more comfortable to use.

The Mobile Perimeter (MP) developed in this research is based on a Nexus 7 Tablet [14] that uses the Android operating system [15]. In this chapter we describe several techniques for adapting to the mobile environment we envision the MP will be used in. The perimetric bowl in standard perimeters is replaced by the tablet's screen. To avoid the need for a chinrest, a software-based pattern tracker locates the non-measured eye, which in turn gives the location of the measured eye. The elimination of a chinrest reduces discomfort by allowing subjects to move their heads during the test. Finally, the MP can handle variable illumination in the environment by measuring the ambient light with the tablet's light meter and compensating for it. In addition, we make use of a button on a wirelessly connected (through bluetooth LE) Simplelink Sensor Tag device from Texas Instruments [16] for subjects to press when they see a stimulus.

2.1 Field of View

A frequently used visual field test (24-2) for glaucoma measures the central 30° field (60° vertically and horizontally). The test requires an actual field of view (FOV) of 52° horizontally (H) × 46° vertically (V). However, the screen of the Nexus 7 is $15cm \times 9cm$, which provides a FOV of 30°H × 18°V when viewed at a distance of $25cm$, as seen in Figure 2.1.

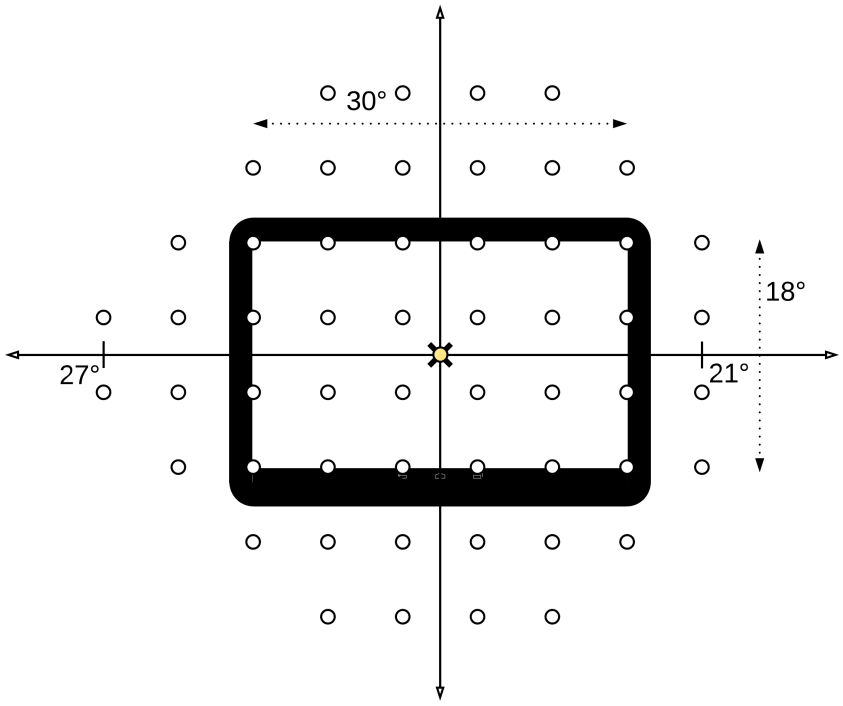
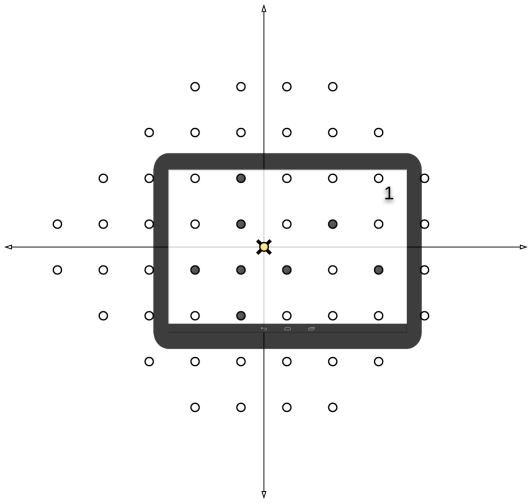


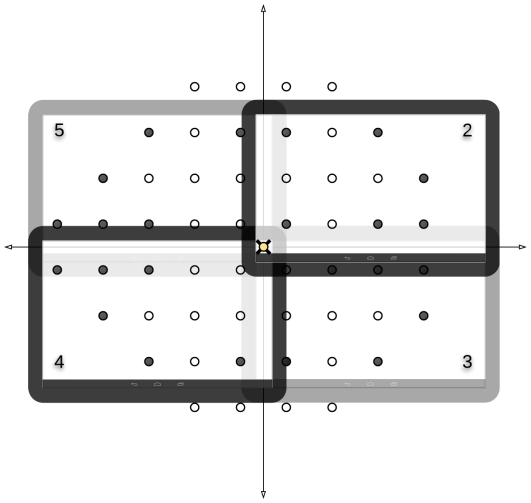
Figure 2.1: Field of View at 25cm distance

To test the required FOV, non-central fixation points are used, which quadruples the effective FOV to 60° × 36°. This is similar to the Dicon perimeters [17] [18] and the Head-mounted perimeter [2]. By placing the fixation point at the bottom of the Nexus 7 screen, the superior visual field that can be tested is extended by 9°V. Another 9°V can be tested by placing the fixation point at the top of the screen. However, the entire vertical visual field is not covered using this technique. To cover the rest of the visual field, the tablet is rotated 90°, which provides a total FOV of 60°H × 60°V. Figure 2.2 shows how the mobile perimeter can cover all points in the 24-2 test. The symbol in the middle of the axes represents the fixation point. The figures visually display the area of the visual field that can be tested if the fixation point is located at the specific corners of the tablet. As can be seen, when the tablet is placed horizontally, not all points can

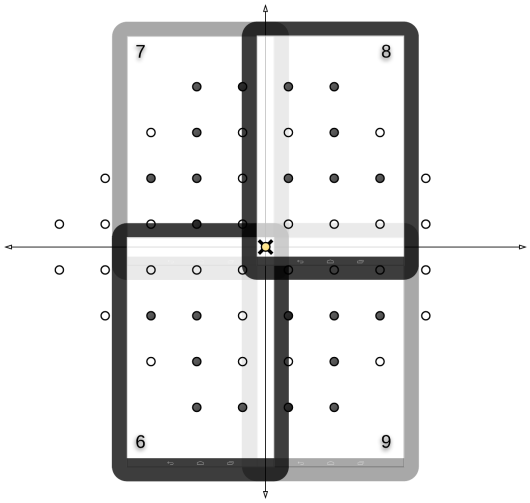
be covered by moving the fixation point to all four corners of the screen, and the reverse is true when the tablet is placed vertically. The filled in dots represent the stimuli that are tested in that orientation on the mobile perimeter.



(a) Center Fixation Points



(b) Horizontally Placed Tablet's Fixation Points



(c) Vertically Placed Tablet's Fixation Points

Figure 2.2: Vertical and Horizontal Fixation Points: How the entire field can be measured

Placing the fixation point in eccentric locations can cause significant fatigue and increases drift velocity [19], which results in unreliable tests. However, by allowing free head movements during the test, the subject is able to fixate on non-central points without having to fixate eccentrically and this reduces the fatigue.

In the MP, the display is flat while the HFA and other perimeters use a hollow, white

spherical bowl to ensure the distance between the visual stimulus and the eye remain constant, and therefore the exact area of the retina that is stimulated by the light rays will also remain constant. As a result, the location of the stimuli on the 2-D tablet display has to be adjusted to achieve the same equality of luminance in all of the stimulus points. Note that the non-central fixation points and the location of the moving subject's eye will also affect the angular projection of the stimulus on the screen. Given the location of the eye, the location of the fixation point, and the desired stimulus angle, one can calculate the exact location to place the stimulus, assuming that the subject's face is parallel to the tablet plane:

$$d_{S,x} = d_{E,z} \times \tan\left(\arctan\left(\frac{d_{F,x} - d_{E,x}}{d_{E,z}}\right) + \theta_{S,x}\right) - (d_{F,x} - d_{E,x}) \tag{2.1}$$

$$d_{S,y} = d_{E,z} \times \tan\left(\arctan\left(\frac{d_{F,y} - d_{E,y}}{d_{E,y}}\right) + \theta_{S,y}\right) - (d_{F,y} - d_{E,y}) \tag{2.2}$$

Where:

$(d_{S,x}, d_{S,y})$: are the stimulus distances in pixels from fixation target for x and y coordinates respectively

$(d_{E,x}, d_{E,y}, d_{E,z})$: are the positions of the eye in pixels from the top left corner of the screen in x, y, and z coordinates respectively The pixel length is using the pixels per inch measurement of the tablet

$(d_{F,x}, d_{F,y})$: are the fixation point distances in pixels from the top left corner of the screen for x and y coordinates respectively

$(\theta_{S,x}, \theta_{S,y})$: are the stimulus angles in degrees from the fixation point for x and y coordinates respectively

Another consequence of using a flat surface is the size of the stimulus has to be adjusted as a function of position on the screen. Stimulus size is based on an angular diameter, which means the non-central fixation points and location of the subject's eye will also affect its angular projection on the screen, and ultimately, on the retina of the subject. To calculate the size of the stimulus points, equations (2.1) and (2.2) are used to calculate the beginning and end of the stimulus point and the difference between the two is the size of the stimulus in the x and y dimension.

If the position and size of the stimulus point are not adjusted, the stimuli would not stimulate the intended positions on the retina, thus reducing the capacity of the test to

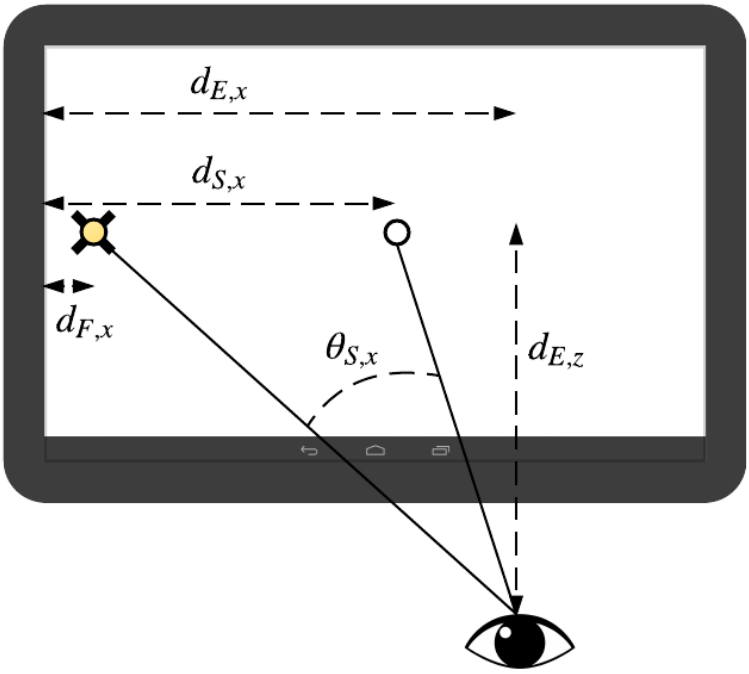


Figure 2.3: Location of the stimulus according to eye location

map the boundaries of sharp changes in retinal sensitivities.

Using dynamic fixaton points as described above allows mobile devices to evaluate the central 30° visual field, and with smartphones increasing in screen size every year, it will become more plausible for the test to be comfortably used on smartphones in addition to tablets. Dynamic fixation also has benefits outside of expanding the field of view - prolonged central fixation usually results in stress and fatigue [20]. With multiple fixation locations, the subject's eye will move and fixate at different points during the test, reducing fatigue, thereby increasing the reliability of the test [17] [18].

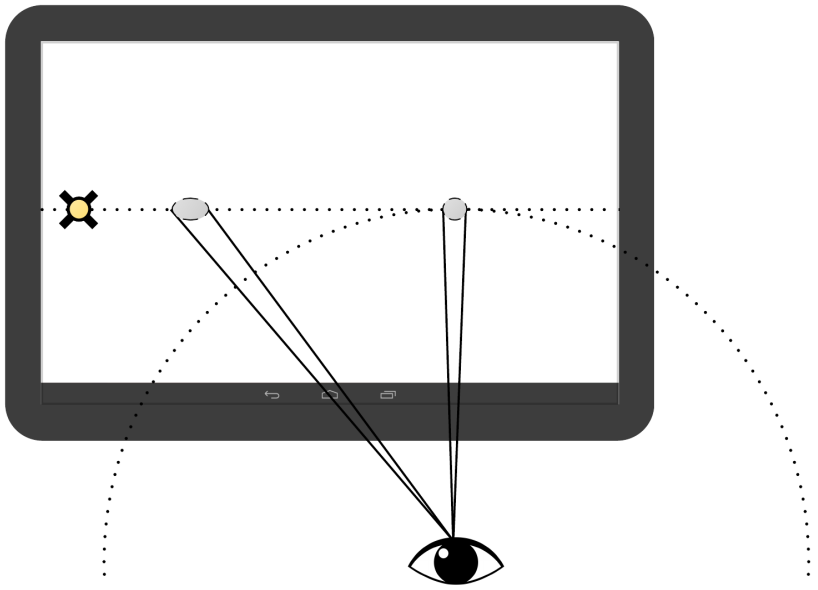


Figure 2.4: Stimulus Variation on Flat Screen

2.2 Compensation for Head Movements

One goal when implementing a mobile perimeter is to allow subjects to perform the visual field test without requiring extra equipment or complicated set-ups. Standard perimeters use a chinrest as part of the perimeter to constrain the subjects head movements and thereby making sure that the distance between the subjects eye and the visual stimuli remains constant. Since it is not feasible to integrate a chinrest into a mobile device we need to develop a method that will allow subjects to move their heads during the test.

The reason the HFA uses a chinrest to keep the subject's head in place is to properly position the subject's eye relative to the fixation point and to ensure the subject's eye is perpendicular to the ground in the world coordinate system (WCS). Knowing the position of the eye relative to the fixation point is important as it is needed in order to display the stimuli onto the correct location on the retina. Ensuring the eye is perpendicular to the ground is also important because there is an ocular counter-roll that occurs when a person rolls their head to the side. A counter-roll is a physiological reflex activated by gravity sensors in the inner ear that stabilizes images on the retina when the head moves [21]. When the head rolls clockwise, the eye will counter-roll counter-clockwise a slight amount. This amount is variable from person to person and has a smaller effect as the roll increases [22]. To eliminate any need to compensate for counter-roll, the HFA simply fixes the subject on the chinrest to make sure the eye is unaffected and stays

perpendicular to the WCS.

Therefore, the MP needs to 1) know where the subject's eye is relative to the fixation point and 2) know how the head is positioned relative to the WCS. With the available sensors on a mobile device, one solution could involve using the front-facing camera to track the head. Then, assuming the position of the eye and head can be tracked, there are two different cases that could happen: 1) The subject's head moves relative to the tablet and 2) The tablet moves relative to the subject's head. In this context, the second can be eliminated as it is unlikely and the usage instructions for the related App will discourage a person from holding the device while doing their visual field test. This simplifies many issues, such as not knowing if a rotation detected was due to the tablet or the subject, which would change the expected counter-roll.

If the mobile device is fixed (for example, it is being supported on a table), we need to obtain the x, y, and z position of the eye relative to the fixation points on the screen of the device, as well as the eye rotation which consists of the roll, pitch and yaw (Figure 2.5), and then account for counter-roll. The position and rotation are referred to as the 6 degrees of freedom (6DoF) of the eye.

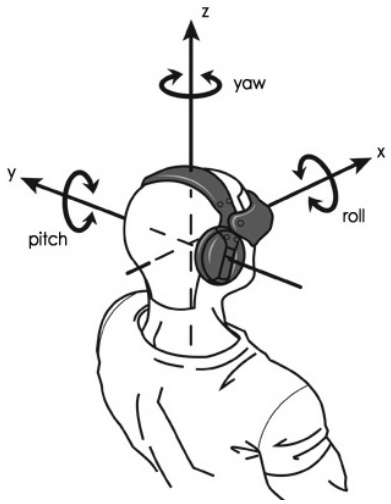


Figure 2.5: Six Degrees of Freedom, image taken from [23]

A solution to this is to track the head. The x, y, z, pitch, and yaw of the head provide information about the center of rotation of the eye and once the location of the center of the eye is found, a vector can be drawn from the eye to the fixation point. The head-tracker's roll can be used to determine if the visual fields should be rotated (in cases of large counter-rolls, it is also possible to warn the patient if he/she is beyond certain limits).

To find the 6DoF of the head, two options were evaluated - using a commercial tool or creating our own. Using a commercial tool would allow quick integration into the MP at the cost of being unable to access the source code for debugging or custom changes. Creating a head tracker would allow for more flexibility in terms of usage (for example, we need to track the head when one eye is covered).

2.2.1 Commercial Head Tracking

The commercial tool evaluated was Visage, a head and facial feature tracking engine developed by Visage Technologies [24]. It can track faces in real time and provides 6DoF of the head. The only calibration required is the users interpupillary distance. However, Visage was difficult to integrate into the system due to failure to work within the constraints of a visual field test.

Visage was able to track a person's head and features relatively well and the estimates of distance were within millimetres of the actual distance when the interpupillary distance was provided. However, Visage would behave poorly when parts of the face were occluded - glasses, eye patches and bangs all caused the head pose estimation to lose track of the face or provide distances that were centimetres off.

Because an eye patch is a required part of a visual field test (the visual field test evaluates one eye at a time) and Visage was unable to cope with such occlusions, a custom way of finding the 6DoF of the eye was needed. We used the fact that an eye patch would always be present during a visual field test and by placing a simple patern on the eye patch, we were able to track the head pose. The next section will describe this method in detail.

2.2.2 Custom Pose Estimator

Our method uses the combination of the properties of the visual field test and a well-known way of calibrating a camera to find the 6DoF of the eye. A set pattern of known size (Figure 2.6) is placed on the eyeglasses of the subject on the side with the eye patch. For subjects who don't use eyeglasses, a pair of frames with no lenses are used to hold the pattern in place. This pattern is tracked using the front-facing camera through the help of standard OpenCV camera calibration libraries [25]. Once the location of the

pattern is found, we estimate where the tested eye is located by using the average person's interpupillary distance. The actual location of the eye for each subject is obtained by manually adjusting the position of a cursor on the image of the face to be aligned with the centre of the pupil. This manual adjustment is done before a test.

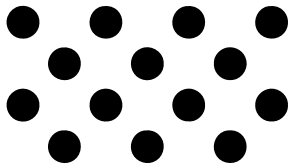


Figure 2.6: Assymmetrical grid of circles used for head tracking

Before we can begin and track the pattern, each camera first requires some set-up. This involves camera calibration, which is used in many computer vision applications to extract intrinsic and extrinsic parameters from 2-D images [26].

Intrinsic parameters describe the properties of the optical system and the camera, such as the focal lengths, the principal point, usually located in the centre of an image, and the image sensor format. There are also non-linear intrinsic parameters, such as radial and tangential distortion of the lens. The extrinsic parameters include the rotation and translation matrix and maps the image in the world coordinate system to the camera coordinate system, which is the coordinate system that follows the axis of the camera [26]. Once the intrinsic parameters have been found through calibration, they can be stored for that device and no further calibration is required. These parameters will later allow us to calculate the real world 6DoF of the pattern. This will be elaborated upon later on.

There are a variety of ways to calibrate cameras. A common way of calibrating cameras is to analyze known patterns on a 2-D plane (2-D plane-based calibration, which is supported by OpenCV [25]) in multiple orientations. Other methods include using a 3-D reference object, a 1-D line-based calibration, or self-calibration [26]. The 2-D plane-based calibration is the simplest method as the pattern used for calibration can be easily made by anyone and there exist OpenCV libraries that perform camera calibration using this method. Another reason to use the 2-D method is that it can provide the location of the pattern in the camera coordinate system. This would allow us to know where the pattern is relative to the camera at all times.

To calibrate the camera of the mobile perimeter, fourteen images of a 20×12 checker-

board pattern were taken at various angles and the intrinsic and extrinsic parameters were extracted through OpenCV's camera calibration library [25]. OpenCV uses a pin-hole camera model to model the transformation of projecting a 3D object onto the image plane [25]. This transformation is seen in Equation 2.3, which is expanded and detailed in Equation 2.4. In this equation, a 3D object point is denoted by $M = [X, Y, Z]^T$. The 2D corresponding point on the image is denoted by $m = [u, v]^T$. $\widetilde{X}$ is used to denote the augmented vector: $\widetilde{M} = [X, Y, Z, 1]^T$ and $\widetilde{m} = [u, v, 1]^T$. $\mathbf{A}$ is the camera intrinsic matrix, ($\mathbf{R}$,$\mathbf{t}$) are the extrinsic parameters, where $\mathbf{R}$ is the rotation matrix and $\mathbf{t}$ is the translation vector. Because the 3D object is a 2D checkerboard plane, if one assumes that the Z coordinate of all the points on the plane is 0, equation 2.4 can be simplified to Equation 2.5, which allows the parameters to be solved for by using Zhang and Bouguet's algorithms [27] [28].

$$s\widetilde{m} = \mathbf{A}[\mathbf{R}|\mathbf{t}]\widetilde{M} \tag{2.3}$$

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{2.4}$$

Where:

$[u, v]$	:	are the coordinates of the object in the camera coordinate system
s	:	is an arbitrary scale factor
$[f_x, f_y]$	:	are the focal lengths of the camera in pixels
$[c_x, c_y]$	:	is the principal point, usually the centre of the image, in pixels
$[X, Y, Z]$	:	are coordinates of the object in the 3D world coordinate system

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ r_{31} & r_{32} & t_3 \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \tag{2.5}$$

Once the intrinsic parameters are found, they are stored for that specific device and no further calibration is necessary. We found that different devices of the same model would have variations in the output luminance as well as the lightmeter measurements. This needs to be investigated further to see how much these variations would affect the results.

We now wish to find the location of the 2D assymmetrical circle pattern in Figure 2.6 that will be placed on the eye-patch during the visual field test and use that to estimate the location of the tested eye. OpenCV provides multiple functions to find three different patterns, and the $findCircles$ function was used to find the location of the assymmetrical circle pattern in the 2D image.

You may notice that the pattern was switched from a checkerboard to an assymmetrical circle pattern. This was due to the OpenCV $findChessboardCorners()$ function being slow when the function fails to identify the corners. The algorithm repeatedly undergoes an erosion process, where each pixel is converted to the minimum of all pixels in its surrounding area, until each square of the checkerboard has been separated and the pattern is found [29]. In the failure case, this process would repeat itself too many times. With an assymmetric grid of circles, the circles are already separated so this problem does not occur. The speed at which the algorithm finds the pattern is 1 - 3 times per second.

The location of the pattern now needs to be transformed to coordinates in the camera coordinate system by using Equation 2.6. The location of the pattern is $[X, Y, Z]$ and are modified to point to the location fo the eye by adding constants $[u_x, u_y, u_z]$, which represent the coordinates of the eye relative to the coordinates of the pattern. These constants are first estimated through the interpupillary distance, and then manually adjusted for before the test by having the subject position a cursor over their pupil. This sum is multiplied by the rotation matrix R and translated by the translation vector t. R and t are the extrinsic parameters for that specific frame, calculated using the OpenCV function $solvePnP$, which uses the intrinsic parameters that were found from camera calibration. The coordinates of the object in the camera coordinate system are denoted by $[x, y, z]$. Once the transformation is performed, a scaling factor s (distance in mm between two checkerboard centres) can be used to obtain the exact x, y, and z coordinates in mm. These coordinates are relative to the camera on the tablet.

Equation 2.7 transforms the coordinates to be the position of the eye in pixels relative to the top left hand corner of the screen in the camera coordinate system. The position of the eye is multiplied by a constant s, which is the scale factor that transforms from coordinates to millimetres. This is transformed to be relative to the top left hand corner of the screen by adding constants $[c_x, c_y, c_z]$, which is the location of the top left hand corner of the screen relative to the camera. Finally, to represent these coordinates in pixels, it is multiplied by a constant p, which is the pixel density of the screen (which can be in

units ppi). This results in the position of the eye in pixels, denoted by $[d_{E,x}, d_{E,y}, d_{E,z}]$, and is required for the input of the equations that calculate stimulus location (Eq. 2.1 and 2.2).

$$s \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{R} \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \right) + \mathbf{t} \tag{2.6}$$

$$\begin{bmatrix} d_{E,x} \\ d_{E,y} \\ d_{E,z} \end{bmatrix} = p \left(s \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} \right) \tag{2.7}$$

Where:

$[x, y, z]$	:	are the coordinates of the object in the camera coordinate system
p	:	is a constant denoting the transformation from units in distance to pixels
$[c_x, c_y, c_z]$	:	are the constants added to translate the origin from the camera to the top left hand corner of the screen in distance
$[u_x, u_y, u_z]$	:	are the constants added to find the position of the tested eye instead of the centre of the object
$[d_{E,x}, d_{E,y}, d_{E,z}]$	:	are the positions of the eye in pixels from the top left corner of the screen in x, y, and z coordinates respectively, needed as input to Equations 2.1 and 2.2

From the extrinsic parameters, the positions of the eye in pixels, the yaw (ϕ), pitch (θ) and roll (ψ) can be found using the rotation matrix, as seen in Equation 2.8. In addition, the roll is multiplied by 0.9 to take into account counter-roll. This number was chosen because various studies have found that the average eye has a counter-roll of approximately 0.9 [21], which means the eye rolls back 10% of the roll.

$$\begin{aligned} \phi &= \operatorname{atan2}(-r_{32}, r_{33}) \\ \theta &= \arcsin(r_{31}) \\ \psi &= 0.9 \times \operatorname{atan2}(-r_{21}, r_{11}) \end{aligned} \tag{2.8}$$

Where:

$$\text{atan2}(y,x) = \begin{cases} \arctan(\frac{y}{x}), & \text{if } x > 0 \\ \arctan(\frac{y}{x}) + \pi, & \text{if } x < 0 \text{ and } y \geq 0 \\ \arctan(\frac{y}{x}) - \pi, & \text{if } x < 0 \text{ and } y < 0 \\ +\frac{\pi}{2}, & \text{if } x = 0 \text{ and } y > 0 \\ -\frac{\pi}{2}, & \text{if } x = 0 \text{ and } y < 0 \\ \text{undefined}, & \text{if } x = 0 \text{ and } y = 0 \end{cases} \tag{2.9}$$

The position of the eye in pixels is used to find the stimulus distance in Equations 2.1 and 2.2, but the rotation of the eye also affects the placement of stimuli. Because the tablet can be assumed to be upright and unmoving, and the subject should be fixating on the fixation point, only the roll will affect the placement of the stimuli on the screen. Equation 2.10 approximates the effect of roll on stimuli position. The roll calculated is relative to the camera coordinate system, but counter-roll is relative to the world coordinate system. Finding the roll relative to the WCS would require data about the orientation of the tablet, but because of the unreliability of these measures and the minimal difference between the coordinate systems of the head and the tablet, we choose to use the approximation.

$$\begin{bmatrix} D_{S,x} & D_{S,y} \end{bmatrix} = \begin{bmatrix} d_{S,x} & d_{S,y} \end{bmatrix} \begin{bmatrix} \cos(-\psi) & -\sin(-\psi) \\ \sin(-\psi) & \cos(-\psi) \end{bmatrix} \tag{2.10}$$

Where:

$[D_{S,x}, D_{S,y}]$: are the stimulus distances in pixels from fixation target for x and y coordinates respectively with roll and counter-roll accounted for

$[d_{S,x}, d_{S,y}]$: are the stimulus distances in pixels from fixation target for x and y coordinates respectively as calculated in Equations 2.1 and 2.2

2.2.2.1 Accuracy of Pose Estimator

This section analyzes the accuracy and speed of the pose estimator by looking at how fast it can estimate a pose, how often it fails to estimate a pose, and the errors of the pose acquired.

As mentioned in the previous section, the pose estimator is able to calculate a pose

at a rate between 1 and 3 times per second. Because the stimuli are only displayed around once per second, this rate is adequate for the estimation of the next position of the stimulus to be displayed. To look at one aspect of the accuracy, we can examine the failure rate, which is the number of times the pose estimator is unable to find an estimate out of the total times. Data from 34 patients show that the failure rate is approximately 4.3%. Most of the failures are due to the subjects moving out of the FOV of the camera. This is quite easy to do because the FOV of the camera can barely fit the subject's head when the tablet is in the vertical orientation. One thing we tried to do to minimize this effect was to make the pattern smaller.

To test the accuracy of the pose estimator, a 6×4 checkerboard that was placed on a pair of glasses was measured at 0°, 5°, 10°, 15°, 20°, and 30° in the yaw, pitch and roll directions. Table 2.1 shows the average error over these points.

Table 2.1: Average error of pose estimator over all 6DoF

Rotation	**Average Error (°)**	**Translation**	**Average Error (cm)**
Yaw	0.8	**X**	0.23
Pitch	0.72	**Y**	0.24
Roll	0.65	**Z**	0.19

Since the difference between two adjacent points that are being tested in the visual field is 6° and the largest stimulus size is 1.72° in diameter, an approximate maximum error of 2° would be acceptable. An error of 0.23 cm or 0.24 cm in the x or y vector results in a maximum of 0.1° error when calculating stimulus position; if the angle being tested is at 15°, the actual angle tested could be 14.9° or 15.1°. An error of approximately 3 cm is allowable for the X and Y vectors. An error of 0.19 cm in the Z vector results in a maximum of 0.3° error when calculating stimulus position. An error of approximately 1 cm is allowable for the Z vector.

The yaw and pitch angles are not used in the calculations of stimulus position so errors associated with these parameters do not affect the test. However, both are under 1° error. For the roll, each degree of error contributes directly to a degree of error in the stimulus angle. A 1° error will result in a 1° shift of the stimulus. A 0.65° error is below the 2° acceptable error, and the data in Table 2.2 suggest that the error is even lower when the head roll is smaller. Since subjects will likely not tilt their heads more than 10°, the average error becomes 0.46°.

Table 2.2: Error of pose estimator for the roll

Roll (°)	**Error (°)**
0	0.2
5	0.52
10	0.67
15	0.53
20	1.0
30	1.0

In the previous section, we approximated the roll of the head by using the roll relative to the camera coordinate system instead of the world coordinate system. The error that this approximation introduces is minimal as the expected roll of a subject is no more than 10°. Even if the tablet's roll is 30°, the resulting error is only around 1°.

2.3 Dynamic Contrast Range

The dynamic contrast range of a perimeter is the range of differential light sensitivities that can be displayed by the perimeter given a fixed background illumination and stimulus size. A high dynamic contrast range improves the perimeter's ability to detect and track visual field defects. The dynamic contrast range of the mobile perimeter was designed to be similar to that of the HFA.

The attenuation scale used by the HFA will be used as a gold standard for the determination of the contrast range of the mobile perimeter. As seen in Table 2.3, the HFA projects a maximum luminance of 10,000 asb onto a background of 31.5 asb, resulting in a maximum luminance of 10,031.5 asb. Since the background illumination of the HFA is greater than 10 asb (the level at which photopic vision occurs), differential light sensitivities can be calculated by the Weber-Fechner equation. The differential light sensitivity measures are translated to attenuation measured by Equation 2.11. This maximum luminance on the HFA corresponds to 0 dB on the HFA attenuation scale. The HFA is able to project a range of 0 - 50 dB, although differential light sensitivities for humans are in the range of 0 to 35 dB.

The Goldmann manual perimeter was widely used when it was first introduced and many of the parameters that are used in perimetry, such as stimulus size and background

Table 2.3: Comparison of dynamic contrast range of the Mobile Perimeter against standard automated perimeters.

	HFA	**Goldmann Manual Perimeter**	**Octopus**	**MP (Nexus 7)**
Max Luminance (asb)	10,031.5	1031.5	1004	1163.65
Background Luminance (asb)	31.5	31.5	4	31.5
Dynamic Contrast Range (dB)	0 - 50	10 - 44	5 - 45	10 - 38

luminance, are based on this perimeter. It has a maximum luminance of 1031.5 asb and a background luminance of 31.5 asb. The maximum stimulus intensity translates to 10 dB on the HFA attenuation scale (using eq. 2.11). The Goldmann perimeter is able to attenuate the stimulus luminance by 34 dB, which results in a dynamic range of 10 - 44 dB.

$$S_{dB} = 25 - 10 \log \left(\frac{L - L_b}{L_b} \right) \tag{2.11}$$

Where:

S_{dB} : is the differential light sensitivity in dB
L : is the stimulus luminance
L_b : is the background luminance

The Octopus perimeter is another example of a clinical automated perimeter. It has a maximum luminance of 1004 asb and a background luminance of 4 asb. The Octopus can attenuate the source illumination by 40 dB. Since the background luminance of the Octopus is only 4 asb (mesopic retinal illumination), the differential light sensitivities are calculated by the Rose-de Vries Law in Equation 2.12 [30]. This results in a maximum stimulus intensity corresponding to -2 dB, which means the dynamic contrast range would be -2 to 38 dB.

$$S_{RV} = 25 - 10 \log \left(\frac{L - L_b}{\sqrt{L_b}} \right) \tag{2.12}$$

Where:

S_{RV} : is the differential light sensitivity in dB, using Rose-de Vries' Law

The background and maximum luminance of the Nexus 7 was measured using a Konica Minolta LS-100 Luminance Meter by measuring the luminance of the screen at maximum brightness with an RGB intensity of (255, 255, 255) and an RGB intensity of (0, 0, 0). The results of the photometer were provided in units of cd/m^2 and were translated to asb for ease of comparison. The lowest background luminance measured for the Nexus 7 screen at RGB(0, 0, 0) was approximately 1.9 asb and at RGB(255, 255, 255) was approximately 1164 asb. If one uses the lowest screen luminance as background, the maximum stimulus intensity will correspond to -3 dB on the HFA (i.e. higher than the HFA standard). However, the implications of using low background luminance (which would be in the mesopic region of human vision) are decreased differential light sensitivities [30], as well as changes in the shape of the hill-of-vision [31]. As a result, it would be better if the background illumination of the Nexus 7 can be increased to the same level of the HFA and still fulfill the requirement of a 0 - 34 dB for the dynamic range of the stimuli.

Increasing the background luminance to 31.5 asb results in dynamic contrast ratio values that are similar to those of the Goldmann manual perimeter, with a maximum stimulus intensity corresponding to 10 dB. To calculate the lower end of the contrast range, the next smallest value (33.1 asb) that can be displayed on the screen after 31.5 asb is used as the stimulus luminance in eq. 2.11. This gives a range of 10 - 38 dB, which is insufficient. The Goldmann manual perimeter bridges the gap (i.e. increases the range by 10 dB) by changing the stimulus size. We will use the same strategy.

The effective intensity perceived by the subject can be increased by using a larger stimulus size (as described in Section 1.2.2) as it physically projects onto a larger area onto the retina. By quadrupling the area of the stimulus, it is psychophysically equivalent to increasing the intensity by 5 dB [5]. The standard stimulus size used by current perimeters is the Goldmann stimulus size III, and all the standard sizes can be seen in Table 1.1. The size IV stimulus quadruples the area of the size III stimulus, and the size V stimulus quadruples the area of the size IV stimulus, providing an additional 10 dB to the dynamic contrast range.

The drawback of using larger stimulus sizes is lower resolution of visual field measurements. The larger size may cause the projected stimuli to fall on both visual field defects and healthy retina, resulting in elevated visual thresholds along the borders of scotomas or a complete failure to detect smaller scotomas.

The mobile perimeter uses the standard size III stimulus whenever possible. It increases the stimulus size when the highest possible contrast ratio is used and the subject is unable to see it. However, because different stimulus sizes are used and the perceived contrast ratio will vary due to many factors, such as individual variation, it will add to higher inter-test and intra-test variability of the mobile perimeter test [32] [33].

2.4 Compensation for Variation in Ambient Illumination

Another goal when implementing a mobile perimeter is to be able to perform the visual field test in patients' homes. Since the lighting conditions might change from home to home, the mobile perimeter has to be able to provide reliable test results under a variety of lighting conditions. This is in contrast to the HFA which operates in dedicated testing facilities with controlled lighting environments. Because the mobile perimeter has an LCD screen, the ambient light and the angle between the screen of the eye will affect the luminance perceived by the eye.

Some of the ambient light that reaches the screen of the mobile perimeter will be reflected off the screen and into the eye. This will change the background luminance perceived by the eye. We will use the light sensor that is positioned on the front of the tablet to measure the room's ambient light and then use these measurements to compensate for changes in room illumination. We assume that the surface of the mobile perimeter is evenly illuminated as uneven lighting of the mobile perimeter's screen can interfere with our ability to compensate for ambient room illumination.

The angle between the screen and the eye also affects the luminance seen by the eye because of the properties of an LCD screen. LCD screens are known to have "viewing cones", which are the directions from which the screen can be viewed. Studies have shown that these effects are a result changes in luminance and chromaticity as a function of the viewing angle [34]. Chromaticity is not a factor for the mobile perimeter as it only displays grey intensities, but luminance is very important for the measurement of differential light thresholds. With the help of the pose estimator, knowing the location of the eye and the stimulus will provide us with the angle of the light rays entering the eye from that location on the screen and allow us to properly compensate for this factor.

2.4.1 Characterization Procedure

The luminance perceived by the eye will change based on both the ambient light and the viewing angle, and we need a reliable way to measure the luminance of the screen when these conditions vary. A photometer that is calibrated to the human eye is able to measure the luminance coming from the screen as seen by the human eye. Using a photometer, the lightmeter on the device, and a protractor, we can now measure how the luminance changes with respect to the ambient light and the angle between the mobile device and the eye. The procedure for this characterization process was as follows:

1) A Konica Minolta LS-100 Luminance Meter (also referred to as a photometer), calibrated to the human eye, measured the luminance on the screen in cd/m^2 for a range of RGB intensities (from RGB grey values of (0,0,0) to (255,255,255)). The photometer was positioned 80 cm away from the screen and its FOV encompassed approximately 50% of the screen. The intensity of the screen was uniform.

2) The photometer measured the range of RGB intensities at a variety of ambient light conditions, measured by the lightmeter on the tablet to be 0 - 100 lux. These lighting conditions included rooms with fluorescent lighting, incandescent lighting and natural lighting (sunlight).

3) The photometer also measured the range of RGB intensities with the tablet positioned at various angles. The tablet placed perpendicular to the photometer is considered to be at an angle of 0° relative to the photometer. The intensities were measured with the tablet placed at 0, 5, 10, 15, and 20° relative to the photometer. This was repeated for only a few different lighting conditions.

2.4.2 Characterization

Using the procedure outlined in Section 2.4.1, we obtained data on how the luminance changed as the angle of the tablet and the ambient light, as measured by the lightmeter on the tablet, were varied. Figure 2.7 shows the change in luminance when the ambient light was fixed at 10 lux and the angle was varied over 0 to 20°. The screen intensities, represented by their repeated RGB value, is on the x axis, and the luminance that was measured on the screen at these different intensities is on the y axis. The various curves on the graph are the angles at which these intensities were measured at. These curves

clearly show that as the angle increased, the luminance decreased, which is what we expected due to the properties of the LCD screen.

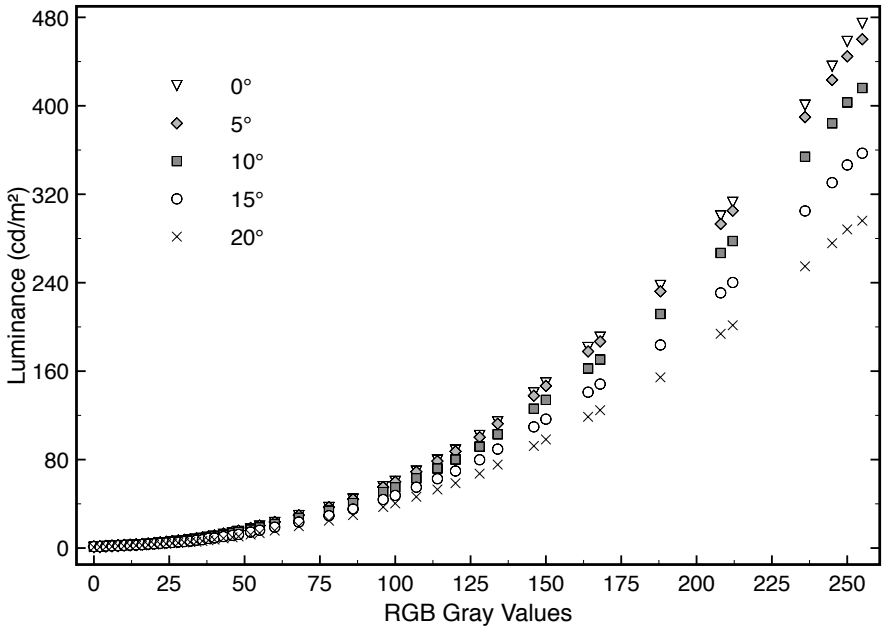


Figure 2.7: Luminance changes as angle varies when ambient light is fixed at 10 lux

Figure 2.8 shows the change in luminance when the angle is fixed at 0° and the ambient light is varied from 0 to 60 lux. In this graph, the x and y axes are the same as in Figure 2.7, but the different curves represent the various ambient light conditions. There is a small constant offset in the luminance curves that is not easily seen in this figure. Figure 2.9 enlarges this graph to show this offset. The enlarged figure shows that as the ambient light increases, the offset increases. There are slight differences between the graphs, but at the lower luminance values, these offsets can greatly affect the contrast ratio being displayed.

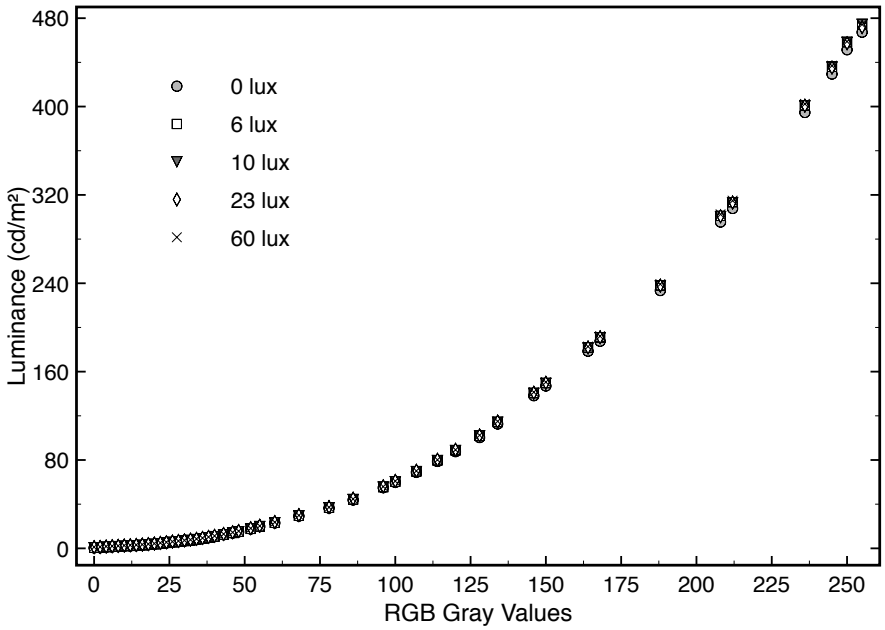


Figure 2.8: Luminance changes as ambient light varies when angle is fixed at 0°

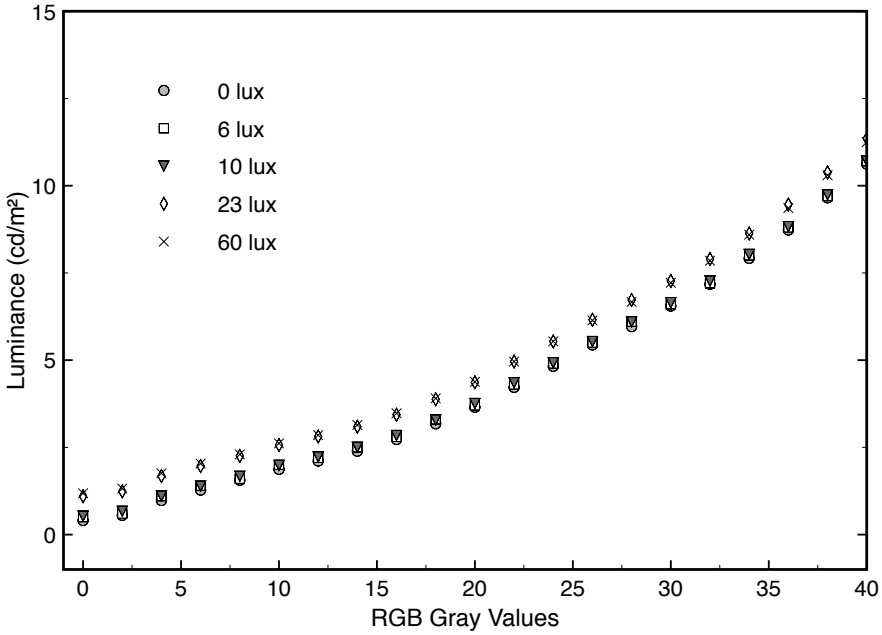


Figure 2.9: Close-up of Figure 2.8

2.4.2.1 Offset Analysis

In the previous section, we saw that differences in the room's ambient light introduce offsets in the luminance curves. In this section, we will analyze these differences.

At various ambient light conditions, the shape of the curves were very similar and would be nearly identical when the offset was eliminated. This offset was likely a direct result of the ambient light reflecting off the screen and adding to the luminance emitted by the screen itself.

We examined the offset by measuring the changes in luminance when the lowest gray intensity (RGB(0,0,0)) is displayed at various ambient light conditions. These measurements were made in a room with even and light gray walls in order to model a variety of backgrounds as well as possible. It was also measured at a very slight angle of less than 5° so the photometer was not in the reflection of the screen. At the lowest intensities, the luminance values measured at 0 and 5° were almost identical and would sometimes increase at 5°, likely a result of changing background reflections on the screen (as we would expect it to decrease at higher angles). Figure 2.10 shows the luminance as the ambient light of the room changes for the lowest gray intensity. The offset differences are clearly much higher as the ambient light increases.

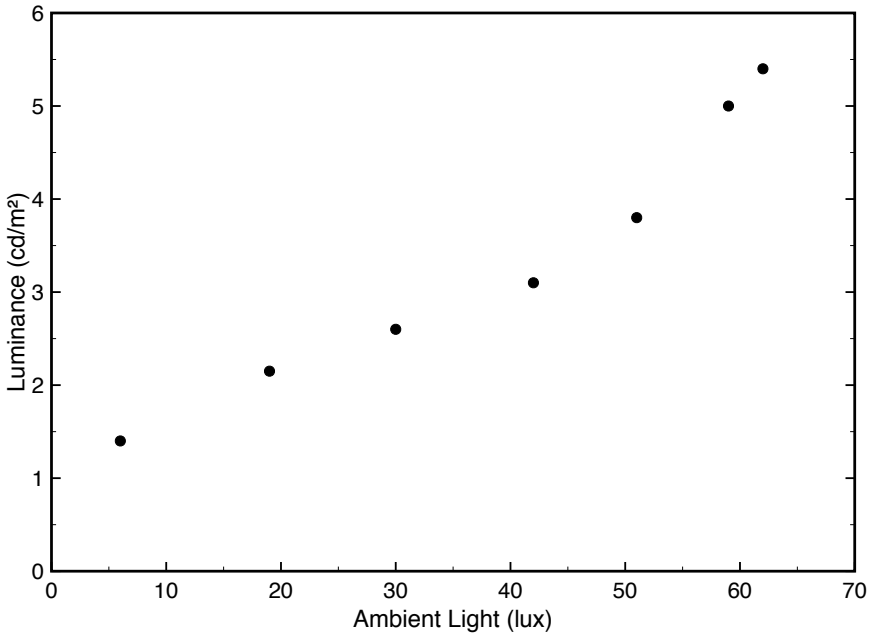


Figure 2.10: Luminance changes as ambient light varies at lowest gray intensity

Equation 2.13 approximates the curve found in Figure 2.10 using a quadratic equation. The difference in luminance (or offset luminance L_o) expected is a function of the lux measured (l) and the device specific constants c_1, c_2, c_3. These constants would have to be re-measured for a different device. The variance in these constants is unknown and further work needs to be done to analyze how much variation there is per device.

$$\begin{aligned} L_o &= c_1 \cdot l^2 + c_2 \cdot l + c_3 \\ c_1 &= 0.0009 \\ c_2 &= 0.0039 \\ c_3 &= 0.8 \end{aligned} \tag{2.13}$$

Although this offset seems very small, because of the exponential nature of the luminance curve, not including this offset could cause approximately a difference of 4 RGB in gray intensity displayed, which is very large when displaying the lower contrast ratios.

2.4.2.2 Gamma Correction

Previously, we also saw that the luminance curves are not linear. In this section, we will look into this issue in more depth.

The exponential shape of the luminance curves is a result of gamma correction. Gamma correction is used for decoding and encoding luminance values because the human eye views luminance in a non-linear manner [35]. This allows for more compact representation of images. Equation 2.14 shows the relationship between the input values V_{in} and output values V_{out}. The input values V_{in} are raised to a power γ, where $\gamma > 1$ is for decoding and $\gamma < 1$ is for encoding. In most computer systems, $A = 1$ and $\gamma = 2.2$ for decoding, and the inverse ($\gamma = 1/2.2$) is for encoding .

$$V_{out} = A \cdot V_{in}^{\gamma} \tag{2.14}$$

The exponential curves in Figures 2.7 and 2.8 are the output luminance where the input data go through the transformation described in Equation 2.14 (γ of 2.2). We can now re-encode the measured luminance to obtain a linear representation of the luminance, which will allow us to more easily characterize the curves. Figures 2.11 and 2.12 show the encoded luminance values ($\gamma = 1/2.2$) of Figures 2.7 and 2.8. In 2.12, the luminance

curves are almost identical for all the various ambient light environments, even when enlarged. This is because the offsets between the curves were eliminated before the encoding was performed. If the offsets had not been eliminated, the slopes of these curves would have differed in a non-linear manner.

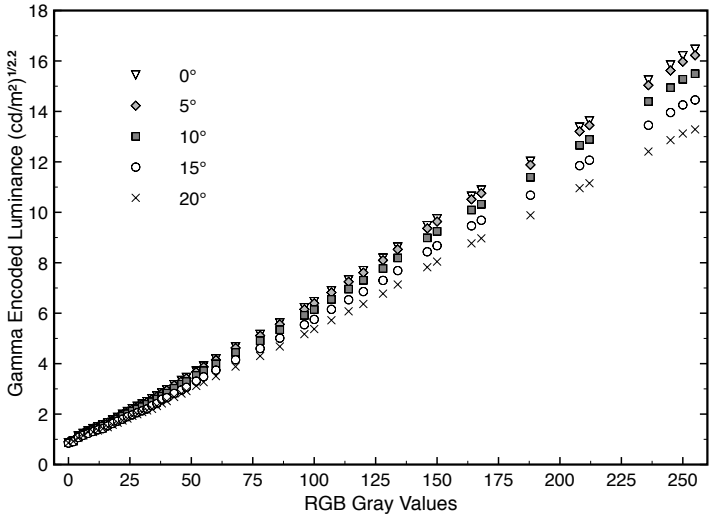


Figure 2.11: Gamma-corrected luminance changes as angle varies when ambient light is fixed at 10 lux

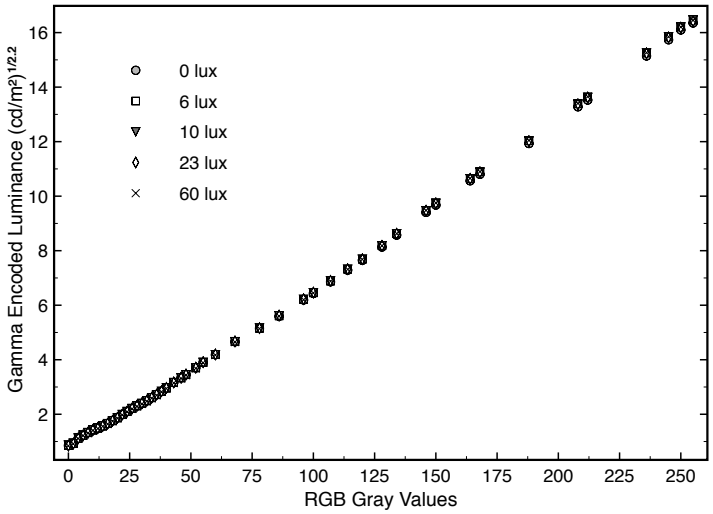


Figure 2.12: Gamma-corrected luminance changes as ambient light varies when angle is fixed at 0°

2.4.2.3 Angle Analysis

From the exponential luminance curves in the previous sections, there was a clear decrease in luminance as the angle between the tablet and the photometer increased. This section will analyze and characterize this decrease.

To do this, we analyzed the linear gamma-corrected luminance changes. In Figures 2.13 and 2.14, the slope and y-intercept of the linearized luminance curves were plotted against changes in angle and ambient light. These slopes and y-intercepts were calculated by eliminating the bottom part of the graph because of the slight invariance. In the graph of the slopes, the ambient light did not affect the slope, while the angle of the device caused it to lower as the angle increased. In the graph of the y-intercepts, neither angle nor ambient light seemed to have much of an effect on the y-intercept.

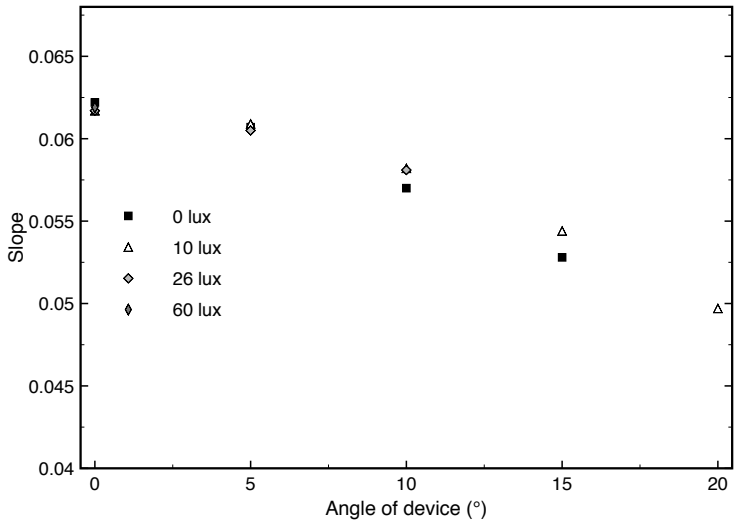


Figure 2.13: Slope of gamma-corrected curves as ambient light and angle change

Equation 2.15 summarizes the above observations. m is the slope of the gamma-corrected curves and varies with angle θ_s. b is the y-intercept of the gamma-corrected curves and does not vary with respect to anything. The constants c_4, c_5, and c_6 are again all device-specific.

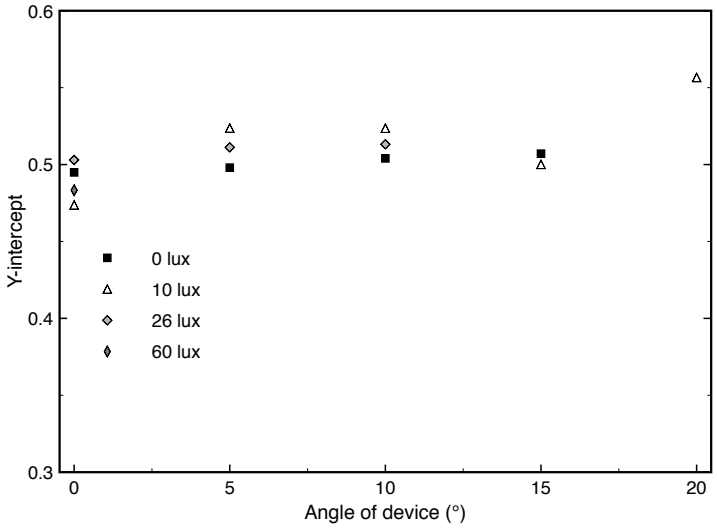


Figure 2.14: Y-intercept of gamma-corrected curves as ambient light and angle change

$$\begin{aligned} m &= c_4 \cdot \theta_s + c_5 \\ b &= c_6 \\ c_4 &= -0.0006 \\ c_5 &= 0.063 \\ c_6 &= 0.5 \end{aligned} \tag{2.15}$$

The angle required in the Equation 2.15 represents the angle between a vector perpendicular to the screen surface and the eye. To find this angle, we find the angle between the vector of the location of the stimulus to the location of the eye ($\vec{v}_{se}$ in Equation 2.16) and the plane of the tablet ($\vec{n}$ in Equation 2.17). $\vec{D}_S$ is the location of the stimulus on the screen, as calculated previously in Equation 2.10. The Z value is 0 because it lies on the plane of the tablet. $\vec{d}_E$ is the location of the eye in the camera coordinate system, as calculated in Equation 2.7.

$$\begin{aligned} \vec{v}_{se} &= \vec{D}_S - \vec{d}_E \\ \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} &= \begin{bmatrix} D_{S,x} \\ D_{S,y} \\ 0 \end{bmatrix} - \begin{bmatrix} d_{E,x} \\ d_{E,y} \\ d_{E,z} \end{bmatrix} \end{aligned} \tag{2.16}$$

$$\vec{n} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{2.17}$$

Using the formula for finding the angle between a plane and a vector, as seen in Equation 2.18, we can find the angle at which the stimulus is entering the eye.

$$\theta_s = 90^\circ - \arcsin\left(\frac{|v_x \cdot n_x + v_y \cdot n_y + v_z \cdot n_z|}{\sqrt{v_x^2 + v_y^2 + v_z^2} \cdot \sqrt{n_x^2 + n_y^2 + n_z^2}}\right) \tag{2.18}$$

2.4.2.4 Final Characterization

Now that we know how both the angle and ambient light affect the luminance curve, we can use this information to calculate what gray intensity (RGB value) is needed to get a specific contrast ratio. First we need to find out what the luminance background is around the position of the intended stimulus (which is dependent on the angle to the eye). Equation 2.19 transforms the gray intensity of the background (RGB_b) into the luminance of the background at that point. It takes into account the angle between the stimulus position and the eye through the angle-dependent slope m, and takes into account the ambient light through the lightmeter-dependent offset L_o. The gray intensity is first multiplied by the right slope m and the y-intercept b is added to obtain the encoded luminance. Then, it is decoded using $\gamma = 2.2$ and the luminance offset L_o is added to find the background luminance L_b.

$$L_b = (RGB_b \cdot m + b)^{2.2} + L_o \tag{2.19}$$

Once we know the background luminance, we calculate the desired stimulus luminance L_s in Equation 2.20. For the desired contrast ratio, specified by attenuation in db (as per HFA standard), the stimulus luminance can be found using the Weber-Fechner equation.

$$L_s = L_b \cdot \left(1 + 10^{(25-db)/10}\right) \tag{2.20}$$

Now we substitude L_s in Equation 2.21 to obtain the gray intensity of the stimulus

(RGB_s).

$$RGB_s = \frac{(L_s - L_o)^{1/2.2} - b}{m} \tag{2.21}$$

Note, m and b are specific to the Nexus 7 device characterized, and would have to be recharacterized for a different device.

2.4.3 Limitations

There are some limitations to the ability to compensate for the ambient light.

Uneven lighting in the room can cause various parts of the screen to have different illumination, meaning the contrast ratios calculated for one side of the screen would be inaccurate for the other side. To avoid this issue, users could rotate the tablet (in the roll direction) to see if there are changes in the lighting conditions. If such differences do exist, the test can be moved to another location. In the current implementation of the mobile perimeter, we chose not to address this issue because the differences that we measured were minimal (around 5 lux difference).

Reflections on the screen from objects in the environment could change the luminance by 3.14 - 12.6 asb. Environments with darker coloured walls would therefore have different results than environments with lighter coloured walls while the lux measured by the photometer was the same. In future work, this could be accounted for by using the front-facing camera to look at the colours of the objects in the view to get an idea of what reflections would affect the screen. For our purposes, we will be assuming that the environment will have light and even coloured walls with no other clutter.

The last two issues involve the light sensor on the device. The first issue is that the spectral response curves of the eye and the light sensor are not the same. The human eye perceives the same brightness between an incandescent and fluorescent light source that are given the same current, with a ratio of 1 (incandescent:fluorescent). Depending on the manufacturer, ambient light sensors will measure different values for the two sources, with ratios that can range from 1.3 to 2.5 [36]. This means that the light sensor will measure higher values in incandescent lighting, which would result in modelling errors. However, since it is the only sensor that we can use, this problem will not be accounted

for.

The second issue is that the characteristics of the light sensor are device-specific. Different mobile devices will have light sensors that measure different illumination in the exact same conditions. Not only that, two Nexus 7 tablets will also have non-linear differences (you cannot add an offset to fix the differences) in their measurements. We tested one person on a calibrated and uncalibrated Nexus 7, and the differences between the differential light thresholds measured in the visual field test were on average around 1 to 2 dB, which is not a significant difference. This problem is difficult to solve and will be considered for future work.

Chapter 3

Experimental Metholodogies

This chapter describes the experimental procedures that will be used in the following two chapters to measure and compare the quality, and capabilities of the Mobile Perimeter described in the Chapter 2. In the following sections, we describe a) the *visual field test* that will be performed, b) the *lighting conditions*, c) the *subject positioning*, and d) the *refractive correction* used for the subject.

The *visual field test* describes the details of the test being run, such as what points are being tested, what fixation point is used, etc. The *lighting conditions* describe the setting and its lighting. The *subject positioning* describes the position of the subject relative to the perimeter, where their head is located, the eye-patch that they are wearing, and any adjustments that are potentially made during the test. The *refractive correction* describes the optical lens correction (i.e. glasses) required for the subject to perform the test on the specific perimeter.

3.1 Humphrey Field Analyzer Methodology

This section describes the experimental conditions for all the experiments that used the Humphrey Field Analyzer (HFA) as the measuring device. This methodology will be referred to as *HFA-Exp.*

Visual Field Test: Each subject undergoes a 24-2 visual field test on the HFA which checks 54 points in the central 30° of the visual field. The HFA uses its own proprietary

algorithm to determine the thresholds and a 200ms stimulus duration. The right eye is tested for all subjects unless otherwise specified. During the entire test, the subject is asked to focus on a fixation point in the centre of the dome of the HFA, as described in Section 1.2.

Lighting Conditions: The location of the test is inside the visual fields room at the Toronto Western Hospital. The lighting of the room is dimmed and the chin and forehead of the subject is resting on the inside of the HFA, minimizing any effect of the surrounding lighting.

Subject Positioning: The subject sits in front of the HFA with their chin resting on the chinrest of the machine and forehead against the top of the machine. The subject wears a black opaque eye-patch on the eye not being tested. The subject may be told to fixate during the test by the technician.

Refractive Correction: The HFA calculates the correction required for the subject to focus at a distance of 30cm using their age and prescription, and the lens correction is placed in the HFA [6].

3.2 Mobile Perimeter Methodology

We perform multiple experiments with different conditions on the Mobile Perimeter; much of the experimental procedure is common to all experiments and we describe that below under the heading 'Visual Field Test'. Subsequent sections will describe the variations from this methodology.

Visual Field Test: Each subject undergoes a 24-2 visual field test on the MP which checks 54 points in the central 30° of the visual field. Ten (10) of those points also undergo double determinations to measure short-term fluctuation, shown in the shaded circles in Figure 3.1. The MP uses a 4:2 double staircase bracketing algorithm, a 200ms stimulus duration and 31.5 asb background luminance. The right eye is tested for all subjects unless otherwise specified for the individual. The test has nine different fixation points (identified as 0 through 8), each of which are used to measure a portion of the visual field, as illustrated in Figure 2.2. The test cycles through each fixation point and the corresponding portion of the visual field to the specific fixation point is tested before the fixation point moves to its next position. Fixation point 0 starts in the middle of

the screen, 1 through 4 cover the four corners, then the tablet is flipped 90°CW, and 5 through 8 cover the corners again.

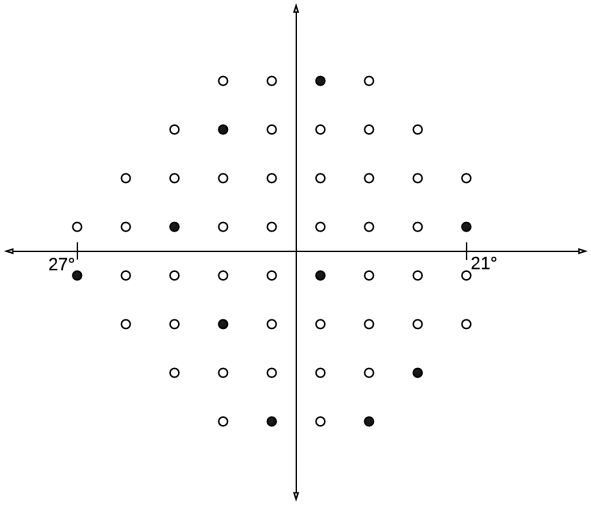


Figure 3.1: Ten points tested twice during the 24-2 test.

3.2.1 Dark Room

This section describes the remaining conditions for the MP experiments in a dark room and will be referred to as *MP-Dark*.

Visual Field Test: The test assumes a completely dark room and fixed position of the eye at a 25cm distance from the MP. The MP also uses a 23 asb background luminance.

Lighting Conditions: The location of the test is in a completely dark room.

Subject Positioning: The MP is placed on a platform attached to a chinrest. The subject sits in front of the MP with their chin resting on a chinrest 25cm away from the MP. The subject wears a black opaque eye-patch on the eye not being tested.

Refractive Correction: If the subject requires correction, he/she will wear a pair of glasses that are (a) their regular distance pair (subjects under 42 years old), (b) their reading glasses, or (c) a pair of pre-fabricated reading glasses that match the correction used by the HFA.

A picture of the set-up is shown in Figure 3.2.

Figure 3.2: Dark Room set-up. The lights were turned off for the test.

3.2.2 Lit Room

This section describes the remaining conditions for the MP experiments in a lit room. There are two slight variations which will be described in the "Visual Field Test" section. The first variant will be referred to as *MP-Lit-Compd* and the second will be referred to as *MP-Lit-Not-Compd*.

Visual Field Test: In the first variant (MP-Lit-Compd), the test compensates for the ambient light in the room using the compensation outlined in Section 2.4. In the second variation(MP-Lit-Not-Compd), the test does not use the ambient light compensation and assumes the subject is in a completely dark room in order to see the difference the compensation has on the visual field test. In both variants, the MP assumes a fixed position of the eye at 25 cm distance from the MP and uses a 30 asb background luminance.

Lighting Conditions: The location of the test is in a lit room with fluorescent overhead lighting and a sun lamp is used to vary the lighting in the room. The room had blank white walls in order to minimize background clutter reflected on the screen.

Subject Positioning: The MP is placed on a platform attached to a chinrest. The subject sits in front of the MP with their chin resting on a chinrest 25cm away from the MP. The subject wears a black opaque eye-patch on the eye not being tested.

Refractive Correction: If the subject requires correction, he/she will wear a pair of glasses that are (a) their regular distance pair (subjects under 42 years old), (b) their reading glasses, or (c) a pair of pre-fabricated reading glasses that match the correction used by the HFA.

A picture of the set-up is shown in Figure 3.3.

Figure 3.3: Lit room set-up.

3.2.3 Head Movement

This section describes the remaining conditions for the MP experiments in a lit room and allows for free head movements. There are two slight variants, which will be described in the "Subject Positioning" section. The first variant will be referred to as *MP-HeadMovement-Patch* and the second will be referred to as *MP-HeadMovement-NoPatch*.

Visual Field Test: This test compensates for both head movement and environmental illuminance. The MP also uses a 30 asb background luminance.

Lighting Conditions: The location of the test is in a lit area with fluorescent overhead

lighting. The location has blank white walls in order to minimize background clutter reflected on the screen.

Subject Positioning: The subject sits in front of the MP with their head free to move during the experiment. He/she is positioned with their head 25-28cm away from the MP with less than 10° head roll. If the test is interrupted due to bad positioning, the researcher adjusts the MP manually. In the first variant (MP-HeadMovement-Patch), the subject wears a black opaque eye-patch on the eye not being tested. In the second (MP-HeadMovement-NoPatch), the subject does not wear an eye-patch.

Refractive Correction: In both variants, the subject wears a pair of glasses that can be (a) their regular distance pair (subjects under 42 years old), (b) a pair of empty frames, (c) their reading glasses, or (d) a pair of pre-fabricated reading glasses that match the correction used by the HFA. A white rectangular "patch" with a pattern of assymetrical circles of known size is taped onto the lens of the glasses on the side that is not being tested.

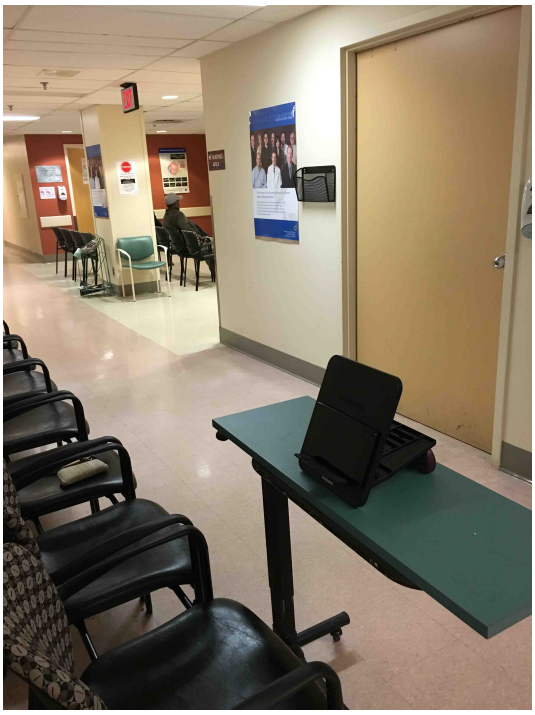
A picture of the set-up is shown in Figure 3.4.

3.3 Mobile Perimeter Demonstration/Learning Methodology

For learning purposes, there are two different demonstrations that can be performed at the beginning of any experiment with people in order to teach the subjects how to use the perimeter. Without this, the results are less reliable because some of the results may simply be due to the lack of experience/understanding with the device. Both tests have the same conditions for lighting, subject positioning and refractive correction as the experiment it precedes. The only changes between the different demonstrations are the points that are tested during the visual field test run. These are outlined below.

Visual Field Test Demo 1: Each subject undergoes a visual field test on the MP which tests only seven points on the visual field ((9°,-3°), (13°,-3°), (15°,-3°), (17°,-3°), (21°,-3°), (9°,15°), (-9°,15°)). The MP uses a 4:2 double staircase bracketing algorithm, a 200ms stimulus duration and 30 asb background luminance. The right eye is tested for all subjects unless otherwise specified. There is only one fixation point, and it is located

(a) Room located in the University of Toronto



(b) Hallway of the Toronto Western Hospital

(c) Lab at Toronto Western Hospital

Figure 3.4: Multiple configurations of the head movement compensation set-up.

on left side of the tablet.

Visual Field Test Demo 2: Each subject undergoes a visual field test on the MP which tests only eight points on the visual field ((9°,-3°), (15°,-3°), (-9°,-3°), (-3°,-9°), (15°,3°), (3°,3°), (15°,15°), (3°,15°)). The MP uses a 4:2 double staircase bracketing algorithm, a 200ms stimulus duration and 30 asb background luminance. The right eye is tested for all subjects unless otherwise specified. There are two fixation points, which are the first two fixation points tested in the MP experiments (0 and 1), each testing four points. The purpose of this procedure, different from Demo 1, is to teach the subjects about the moving fixation point, which is a new feature quite different from any previous HFA experience. In addition, it takes some getting used to on the mobile perimeter.

When referencing a demonstration, depending on which MP experiment it is preceding, a *"-Demo1"* or *"-Demo2"* will be concatenated to the end of the experiment name.

3.4 Mobile Perimeter Mini-Test Methodology

Six small tests were used to verify the accuracy of the head pose estimation. All tests have the same conditions for lighting and refractive correction. Most of the visual field test and subject positioning conditions are the same and these are outlined below. The differing conditions are outlined in subsections below.

Visual Field Test: Each subject undergoes a visual field test on the MP which tests nine points on the visual field ((9°,-3°), (11°,-3°), (13°,-3°), (15°,-3°), (17°,-3°), (19°,-3°), (21°,-3°), (15°,-1°), (15°,1°)). The MP uses a 4:2 double staircase bracketing algorithm, a 200ms stimulus duration and 30 asb background luminance. The right eye is tested for all subjects. There is only one fixation point, and it is located in the middle left-hand side of the tablet.

Lighting Conditions: The location of the test is in a lit area with fluorescent overhead lighting. The location had blank white walls in order to minimize background clutter reflected on the screen.

Subject Positioning: The subject sits in front of the MP with their head free to move during the experiment. If the test is interrupted due to bad positioning, the researcher

adjusts the MP manually. The subject does not wear an eye-patch.

Refractive Correction: The subject wears a pair of glasses that can be (a) their regular distance pair (subjects under 42 years old, because their lens is able to compensate for close distances)), (b) a pair of empty frames, (c) their reading glasses, or (d) a pair of pre-fabricated reading glasses that match the correction used by the HFA. A white rectangular "patch" with a pattern of assymetrical circles of known size is taped onto the lens of the glasses on the side that is not being tested.

3.4.1 Close-up Mini-Tests (2)

For these mini-tests, the subject's head is positioned 18cm away from the MP with no head roll. In one variant, the MP does not track the head position and assumes the subject is 25cm away from the MP with no head roll. This is referred to as *MP-MiniTest-Close-NotCompd*. In the second variant, the MP does track the head position and is referred to as *MP-MiniTest-Close-Compd*.

3.4.2 Far Distance Mini-Tests (2)

For these mini-tests, the subject's head is positioned 32cm away from the MP with no head roll. In one variant, the MP does not track the head position and assumes the subject is 25cm away from the MP with no head roll. This is referred to as *MP-MiniTest-Far-NotCompd*. In the second variant, the MP does track the head position and is referred to as *MP-MiniTest-Far-Compd*.

3.4.3 Head-tilt Mini-Tests (2)

For these mini-tests, the subject's head is positioned 25cm away from the MP and rolled counter-clockwise 15°. In one variant, the MP does not track the head position and assumes the subject is 25cm away from the MP with no head roll. This is referred to as *MP-MiniTest-Tilt-NotCompd*. In the second variant, the MP does track the head position and is referred to as *MP-MiniTest-Tilt-Compd*.

3.5 Summary of Methodologies

In total, there are fourteen different methodologies that are used in different studies presented in Chapter 4 to study specific features of the MP. These will be combined and re-used in different studies and will be referred to by the names described in the previous sections. Table 3.1 is a summary of these methodologies and their major properties and how they differ from each other. The first column contains all the different names of the methodologies. The rest of the table show the conditions that have been outlined in all the previous sections: Visual Field Test, Lighting Conditions, Subject Positioning, and Refractive Correction. Only details that differentiate between the tests are included in the table. The Demos are performed before the other tests and take on their conditions. This is illustrated in the table using X to represent the test that it precedes.

Table 3.1: Summary of all methodologies

	Visual Field Test	**Lighting**	**Positioning**	**Correction**
HFA-Exp	24-2	Controlled	On machine (30cm) + patch	HFA calculated
MP-DarkRoom	24-2 + 10 pts, No Compensation, 9 fixation pts	Dark	Chinrest (25cm) + patch	Glasses
MP-LitRoom-Compensated	24-2 + 10 pts, Lighting Compensated, 9 fixation pts	Lit	Chinrest (25cm) + patch	Glasses
MP-LitRoom-NotCompensated	24-2 + 10 pts, No Compensation, 9 fixation pts			
MP-HeadMovement-Patch	24-2 + 10 pts, Lighting and Movement Compensated, 9 fixation pts	Lit	Free to move (25-28cm) + patch	Glasses + pattern
MP-HeadMovement-NoPatch			Free to move (25-28cm)	
X-Demo1	7 pts, 1 fixation pt	X	X	X
X-Demo2	8 pts, 2 fixation pts	X	X	X
MP-MiniTest-Close-Compensated	9 pts, Movement Compensated, 1 fixation pt	Lit	Chinrest (18cm)	Glasses + pattern
MP-MiniTest-Close-NotCompensated	9 pts, Movement Uncompensated, 1 fixation pt			
MP-MiniTest-Far-Compensated	9 pts, Movement Compensated, 1 fixation pt	Lit	Chinrest (32cm)	Glasses + pattern
MP-MiniTest-Far-NotCompensated	9 pts, Movement Uncompensated, 1 fixation pt			
MP-MiniTest-Tilt-Compensated	9 pts, Movement Compensated, 1 fixation pt	Lit	Chinrest (25cm + 15° roll)	Glasses + pattern
MP-MiniTest-Tilt-NotCompensated	9 pts, Movement Uncompensated, 1 fixation pt			

3.6 Methods of Analyses

This section outlines the different metrics and methods that are used to evaluate the performance of the MP compared to the HFA. These will be applied to compare the results of the experiments using these methodologies that are presented in Chapter 4.

3.6.1 Mean Sensitivity

To compare visual fields, a visual field index called the mean sensitivity (MS) is used. The mean sensitivity is the average of all measured differential light sensitivities of the test, except for the two points in the physiological blind spot. It decreases as the visual field defects become more severe. The following is the formula to calculate MS:

$$MS = \frac{\sum_{i=1}^{N} x_i}{N} \tag{3.1}$$

where,

MS is the mean sensitivity

N is the number of retinal points tested on the visual field

x_i is the differential light sensitivity measured at a retinal point i on the visual field

3.6.2 Short-term and Long-term Fluctuation

To look at the variability between tests, three indices are used: short-term fluctuation (SF), long-term heterogeneous fluctuation (LF-he), and long-term homogeneous fluctuation (LF-ho). SF is used to examine intra-test variability, while LF-he and LF-ho are used to examine inter-test variability. SF analyzes the variability between two measurements of the same point, known as double-determination points. LF-he analyzes the variability between two tests and is location dependent, comparing points at the same position from each test. LF-ho also analyzes the variability between two tests, but it is location independent, and compares the average of all points from each test.

$$SF = \sqrt{\frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{R} x_{ijk} - x_{ij\cdot}}{NM_R(R-1)}} \tag{3.2}$$

where,

SF is the short-term fluctuation

N is the number of sessions

M is the number of retinal points tested

M_R is the number of retinal points that had multiple differential light sensitivity determinations

R is the number of repeated differential light sensitivity determinations per retinal point

x_{ijk} is the differential light sensitivity measured in session i, retinal point j, repetition k

$x_{ij\cdot}$ is the mean differential light sensitivity in session i, retinal point j

$$LFhe = \sqrt{\frac{\sum_{i=1}^{N}\sum_{j=1}^{M} x_{ij\cdot} - x_{\cdot j\cdot}}{N(M-1)} - \frac{M_R}{M}\frac{SF^2}{R}} \tag{3.3}$$

where,

$LFhe$ is the heterogeneous long-term fluctuation

$x_{ij\cdot}$ is the mean differential light sensitivity measured in session i, retinal point j

$x_{\cdot j\cdot}$ is the mean differential light sensitivity at retinal point j measured over all sessions and repetition

$$LFho = \sqrt{\frac{\sum_{i=1}^{N} x_i.. - x...}{N-1} - \frac{LFhe^2}{M} - \frac{M_R}{M}\frac{SF^2}{M \cdot R}} \tag{3.4}$$

where,

$LFho$ is the homogeneous long-term fluctuation

$x_i..$ is the mean differential light sensitivity measured in session i over all retinal points and repetitions

$x...$ is the mean differential light sensitivity measured over all sessions, retinal points, and repetitions

3.6.3 Two-tailed Paired T-test

A two-tailed paired t-test can be applied on the metrics outlined in the previous sections to evaluate the agreement between two clinical measurements. This test is used when there are very few data points (in these cases, the number of data points are approximately the size of the study group) and uses different probability distributions for different numbers of sample sizes [37].

$$t = \frac{\overline{X_D}}{\frac{S_D}{\sqrt{n}}} \tag{3.5}$$

$$d.o.f. = n - 1 \tag{3.6}$$

where,

t is the t value calculated to compare with the critical value

$\overline{X_D}$ is the mean of the differences between the pairs

S_D is the standard deviation of the differences between the pairs

n is the total number of pairs in the dataset

$d.o.f.$ is the degrees of freedom, used to determine the critical value

This test takes in two sets of data, for example, one set of mean sensitivities measured by the MP and another set of mean sensitivities measured by the HFA, and pairs them up according to subject. Equations 3.5 and 3.6 are used on the datasets to determine a t value. Then, using a T table and finding the value with the corresponding $d.o.f.$ and the probability that was chosen to be significant for the experiment, a *critical value* is found. The t value is then compared with this critical value, and if it is larger, there is a statistically significant difference between the two datasets. The probability chosen for all experiments is 0.05, meaning if the t value is greater than the critical value, there is only a 5% probability that the data differences between the experiments would occur.

3.6.4 95% Interval Difference Analysis

Analyzing the differences between the metrics measured on the two perimeters also gives insight into the agreement between two clinical measurements. Looking at the differences between the different metrics can reveal possible perimeter-related errors [38]. In this method, a scattergram is used, with the x-axis being the mean sensitivity measured by the HFA, and the y-axis being the difference in metrics between two perimeters. The limits where 95% of differences will lie can be calculated using Equation 3.7. This limit can then be used to evaluate how egregious the differences are for that specific metric. This evaluation is based on knowledge of the clinical measurement and what kinds of differences are still clinically useful.

$$L_{95} = \overline{X_D} \pm 1.96 \times S_D \tag{3.7}$$

where,

L_{95} is the limit where 95% of differences will lie

$\overline{X_D}$ is the mean of the differences between the pairs

S_D is the standard deviation of the differences between the pairs

Chapter 4

Comparison between Perimeters in Healthy Subjects

In this chapter, the MP is evaluated against the HFA in a study involving healthy subjects with normal visual fields. The study is broken into three parts: a) Dark Room Study b) Lit Room Study and c) Head Movement Compensation Study. The goal of the *Dark Room Study* is to examine the ability of a tablet to test a person's visual field without any light or head movement compensation. The goal of the *Lit Room Study* is to examine the ability of a tablet to test a person's visual field in various lighting conditions and without any head movement compensation. The goal of the *Head Movement Compensation Study* is to test the ability of the tablet to measure a visual field using both lighting and head movement compensation.

4.1 Subjects

There were two groups of healthy subjects that were tested. One was a group with all subjects younger than 42 years of age. Recall that age-related presbyopia, where the lens of the eye starts to harden with age, results in increased difficulty focusing on nearby objects. The younger control group will minimize any effects of presbyopia on the results. However, glaucoma is age-related and so the second control group contains subjects older than 42 years of age.

The younger control group contains a total of 10 subjects (6 males and 4 females, ages

20 to 28: mean age 24.3) who were all tested on the MP and HFA perimeters. These will be referred to as the CY set. All subjects had normal vision or corrected-to-normal vision through the use of glasses. These subjects are detailed in Table 4.1. Their age, the eye that was tested, the refractive lens used by the HFA, their actual distance prescription, the false positives, false negatives and fixation losses are all listed in the table. False positives, false negatives and fixation losses. as described in Section 1.2.3 were taken from the subjects' HFA-Exp test.

Table 4.1: Summary of under 42 control subjects. FP stands for false positives, FN stands for false negatives, and FL stands for fixation losses.

	Age	**Eye Tested**	**HFA Refractive Lens**	**Distance Prescription**	**FP (%)**	**FN (%)**	**FL (%)**
CY-1	24	Right	+0.00 DS	+0.00 DS	14	3.5	2
CY-2	20	Right	+1.50 DS -3.00 DC x 174	+1.50 DS -3.00 DC x 174	0	1	0
CY-3	25	Right	-2.75 DS	-5.75 DS -0.50 DC x 141	0	4	0
CY-4	27	Right	-2.25 DS	-5.25 DS	0	1	1
CY-5	28	Right	+0.00 DS	-0.75 DS -0.50 DC x 109	14	4	0
CY-6	23	Right	-1.50 DS -1.50 DC x 179	-4.75 DS -1.50 DC x 179	0	0	0
CY-7	25	Right	+0.00 DS -2.00DC x 176	+3.00 DS -2.00 DC x 176	0	3	3
CY-8	24	Right	+0.00 DS	+0.00 DS	1	0	0
CY-9	23	Right	-1.50 DS	-4.50 DS -0.75 DC x 27	0	0	0
CY-10	24	Right	+0.00 DS	-1.75 DS -0.25 DC x 173	1	0	0

The older control group contains a total of 8 subjects (5 males and 3 females, ages 53 to 82: mean age 64.9) who were all tested on the MP and HFA perimeters. They will be referred to as the CO group. All subjects had normal vision or corrected-to-normal vision. These subjects are detailed in Table 4.2. Their age, the eye that was tested, the refractive lens used by the HFA, their actual distance prescription, the false positives, false negatives and fixation losses are all listed in the table.

Table 4.2: Summary of over 42 control subjects. FP stands for false positives, FN stands for false negatives, and FL stands for fixation losses.

	Age	Eye Tested	HFA Refractive Lens	MP Refractive Lens	FP (%)	FN (%)	FL (%)
CO-1	56	Right	+1.00 DS	+1.00 DS	0	0	7.6
CO-2	65	Right	+5.50 DS	+5.50 DS	5	4	21
CO-3	53	Right	+1.75 DS -0.50 DC x 111	+1.75 DS -0.50 DC x 111	4	0	0
CO-4	57	Right	+2.25 DS -0.25 DC x 81	+2.25 DS -0.25 DC x 81	0	1	1
CO-5	82	Right	+1.25 DS	+1.25 DS	1	2	20
CO-6	82	Right	+0.00 DS	+1.25 DS	8	14	19
CO-7	62	Right	+1.25 DS	+1.25 DS	0	3	3
CO-8	62	Right	+2.75 DS -0.25DC x 117	+2.75 DS -0.25DC x 117	6	0	54

4.2 Baseline

Each part of the study on healthy control groups requires a comparison between the MP in various settings and the HFA. We performed a baseline test on all control subjects (under and over 42 years old). Recall the methodology for a test on the HFA in 3.1. All subjects underwent two tests of HFA-Exp, the first referred to as HFA-Exp-1 and the second referred to as HFA-Exp-2. These occurred in one session, with a five minute break between the two tests. These results will be considered the gold standard and are used as a baseline to compare all further studies on the MP.

4.3 Dark Room Study

The purpose of the Dark Room Study is to test the plausibility of the Mobile Perimeter without any type of compensation included. It will also serve as another baseline to compare the other Mobile Perimeter studies with. This study was performed on only the under-42 age group control subjects. The subjects went through a series of tests in a completely dark room on a chin-rest. Recall the methodology for the dark room test

on the MP in Section 3.2.1. The first test used the methodology from MP-Dark-Demo1, the purpose of which was to acclimate subjects to the MP set-up. Then two MP-Dark tests were run with a five minute break in between the two. The first test is referred to as MP-Dark-1, and the second as MP-Dark-2.

4.3.1 Dark Room Results

To compare the results, the mean sensitivity (MS), short-term fluctuation (SF), long-term heterogeneous fluctuation (LF-he), long-term homogeneous fluctuation (LF-ho), and the differences in the differential light sensitivities, as described in Section 1.1, were analyzed between the two perimeters.

4.3.1.1 Differential Light Sensitivity Thresholds

The 24-2 visual field test reports 54 numbers, representing the threshold at which each point can be seen 50% of the time. This is called the differential light sensitivity threshold. An example of the test results can be seen in Figure 4.1a. This shows the thresholds measured at each point on the visual field for subject CY-1 on the MP. The numbers with brackets are the double determination points. For comparison, Figure 4.1b shows the test results measured by the HFA, and Figure 4.1c show the differences between the fields at each point (MP results subtracted by the HFA results). The test results on the HFA do not have double determination points as it is using a much faster algorithm that does not have the time to test points two times.

One metric to assess is the difference between the thresholds measured on the HFA and the MP. The results from the HFA are the gold-standard and examining the differences between the two thresholds show how well the MP was able to perform. As a baseline to compare with, the differences between the two HFA sessions are examined.

Each of the thresholds at all 54 points measured by session MP-Dark-2 were subtracted from the thresholds measured by HFA-Exp-2, yielding 54 differences in thresholds. These differences were calculated for each of the 10 subjects and categorized into absolute differences between a) 0 - 4 dB, b) 5 - 10 dB, and c) >10 dB. This was repeated for differences between the thresholds measured by HFA-Exp-1 and HFA-Exp-2.

Table 4.3 shows the categorized threshold differences. The second to fourth columns

			30	32	32 (28)	30		
		30	30 (26)	26	28	28	34	
	32	30	34	34	32	30	28	34
30	32	34 (30)	28	34	34	34	34	30 (34)
32 (32)	30	32	34	34	34 (34)	34	0	30
	34	32	34 (28)	34	34	34	26	30
		32	28	34	32	34	32 (30)	
			28	26 (26)	30	34 (34)		

(a) Mobile Perimeter Visual Field (Dark Room)

			30	29	28	29		
		33	31	31	31	30	30	
	27	30	33	32	31	32	31	28
30	34	34	34	34	31	34	33	25
30	34	34	34	34	34	34	0	33
	33	32	34	34	32	34	32	33
		32	31	29	32	32	34	
			30	28	29	34		

(b) Humphrey Field Analyzer Visual Field

			0	3	4	1		
		-3	-1	-5	-3	-2	4	
	5	0	1	2	1	-2	-3	6
0	-2	0	-6	0	3	0	1	5
2	-4	-2	0	0	0	0	0	-3
	1	0	0	0	2	0	-6	-3
		0	-3	5	0	2	-2	
			-2	-2	1	0		

(c) Difference between HFA and MP

Figure 4.1: Comparison of Visual Fields for Subject CY-1 between the HFA and MP (Dark Room).

show the percentage of points that had differences within each category for each subject (identified in the first column) between MP-Dark-2 and HFA-Exp-2. The fifth to seventh columns show the same, but between HFA-Exp-2 and HFA-Exp-1. The last row contains the averages of the group.

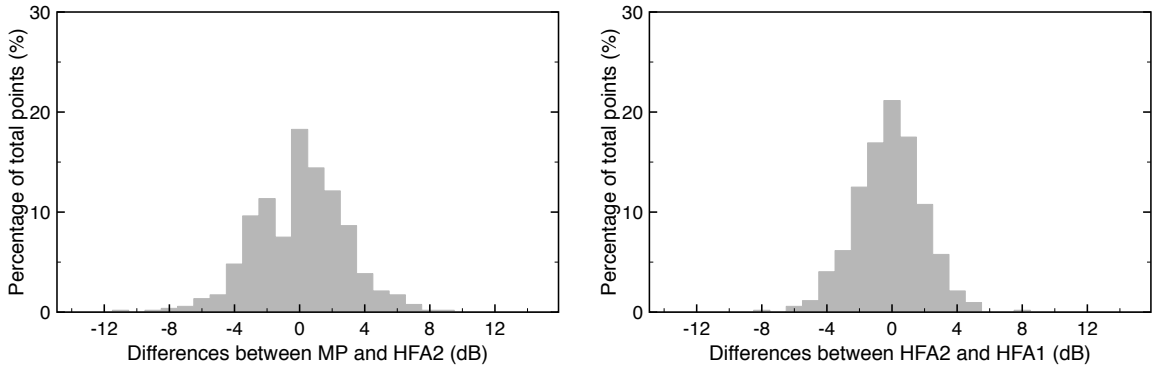
Table 4.3: Dark Room Threshold Differences

	MP-Dark-2 vs. HFA-Exp-2			**HFA-Exp-1 vs. HFA-Exp-2**		
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**>10 dB (%)**
CY-1	87	13	0	96	3.8	0
CY-2	94	5.8	0	98	1.9	0
CY-3	92	5.8	2	96	3.8	0
CY-4	88	12	0	100	0	0
CY-5	90	9.6	0	96	3.8	0
CY-6	83	17	0	100	0	0
CY-7	88	12	0	92	7.7	0
CY-8	92	7.7	0	98	1.9	0
CY-9	92	7.7	0	100	0	0
CY-10	98	1.9	0	92	7.7	0
Mean	**91**	**9.2**	**0**	**97**	**3.1**	**0**

In general, the results were quite similar between the two sets of comparisons. MP-Dark-2 had 91% of the threshold differences in the 0 - 4 dB range with HFA-Exp-2, while the two HFA-Exp tests had 97% of the differences in that range. There was one case in the MP-Dark-2 group where the threshold difference was greater than 10 dB. Subject CY-3 had one threshold measuring 20 dB on the MP and 31 dB on the HFA. This is clearly just an anomaly as it was measured on a peripheral point and may have been slightly obstructed by the frame of the glasses the subject was wearing.

This data is presented in the form of a histogram (Figure 4.2) to get a sense of how the threshold differences are spread out among the different categories and to perhaps display any outlier behaviour. The x-axis shows the threshold differences between two visual field tests. The y-axis is the percentage of points for all subjects in that group

that have a specific threshold difference.



(a) MP-Dark-2 vs. HFA-Exp-2 (b) HFA-Exp-2 vs. HFA-Exp-1

Figure 4.2: Histogram of differences in differential light sensitivities for the Dark Room Study.

From the histograms, the same behaviour is clear, most of the threshold differences are between -4 and 4 dB, with slightly more outside of that range. There is a dip in the -1 bucket for MP-Dark, likely caused because the MP does not test for thresholds that are odd and the thresholds that are greater than 34 dB measured by HFA-Exp are truncated to 34. The mean in Figure 4.2a is 0.037 dB, with a standard deviation (s.d.) of 2.8 dB. Figure 4.2b has a mean of -0.16 dB (s.d. 2.07 dB). A mean closer to 0 dB represents a better match between the two tests being compared, and a smaller standard deviation represents a smaller spread of differences. This shows a good match between the tests with no large discrepancies.

4.3.1.2 Mean Sensitivity

The mean sensitivities for both perimeter sessions (MP-Dark-1, MP-Dark-2, HFA-Exp-1, and HFA-Exp-2) are outlined in Table 4.4. Each row of the table contains all four mean sensitivity measurements (from each session) for each subject. The last row contains the averages of all the subjects in that group. From this table, the mean sensitivities measured across sessions and perimeters appear to match well with each other.

There were only two subjects (CY-7 and CY-10) who experienced a difference larger than 1 dB in MS from HFA-Exp-1 to HFA-Exp-2. This difference was an increase from one test to the other, suggesting that there was some learning effect happening. There were also two subjects (CY-2 and CY-8) who experienced a difference larger than 1.5 dB

Table 4.4: Mean Sensitivity of Control Group in Dark Room

	Mean Sensitivity (dB)			
	MP-Dark-1	**MP-Dark-2**	**HFA-Exp-1**	**HFA-Exp-2**
CY-1	32.13	31.29	32.15	31.62
CY-2	31.35	29.29	30.92	30.87
CY-3	28.87	29.61	29.88	30.46
CY-4	32.42	31.29	30.75	29.92
CY-5	32.97	32.87	33.00	32.75
CY-6	29.81	30.19	29.35	28.92
CY-7	30.52	31.10	29.17	30.37
CY-8	32.39	30.71	30.21	30.87
CY-9	30.87	30.84	31.63	31.62
CY-10	30.61	31.68	30.15	31.88
Mean	**31.19**	**30.90**	**30.72**	**30.93**

in MS from MP-Dark-1 to MP-Dark-2. This difference was a decrease from one test to the other, and these subjects claimed to be tired after the first test and not concentrating as hard on the second. One subject (CY-4) had a 1.5 dB between the averages of the MP-Dark and HFA-Exp test, and said that they understood the test better for the MP-Dark study and would press the button even when not 100% sure there was a flash, resulting in a higher MS for MP-Dark.

Recall in Section 3.6, a two-tailed paired t-test and a scattergram of the differences between the measurements are used to evaluate the agreement of metrics between the two perimeters. The MS of MP-Dark were placed into one group, and the MS of HFA-Exp were placed in another. These groups were paired by subject and test order (i.e. CY-1's MP-Dark-1 MS was paired with HFA-Exp-1 MS, and MP-Dark-2 MS was paired with HFA-Exp-2 MS) in the t-test. The t-test indicated that the MP-Dark did not measure a statistically-significant different MS than HFA-Exp ($p<0.05$).

Figure 4.3 shows a scattergram of the differences in mean sensitivities measured between the two perimeters against the actual mean sensitivity measured by the HFA. The y-axis is the difference in MS between MP-Dark-1 and HFA-Exp-1, and MP-Dark-2 and

HFA-Exp-2. The x-axis is the MS measured by HFA-Exp-2 for each subject.

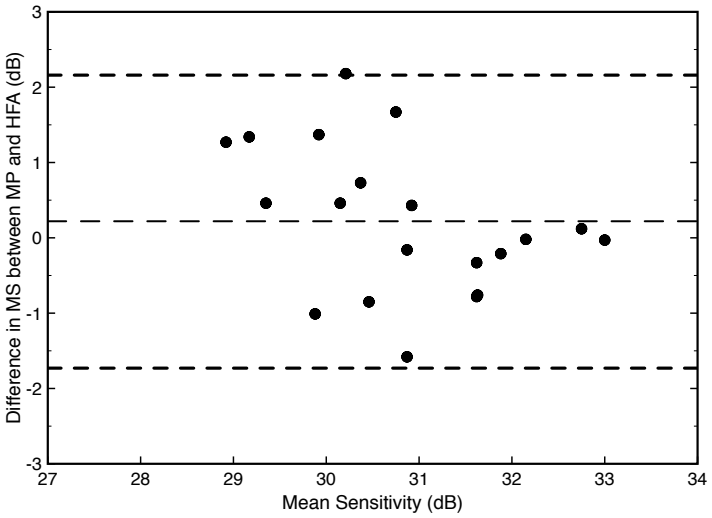


Figure 4.3: Scattergram of MS for MP-Dark vs HFA-Exp

The spread of the subjects' MS was low, ranging from 29 to 33 dB, which is expected with healthy subjects under 42 years of age. The mean of the differences between the two perimeters was 0.22 dB (shown in Figure 4.3 as the middle dotted line) with a standard deviation of 0.99. Statistically, 95% of measurements taken using the MP would likely be within the interval -1.7 to 2.16 dB (the outer dotted lines in Figure 4.3, which are calculated as follows: $mean \pm 1.96 \times s.d.$). The difference between two mean sensitivities measured by the same perimeter can vary by $\pm$ 2 dB, so the fact that all differences are within the interval shows good agreement between the two perimeters.

It is also interesting to note that the differences in MS for the higher mean sensitivities (>31.5 dB) cluster around 0. This is because the subjects that measured very high MS had thresholds measured at >34 dB on the HFA, and they were reduced to 34 dB to better compare the two perimeters. This decrease in the HFA mean sensitivity would result in differences closer to 0.

4.3.1.3 Test Repeatability

The short-term (SF), long-term heterogeneous (LF-he), long-term homogeneous (LF-ho) fluctuations for both perimeters are summarized in Table 4.5. Each row of the table contains the test repeatability metrics for both perimeters for each subject. The last two rows are the mean and standard deviation for each metric.

The second column contains the short-term fluctuations of the two MP-Dark tests. The ten double-determination points were used to determine the SF. Unfortunately, the short-term fluctuations were not available for the HFA sessions (because the algorithm the HFA uses is more complex and optimizes for time) so only the MP values are documented.

Table 4.5: Test Repeatability Metrics for MP-Dark vs HFA-Exp

	SF	**LF-he**		**LF-ho**	
	MP-Dark	**MP-Dark**	**HFA-Exp**	**MP-Dark**	**HFA-Exp**
CY-1	1.79	1.18	1.10	0.56	0.41
CY-2	2.37	1.48	0.89	1.44	-
CY-3	1.76	1.52	1.15	0.60	0.38
CY-4	2.17	1.28	0.93	0.77	0.58
CY-5	1.64	0.98	1.06	-	0.38
CY-6	2.35	1.14	0.82	0.20	0.28
CY-7	1.61	1.43	1.26	0.35	0.82
CY-8	1.79	1.44	0.92	1.17	0.44
CY-9	2.02	0.89	0.91	-	-
CY-10	1.90	1.29	1.32	0.73	1.25
Mean	**1.94**	**1.26**	**1.04**	**0.73**	**0.57**
Stdev	**0.27**	**0.20**	**0.17**	**0.41**	**0.32**

The third and fourth columns contain the LF-he for the MP-Dark and HFA-Exp tests respectively, while the fifth and sixth contain the LF-ho, again for the two perimeters respectively. For both perimeters, the two long-term fluctuations were calculated by comparing the values of the thresholds between the two individual sessions of the corresponding perimeter. The LF-ho columns are blank for some subjects, indicating the mean sensitivities between the two tests being compared are very small.

In general, the test repeatability metrics were quite low, which shows low variability between tests. The short-term fluctuation of the MP had a mean of 1.90 dB, with a standard deviation of 0.27 dB. In a study with a head-mounted perimeter, a similar group of controls had a short-term fluctuation mean of 1.43 dB and a standard deviation of 0.44 dB on the HFA [2]. These means are less than 0.5 dB off from each other, which means the variability within the test on the MP is acceptable. For the long-term

fluctuation metrics, the MP had measured slightly higher than the HFA. The means for the MP metrics were less than 0.25 dB more than the HFA metrics, and the standard deviations were larger by only 0.1 dB, which also indicates an acceptable amount of fluctuation between tests.

All test repeatability metrics measured higher on the MP than the HFA. Some of this could be due to the fact that the HFA uses an unknown algorithm and is likely doing some smoothing in the measured field which would result in better inter-test comparisons. The MP measures every point for the exact intensity threshold and a few misses or distractions could cause a slightly different threshold to be measured.

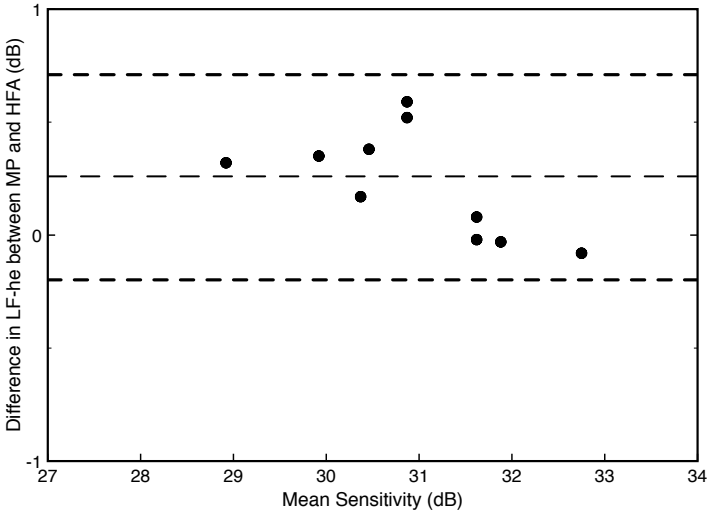


Figure 4.4: Scattergram of LF-he for MP-Dark vs HFA-Exp

From a two-tailed paired t-test, there is no significant difference in the LF-he between the MP and the HFA ($p < 0.05$). The scattergram in Figure 4.4 is similar to the one in the previous subsection, except the y-axis is now the differences in LF-he (instead of MS) between MP-Dark and HFA-Exp. The graph shows a trend skewed slightly above 0, with a mean of 0.20 dB (s.d. 0.24 dB). This skew indicates that the LF-he of the MP is slightly higher than the LF-he of the HFA. However, the interval difference is less than 1 dB, so this slight difference is not significant.

From a two-tailed paired t-test, there is no significant difference in the LF-ho between the MP and the HFA ($p < 0.05$). The scattergram in Figure 4.5 (y-axis is now the differences in LF-ho between MP-Dark and HFA-Exp) indicates that there is good agreement between the two perimeters. The mean is 0.02 dB (s.d. 0.43 dB), and the 95% interval is not a significant difference for LF-ho measurements on a perimeter.

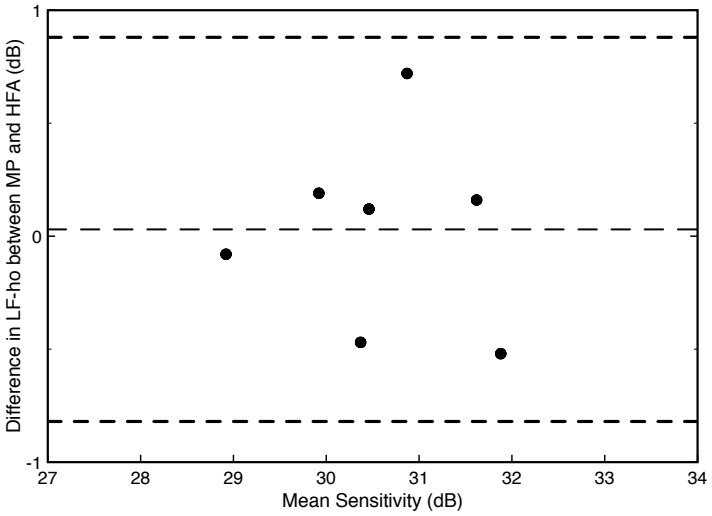


Figure 4.5: Scattergram of LF-ho for MP-Dark vs HFA-Exp

4.4 Lit Room Study

The purpose of the Lit Room Study is to test the light compensation the MP is using by testing subjects in varying lighting conditions. This study was only performed on the under-42 control subjects. These subjects were split into two groups, one peforming the study in a brighter room, and the other in a dimly lit room.

The procedure of the study is as follows: at least one week after the Dark Room Study, the subjects went through another series of tests in an illuminated room on a chin-rest. Recall the methodology for the lit room tests on the MP in Section 3.2.2. The first test, MP-Lit-Compd-Demo1, was to acclimate subjects to the new environment. Then two MP-Lit-Compd tests were run with a five minute break in between, the first referred to as MP-Lit-Compd-1, and the second as MP-Lit-Compd-2.

Half of the subjects ran these tests in a room where the illumination was measured at 6-7 lux on the lightmeter. To obtain this illumination, the lights in the room were turned off and a sun-lamp was directed at the wall behind the subject to reflect light onto the screen. The other half ran the tests with the illumination measured at around 35 lux by the lightmeter. This illumination was acquired by keeping the sun-lamp set-up and turning on the fluorescent overhead lights of the room.

At least one day later, the subjects who went through the illuminated room tests in the brighter room repeated the same procedure as that session, but with the light

compensation turned off: MP-Lit-Not-Compd-1 and MP-Lit-Not-Compd-2. The purpose of this set of tests is to verify that the light compensation is indeed improving the mobile perimeter.

4.4.1 Lit Room Results

To compare the results, the mean sensitivity (MS), short-term fluctuation (SF), long-term heterogeneous fluctuation (LF-he), long-term homogeneous fluctuation (LF-ho), and the differences in the differential light sensitivities were analyzed between the two perimeters.

4.4.1.1 Differential Light Sensitivity Thresholds

The visual field test results for subject CY-7 on the MP (in a lit room) and HFA, as well as the differences in the test results, can be seen in Figure 4.6. This figure also shows the tests results for the uncompensated lit room tests and how it compared to the HFA (Figures 4.6c and 4.6e).

Each of the thresholds at all 54 points measured by session MP-Lit-Compd-2 were subtracted from the thresholds measured by HFA-Exp-2 and placed into the categorized differences mentioned in the previous section (0 - 4 dB, 5 - 10 dB, and >10 dB). This was repeated for differences between the thresholds measured by HFA-Exp-2 and HFA-Exp-2.

Table 4.6 shows the categorized threshold differences between MP-Lit-Compd-2 and HFA-Exp-2, and between HFA-Exp-2 and HFA-Exp-1. The results appear to be almost identical to the dark room results (Table 4.3), where 91% of the threshold differences are in the 0 - 4 dB range. There are also no threshold differences in the >10 dB range. This suggests that the light compensation is performing as expected and works just as well as the dark room MP.

Table 4.7 shows the categorized threshold differences for only the subjects who performed the uncompensated lit room tests. This table shows the differences between MP-Lit-Not-Compd-2 and HFA-Exp-2, MP-Lit-Compd-2 and HFA-Exp-2, and HFA-Exp-2 and HFA-Exp-1. The latter two do not have any in the >10 dB category and so it is omitted from the table. As seen in the table, the MP-Lit-Not-Compd tests show a lower percentage of threshold differences in the 0 - 4 dB range, with the mean being 83%, compared to 90% when compensating for light. The MP-Lit-Not-Compd tests also

			28	26	26 (26)	28			
		28	32 (30)	34	26	30	30		
	26	30	30	34	34	32	32	34	
24	34	34 (34)	32	34	34	32	34	34 (34)	
28 (24)	30	34	34	34	34 (34)	34	0	32	
	28	30	30 (28)	34	34	32	28	34	
		28	30	34	34	30	28 (30)		
			30	30 (28)	26	26 (28)			

(a) MP (Lit Room)

			28	23	30	29			
		29	29	31	30	30	32		
	28	27	30	31	29	31	33	31	
24	28	30	32	34	33	31	33	31	
26	30	32	32	34	33	32	0	28	
	30	31	33	32	31	32	28	31	
		32	31	30	31	31	30		
			31	31	33	30			

(b) HFA

			24	28	24 (28)	22			
		30	22 (24)	26	22	28	30		
	26	28	28	30	24	30	28	34	
20	26	28 (34)	34	34	34	32	34	30 (34)	
12 (22)	16	30	28	34	34 (34)	32	0	30	
	28	28	30 (30)	34	28	24	28	34	
		24	28	34	30	26	20 (28)		
			26	24 (28)	26	28 (24)			

(c) MP (Lit Room - Uncompensated)

			0	3	-4	-1			
		-1	3	3	-4	0	-2		
	-2	3	0	3	5	1	-1	3	
0	6	4	0	0	1	1	1	3	
2	0	2	2	0	1	2	0	4	
	-2	-1	-3	2	3	0	0	3	
		-4	-1	4	3	-1	-2		
			-1	-1	-7	-4			

(d) Difference between HFA and MP (Compensated)

			-4	5	-6	-7			
		1	-7	-5	-8	-2	-2		
	-2	1	-2	-1	-5	-1	-5	3	
-4	-2	-2	2	0	1	1	1	-1	
-14	-14	-2	-4	0	1	0	0	2	
	-2	-3	-3	2	-3	-8	0	3	
		-8	-3	4	-1	-5	-10		
			-5	-7	-7	-2			

(e) Difference between HFA and MP (Uncompensated)

Figure 4.6: Comparison of Visual Fields for Subject CY-7 between the HFA and MP (Lit Room).

Table 4.6: Lit Room Threshold Differences

	MP-Lit-Compd-2 vs. HFA-Exp-2			**HFA-Exp-1 vs. HFA-Exp-2**		
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**>10 dB (%)**
CY-1	85	15	0	96	3.8	0
CY-2	90	9.6	0	98	1.9	0
CY-3	92	7.7	0	96	3.8	0
CY-4	85	15	0	100	0	0
CY-5	92	7.7	0	96	3.8	0
CY-6	90	10	0	100	0	0
CY-7	94	6	0	92	7.7	0
CY-8	92	7.7	0	98	1.9	0
CY-9	92	7.7	0	100	0	0
CY-10	96	3.8	0	92	7.7	0
Mean	**91**	**9.0**	**0**	**97**	**3.1**	**0**

have a few threshold differences that were >10 dB. There is a definite difference in the performance of the perimeter with and without light compensation.

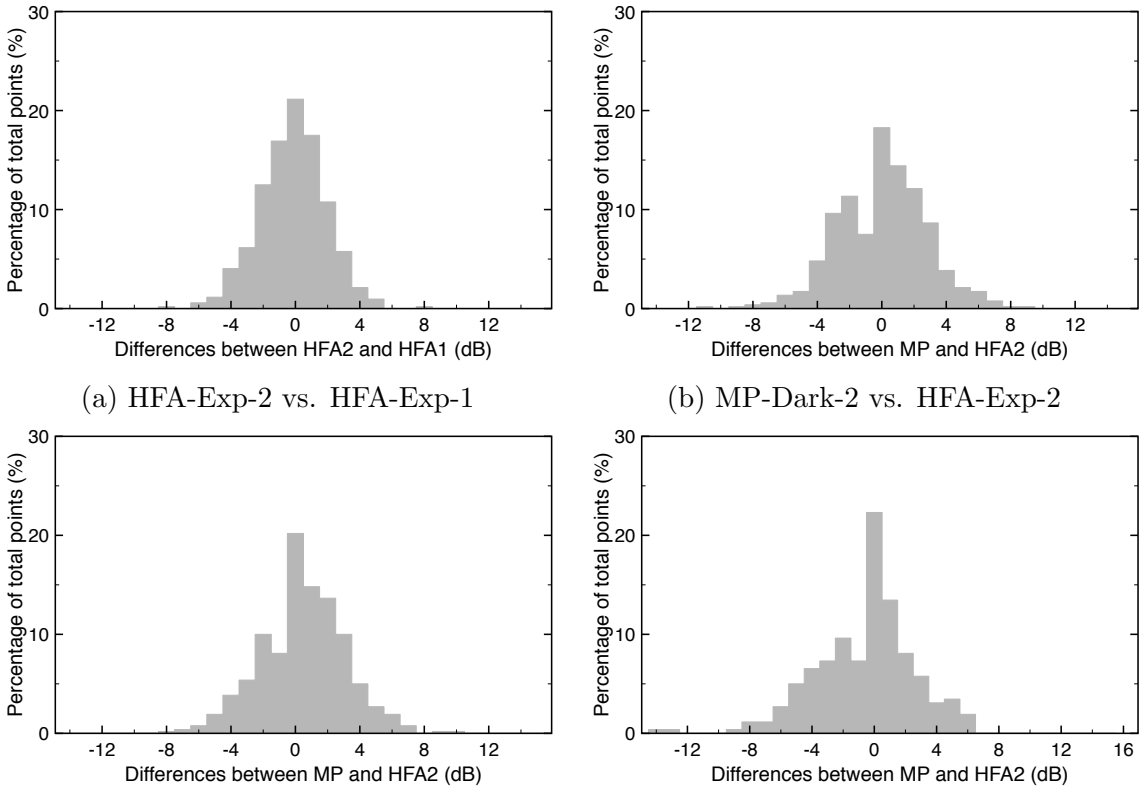
There is almost no difference between the group that performed the study in the dimmer room and the group in the brighter room. The group in the brighter room had 90% of its threshold differences in the 0 - 4 dB range, with the average of the groups being 91%. The group in the dimmer room had 92% in the 0 - 4 dB range.

Figure 4.7 contains histograms of the differential thresholds for a) HFA-Exp, b) MP-Dark, c) MP-Lit-Compd and d) MP-Lit-Not-Compd. The same trends seen in the previous tables are clear from these graphs. The dark and lit room tests show very similar trends, and the uncompensated lit room test has a smaller percentage of the differential thresholds in the -4 to 4 dB range compared to the others. The uncompensated lit room test has a larger and more uneven spread, with a mean of -0.59 dB (s.d.) of 3.18 dB, while the compensated lit room test (for the same 5 subjects) had a mean of 0.758 dB (s.d. 2.69 dB). For all subjects, HFA-Exp had a mean of -0.16 dB (s.d. 2.07), and MP-Lit-Compd had a mean of 0.48 dB (s.d. 2.63 dB).

Table 4.7: Lit Room Threshold Differences Without Compensation

	MP-Lit-Not-Compd-2 vs. HFA-Exp-2			**HFA-Exp-1 vs. HFA-Exp-2**		**MP-Lit-Compd-2 vs. HFA-Exp-2**	
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**
CY-1	83	15	1.9	96	3.8	85	15
CY-4	85	15	0	100	0	85	15
CY-5	88	12	0	96	3.8	92	7.7
CY-7	69	29	1.9	92	7.7	94	5.8
CY-8	92	7.7	0	98	1.9	92	7.7
Mean	**83**	**16**	**0.8**	**97**	**3.5**	**90**	**10**

The mean of MP-Lit-Not-Compd is more than 1 dB lower than MP-Lit-Compd, and the standard deviation is also higher. The results of the uncompensated tests were definitely poorer than the rest. Looking at the analysis of the differences in thresholds, it appears that the light compensation has a positive effect, bringing the results closer to MP-Dark and HFA-Exp, as well as having more consistent results.



(a) HFA-Exp-2 vs. HFA-Exp-1

(b) MP-Dark-2 vs. HFA-Exp-2

(c) MP-Lit-Compd-2 vs. HFA-Exp-2

(d) MP-Lit-Not-Compd-2 vs. HFA-Exp-2

Figure 4.7: Histogram of differences in differential light sensitivities for the Lit Room Study.

4.4.1.2 Mean Sensitivity

The mean sensitivities for perimeter sessions MP-Lit-Compd-1, MP-Lit-Compd-2, HFA-Exp, and MP-Dark are outlined in Table 4.8. Each row contains the MS measurements for all sessions for each subject. The fourth column is the average of the MS measurements of HFA-Exp-1 and HFA-Exp-2. The fifth column is the average of the MS measurements of MP-Dark-1 and MP-Dark-2.

The mean sensitivities of MP-Lit-Compd are less than 0.5 dB greater than what was measured by HFA-Exp, and the difference is even smaller between MP-Lit-Compd and MP-Dark. This further suggests that the light compensation is working in the correct manner. There are also no large differences in MS between MP-Lit-Compd-1 and MP-Lit-Compd-2.

To see what the difference was when there was no light compensation, Table 4.9 outlines the mean sensitivities for perimeter sessions MP-Lit-Not-Compd, MP-Lit-Compd,

Table 4.8: Mean Sensitivity of Control Group in Lit Room

	Mean Sensitivity (dB)			
	MP-Lit-Compd-1	**MP-Lit-Compd-2**	**HFA-Exp**	**MP-Dark**
CY-1	32.16	31.81	31.88	31.71
CY-2	31.10	30.52	30.89	30.32
CY-3	30.42	30.97	30.17	29.32
CY-4	31.65	31.35	30.34	31.85
CY-5	33.39	33.19	32.88	32.92
CY-6	29.39	29.39	29.13	30.00
CY-7	30.90	30.65	29.77	30.81
CY-8	32.35	31.87	30.54	31.55
CY-9	31.19	31.55	31.63	30.85
CY-10	31.81	32.00	31.02	31.15
Mean	**31.44**	**31.33**	**30.83**	**31.05**

HFA-Exp, and MP-Dark for only the subjects that performed the MP-Lit-Not-Compd experiments. All four columns containing the mean sensitivities are averages of both sessions for the specific test.

The MS of MP-Lit-Not-Compd was more than 1 dB lower than MP-Lit-Compd and MP-Dark, while only 0.5 dB lower than HFA-Exp. In contrast, MP-Lit-Compd and MP-Dark both have mean MS greater than 0.7 dB than HFA-Exp. This suggests that MP-Lit-Not-Compd is a better match to HFA-Exp, but there was definitely some learning that happened between the HFA-Exp and MP-Dark/MP-Lit-Compd tests for some of the subjects in this group. CY-4 confirmed the effect of learning when questioned after the study. CY-7 and CY-8 are the other two subjects that experienced a 1 dB increase, but were not questioned. Since MP-Dark was able to closely match HFA-Exp over all 10 subjects, it is better to compare the MP-Lit-Not-Compd results to MP-Dark rather than only comparing to HFA-Exp. Comparing it to MP-Dark shows a clear deterioration of mean sensitivity measured.

Again, a two-tailed paired t-test and a scattergram of the differences in measurements are used to evaluate the agreement between the two perimeters. A two-tailed paired t-

Table 4.9: Mean Sensitivity of Control Group in Lit Room - Uncompensated

	Mean Sensitivity (dB)			
	MP-Lit-Not-Compd	**MP-Lit-Compd**	**HFA-Exp**	**MP-Dark**
CY-1	30.58	31.98	31.88	31.71
CY-4	30.10	31.50	30.34	31.85
CY-5	32.55	33.29	32.88	32.92
CY-7	28.44	30.77	29.77	30.81
CY-8	31.00	32.11	30.54	31.55
Mean	**30.53**	**31.93**	**31.08**	**31.77**

test indicates that MP-Lit-Compd did not measure a statistically-significant different MS than HFA-Exp ($p < 0.05$). The t-test also indicates that MP-Lit-Not-Compd was not statistically significantly different from HFA-Exp. However, a two-tailed paired t-test between MP-Lit-Compd and MP-Lit-Not-Compd indicates a significantly different mean between the two.

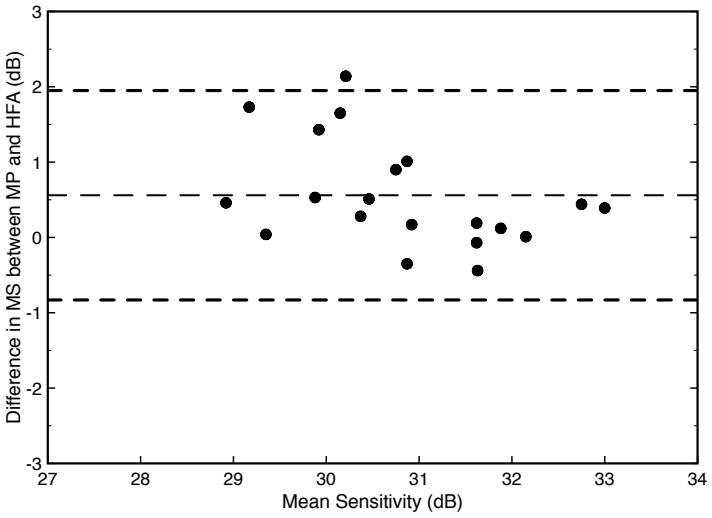


Figure 4.8: Scattergram of MS for MP-Lit-Compd vs HFA-Exp

Figure 4.8 and 4.9 present the differences in MS between the two perimeters for MP-Lit-Compd and MP-Lit-Not-Compd respectively. For MP-Lit-Compd, the mean of the differences between the two perimeters was 0.56 dB (the middle dashed line) with a standard deviation of 0.71. For MP-Lit-Not-Compd, the mean was -0.55 (s.d. 0.94).

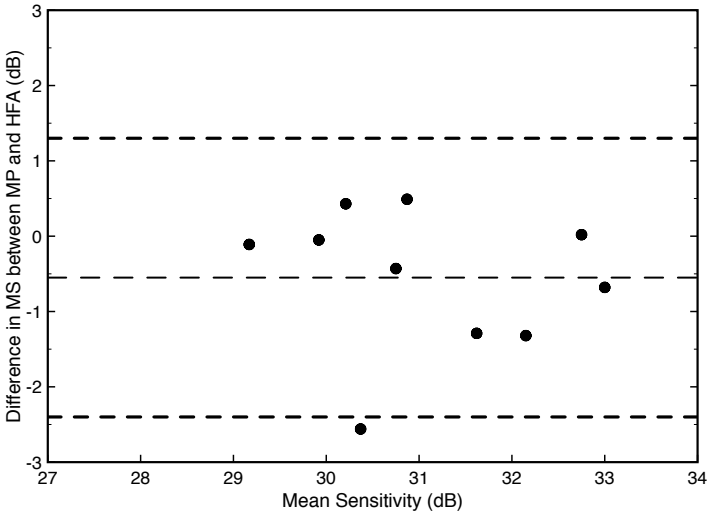


Figure 4.9: Scattergram of MS for MP-Lit-Not-Compd vs HFA-Exp

Both have 95% intervals that are reasonable, with differences that do not exceed ±2 dB by much. However, the interval for MP-Lit-Not-Compd is approximately 1 dB larger than the one for MP-Lit-Compd (33% of the interval for MP-Lit-Compd). Again, we see that the differences in MS for the higher mean sensitivities (>31.5 dB) tend to cluster around 0. Overall, both MP-Lit-Compd and MP-Lit-Not-Compd have good agreement with HFA-Exp, but MP-Lit-Compd appears to have more consistent results.

4.4.1.3 Test Repeatability

The short-term (SF), long-term heterogeneous (LF-he), long-term homogeneous (LF-ho) fluctuations for MP-Lit-Compd and MP-Lit-Not-Compd are summarized in Tables 4.10 and 4.11 respectively. Each row of the table contains the test repeatability metrics for both perimeters for each subject. The last two rows are the mean and standard deviation for each metric. These tables are identical to the test repeatability summarizing table in the previous section except Table 4.11 has an additional row after the first average that shows the average metrics for MP-Lit-Compd for only the 5 subjects that also performed the MP-Lit-Not-Compd tests.

In general, the test repeatability metrics were again quite low, which shows low variability between tests. The short-term fluctuation for MP-Dark had a mean of 1.90 dB, while both MP-Lit-Compd and MP-Lit-Not-Compd had lower means (1.54 dB and 1.83 dB respectively). The variability within the test on the MP is acceptable, although

Table 4.10: Test Repeatability Metrics for MP-Lit-Compd vs. HFA-Exp

	SF	**LF-he**		**LF-ho**	
	MP	**MP**	**HFA**	**MP**	**HFA**
CY-1	1.82	0.76	1.10	0.21	0.41
CY-2	2.00	1.01	0.89	0.38	-
CY-3	1.26	1.22	1.15	0.34	0.38
CY-4	1.92	1.20	0.93	0.09	0.58
CY-5	1.64	0.72	1.06	0.06	0.38
CY-6	0.89	1.30	0.82	-	0.28
CY-7	1.58	1.41	1.26	-	0.82
CY-8	1.38	1.24	0.92	0.29	0.44
CY-9	1.45	0.84	0.91	0.21	-
CY-10	1.45	0.99	1.32	-	1.25
Mean	**1.54**	**1.07**	**1.04**	**0.23**	**0.57**

MP-Lit-Compd obtained slightly better results compared to MP-Lit-Not-Compd (1.67 dB vs. 1.83 dB). For the long-term fluctuation metrics, the MP-Lit-Compd improved very slightly over the MP-Dark (1.07 dB vs 1.26 dB for LF-he, and 0.23 dB vs 0.73 dB for LF-ho), and was on par or better than HFA-Exp. MP-Lit-Not-Compd had poorer performance for the LF-he metric compared to all other methodologies. This is likely because there was no light compensation, resulting in inconsistent measurements across tests.

From a two-tailed paired t-test, there is no significant difference in the LF-he between the MP and the HFA ($p < 0.05$) for both MP-Lit-Compd and MP-Lit-Not-Compd. The scattergrams in Figure 4.10 and 4.11 display the differences in LF-he between the MP and HFA for both MP-Lit-Compd and MP-Lit-Not-Compd respectively. Both graphs show a downward trend as the mean sensitivity increases, again likely due to the truncating of >34 dB thresholds for HFA-Exp.

MP-Lit-Compd had a mean difference of 0.03 dB (s.d. 0.29 dB), while MP-Lit-Not-Compd had a mean difference of 0.38 dB (s.d. 0.23 dB). Assuming the higher mean sensitivity values increased their LF-he to better represent the variability between

Table 4.11: Test Repeatability Metrics for MP-Lit-Not-Compd vs. HFA-Exp

	SF	**LF-he**		**LF-ho**	
	MP	**MP**	**HFA**	**MP**	**HFA**
CY-1	1.22	1.38	1.10	0.31	0.41
CY-4	1.70	1.51	0.93	0.23	0.58
CY-5	1.61	1.10	1.06	0.27	0.38
CY-7	2.81	1.87	1.26	-	0.82
CY-8	1.79	1.29	0.92	0.46	0.44
Mean	**1.83**	**1.43**	**1.05**	**0.32**	**0.53**
MP-Lit-Compd Mean	**1.67**	**1.06**		**0.16**	

the tests, the means would increase for both compensated and uncompensated tests. However, MP-Lit-Compd has a small interval centered around 0 dB, so the increase would not create a drastic difference, meaning the agreement with HFA-Exp is still satisfactory. MP-Lit-Not-Compd has an interval where its lower bound is around the 0 dB spot, meaning with the expected shift, the agreement with HFA-Exp could be out of the tolerable range.

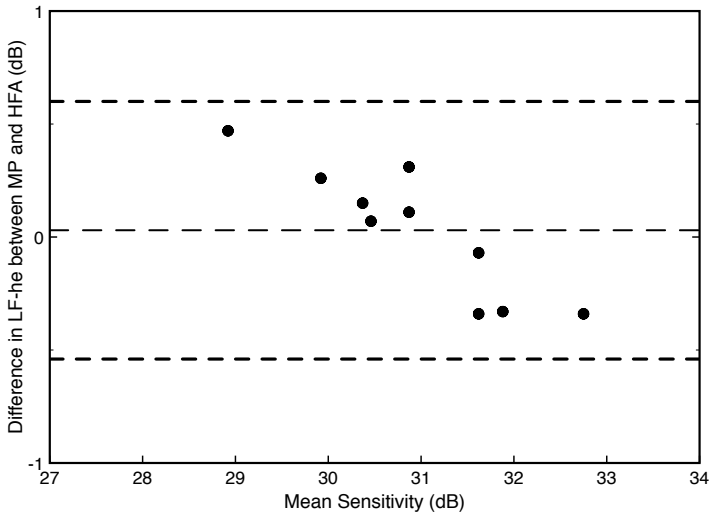


Figure 4.10: Scattergram of LF-he for MP-Lit-Compd vs HFA-Exp

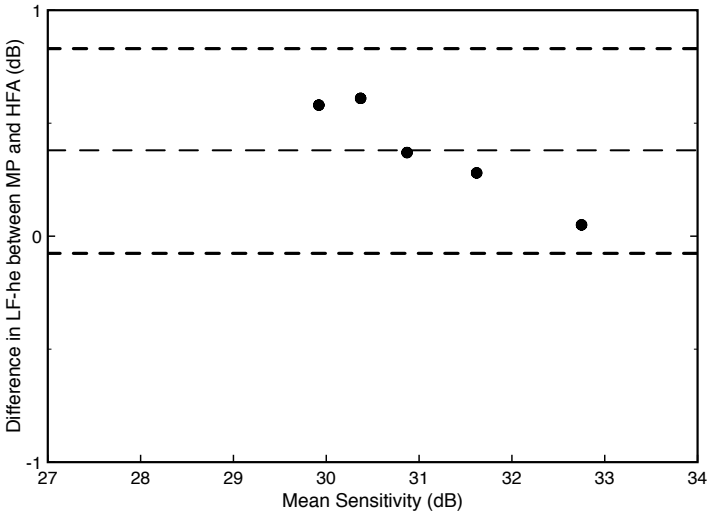


Figure 4.11: Scattergram of LF-he for MP-Lit-Not-Compd vs HFA-Exp

From a two-tailed paired t-test, there is no significant difference in the LF-ho between the MP and the HFA ($p < 0.05$) for both MP-Lit-Compd and MP-Lit-Not-Compd. The scattergrams in Figure 4.12 and 4.13 display the differences in LF-ho between the MP and HFA for both MP-Lit-Compd and MP-Lit-Not-Compd respectively.

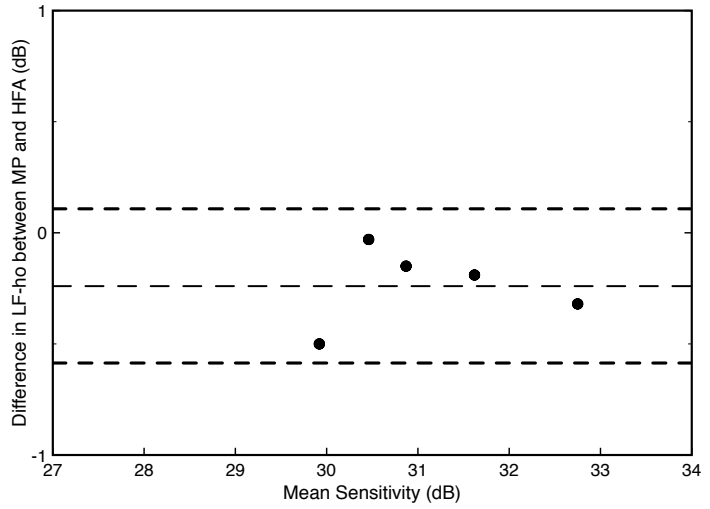


Figure 4.12: Scattergram of LF-ho for MP-Lit-Compd vs HFA-Exp

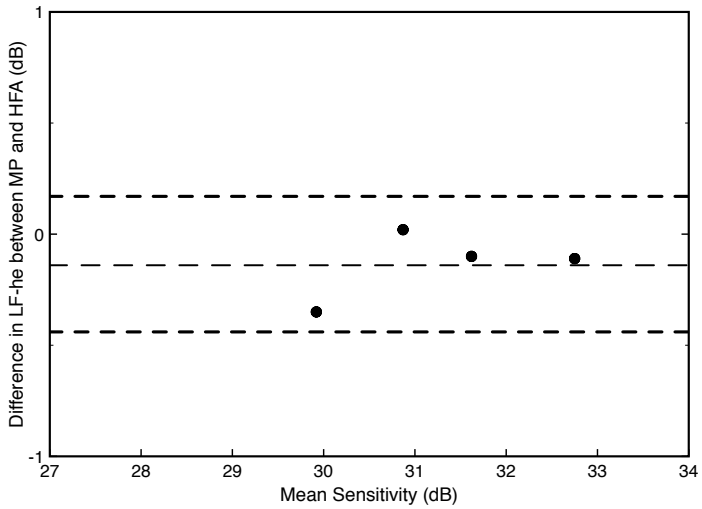


Figure 4.13: Scattergram of LF-ho for MP-Lit-Not-Compd vs HFA-Exp

MP-Lit-Compd had a mean difference of -0.24 dB (s.d. 0.18 dB), while MP-Lit-Not-Compd had a mean difference of -0.14 dB (s.d. 0.16 dB). Both have intervals with the top bound near the 0 dB point, meaning both had lower LF-ho measurements than HFA-Exp. This simply means both had very similar overall results over the two sessions compared to the two sessions on HFA-Exp, which is understandable because the subjects are likely to be 'experts' at doing the test after so many tests.

4.5 Head Movement Compensation Study

The purpose of the Head Movement Compensation Study is to test the head movement compensation on the MP by testing subjects without a chin-rest and examine how well the final MP compared to the HFA. This was done through two separate studies. The first study verified that the head compensation was able to detect the blind spot of subjects with normal vision by only testing a few select points with and without head compensation on. The second study was a complete test of the perimeter with both light and head movement compensation turned on. These two studies and their results will be outlined in the following sections.

4.5.1 Blindspot Compensation Study

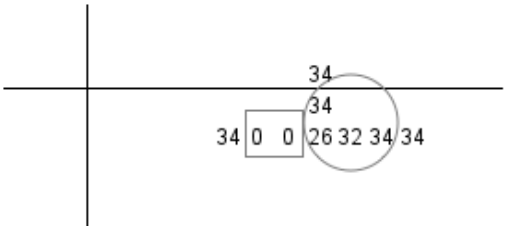
The Blindspot Compensation Study assesses the head compensation ability of the MP by testing the blind spot of the user at different distances and head rotations with and without head compensation turned on. This study was performed on three subjects.

The procedure is as follows: Recall the methodology for the mini-tests in Section 3.4. Subjects perform all six mini-tests outlined, testing nine points on the visual field. These nine points all cluster around the blind-spot, which is located on average around 15° temporally and 1.5° below the horizontal meridian [39]. These tests are split into 3 pairs, each pair with one having head movement compensation on and the other off. For one pair, the subjects are positioned 18 cm away from the tablet. In another pair, the subjects are positioned 32 cm away. In the last pair, the subjects are 25 cm away, and their head is tilted counter-clockwise 15°.

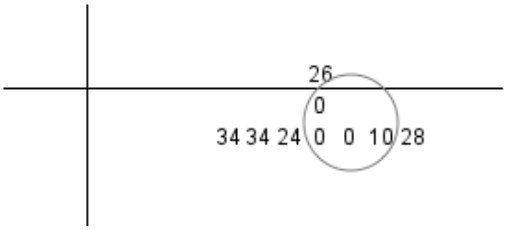
4.5.1.1 Blindspot Compensation Results

In the close-up mini-tests, where subjects were positioned 18 cm away from the screen, the no-compensation test was operating under the illusion that the subject was positioned 25 cm away. This means the expected placement of the blindspot would be shifted 4° to the left of the expected blindspot location. This is illustrated in Figure 4.14. In these images, the horizontal and vertical axes represent the axes seen before in a full visual field test (Figure 4.6), but are truncated to only show the part of the visual field being tested, which spans from 9° to 19° horizontally and 1° to -3° vertically. The vertical line of numbers is the 15° point at which the blindspot is generally located. The fields on the left show the blindspot shifted to the left (expected spot circled, wrong blindspot enclosed in a square), and the fields on the right show the blindspot detected in the correct spot (circled) with head movement compensation turned on. Similar results were seen in all subjects.

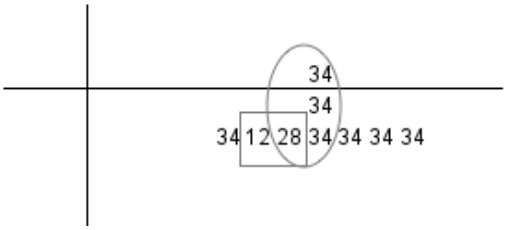
In the far-distance mini-tests, where subjects were positioned 32 cm away from the screen, the no-compensation test would have an expected placement of the blindspot shifted 4° to the right of the expected blindspot location. This is illustrated in Figure 4.15. The first picture shows the shift to the right, and the second is the test with head movement compensation turned on, where the blindspot was again located in the right spot.



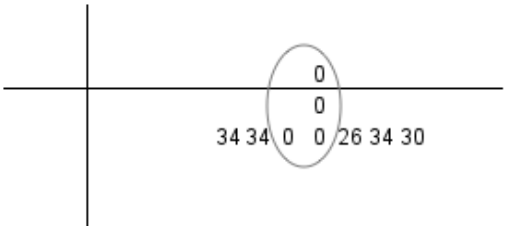
(a) Subject 1: No Compensation



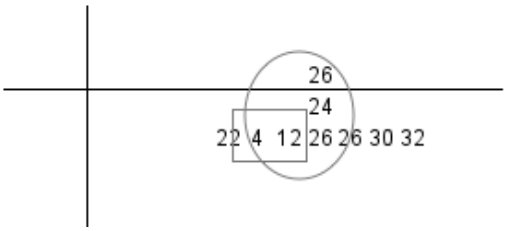
(b) Subject 1: With Head Movement Compensation



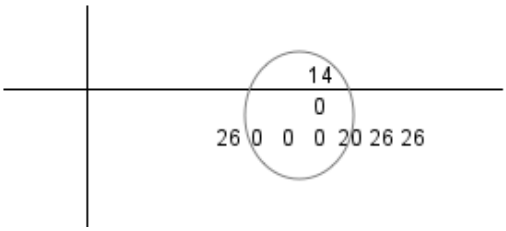
(c) Subject 2: No Compensation



(d) Subject 2: With Head Movement Compensation



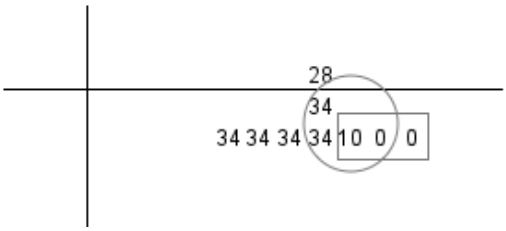
(e) Subject 3: No Compensation



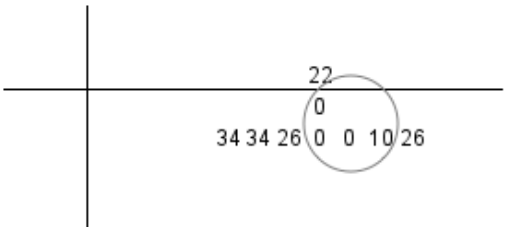
(f) Subject 3: With Head Movement Compensation

Figure 4.14: Results of close-up blindspot testing for three subjects at 18 cm distance from MP

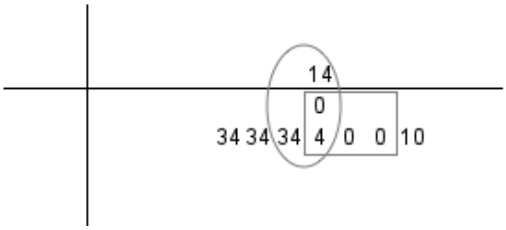
In the head-tilt mini-tests, where subjects were positioned 25 cm away from the screen and head tilted 15° CCW, the no-compensation test would have an expected placement of the blindspot shifted 4° above the expected blindspot location. This is illustrated in Figure 4.16. The first picture shows the shift upwards, and the second is the test with head movement compensation turned on, where the blindspot was again located in the right spot.



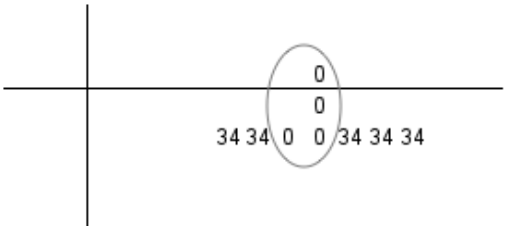
(a) Subject 1: No Compensation



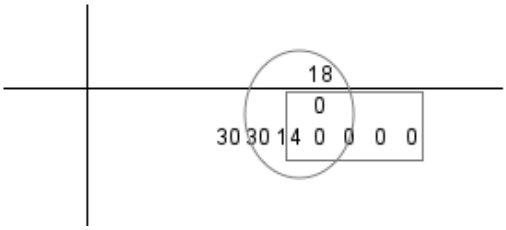
(b) Subject 1: With Head Movement Compensation



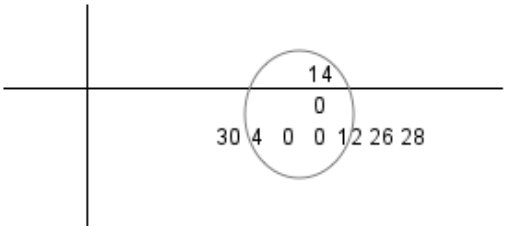
(c) Subject 2: No Compensation



(d) Subject 2: With Head Movement Compensation

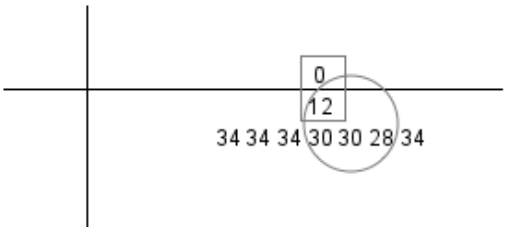


(e) Subject 3: No Compensation

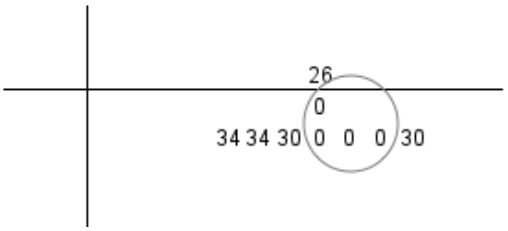


(f) Subject 3: With Head Movement Compensation

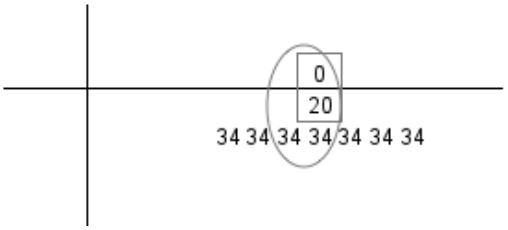
Figure 4.15: Results of far blindspot testing for three subjects at 32 cm distance from the MP



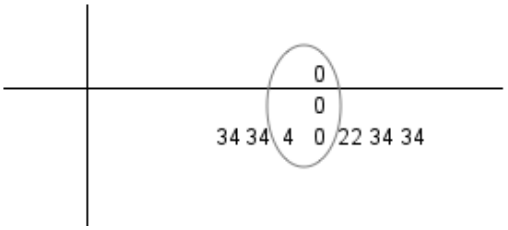
(a) Subject 1: No Compensation



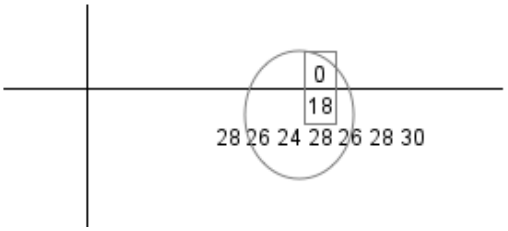
(b) Subject 1: With Head Movement Compensation



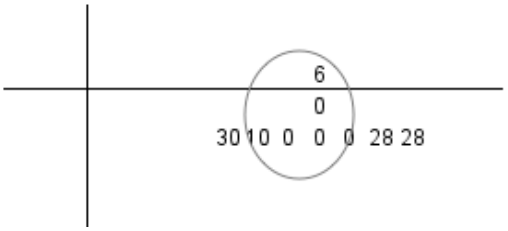
(c) Subject 2: No Compensation



(d) Subject 2: With Head Movement Compensation



(e) Subject 3: No Compensation



(f) Subject 3: With Head Movement Compensation

Figure 4.16: Results of one subject at 25 cm distance from MP and head tilted 15° CCW

4.5.2 Full Head Movement Compensation Study

The purpose of the Full Head Movement Compensation Study is to verify that the head compensation has no detrimental effect on test results. This study was performed on all control subjects. The younger control group (CY) went through the following procedures at least one week after the Lit Room Study. The older control group (CO) went through them at least one week after the HFA-Exp baseline. For clarity, the HFA-Exp tests for group CY will be referred to as HFA-Exp-CY-1 and HFA-Exp-CY-2, and the tests for group CO will be referred to as HFA-Exp-CO-1 and HFA-Exp-CO-2.

The procedure of the study is as follows: Recall the methodology for the head movement tests on the MP in Section 3.2.3. All subjects first underwent MP-HeadMovement-NoPatch-Demo1, again to acclimate the subjects to the new set-up. A reminder, the MP-HeadMovement-NoPatch methodology does not use an opaque eye-patch and only relies on the asymmetrical circle pattern on a white patch taped onto the subject's glasses to block out their left eye. Then two MP-HeadMovement-NoPatch tests were run with a five minute break in between, the first referred to as MP-HeadMovement-NoPatch-CY-1 for the <42 control group, MP-HeadMovement-NoPatch-CO-1 for the >42 control group, and the second as MP-HeadMovement-NoPatch-CY-2 and MP-HeadMovement-NoPatch-CO-2 for the <42 and >42 control groups respectively.

The control group CY ran these tests in a room where the illumination was measured at 35 lux on the lightmeter. To obtain this illumination, the lights in the room were turned on and a sunlamp was directed at the wall behind the subject to reflect light onto the screen (the same illumination settings for the brighter Lit Room Study). The control group CO ran the study in a various room where the illumination was measured at 7 lux on the lightmeter, provided solely by the light in the room.

The following sections compare the results by looking at the mean sensitivity (MS), short-term fluctuation (SF), long-term heterogeneous fluctuation (LF-he), long-term homogeneous fluctuation (LF-ho), and the differences in the differential light sensitivities were analyzed between the two perimeters.

4.5.2.1 Differential Light Sensitivity Thresholds

The visual field test results for subject CY-2 on the MP and HFA, as well as the differences in the test results, can be seen in Figure 4.17.

			30	30	30 (30)	30		
		30	30 (32)	34	30	30	34	
	34	30	34	34	32	30	34	34
28	32	34 (34)	34	34	34	34	34	34 (32)
32 (34)	34	34	34	34	34 (34)	34	0	34
	34	34	34 (32)	34	34	30	34	34
		32	34	34	34	32	32 (34)	
			34	30 (32)	30	32 (32)		

(a) Mobile Perimeter Visual Field

			28	28	29	29		
		28	31	30	31	30	30	
	28	30	31	32	32	32	31	31
26	30	31	32	33	34	31	33	30
31	30	33	32	33	34	32	0	29
	31	32	32	32	33	31	30	29
		32	32	30	32	32	32	
			31	30	29	33		

(b) Humphrey Field Analyzer Visual Field

			2	2	1	1		
		2	-1	4	-1	0	4	
	6	0	3	2	0	-2	3	3
2	2	3	2	1	0	3	1	4
1	4	1	2	1	0	2	0	5
	3	2	2	2	1	-1	4	5
		0	2	4	2	0	0	
			3	0	1	-1		

(c) Difference between HFA and MP

Figure 4.17: Comparison of Visual Fields for Subject CY-2 between the HFA and MP.

Each of the thresholds at all 54 points measured by session HFA-Exp-CY-2 and HFA-Exp-CO-2 were subtracted from the thresholds measured by MP-HeadMovement-Patch-CY-2 and MP-HeadMovement-Patch-CO-2 respectively. Table 4.12 and 4.13 show the

categorized threshold differences for each group.

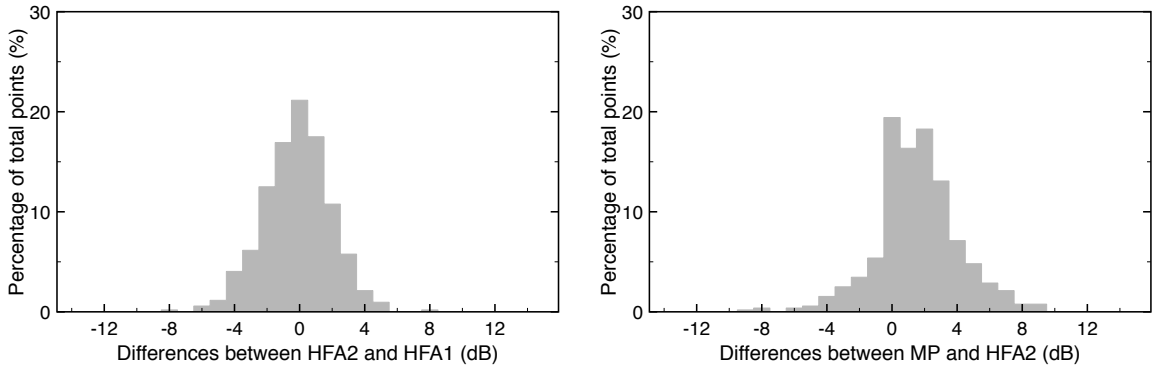
Table 4.12: Head Movement Compensation Threshold Differences for Group CY

	MP-HeadMovement-NoPatch-CY-2 vs. HFA-Exp-CY-2			**HFA-Exp-CY-1 vs. HFA-Exp-CY-2**		
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**>10 dB (%)**
CY-1	85	15	0	96	3.8	0
CY-2	94	5.8	0	98	1.9	0
CY-3	85	15.4	0	96	3.8	0
CY-4	69	31	0	100	0	0
CY-5	94	5.8	0	96	3.8	0
CY-6	77	23	0	100	0	0
CY-7	90	10	0	92	7.7	0
CY-8	87	13.5	0	98	1.9	0
CY-9	96	3.8	0	100	0	0
CY-10	94	5.8	0	92	7.7	0
Mean	**87**	**12.9**	**0**	**97**	**3.1**	**0**

For the younger control group, the threshold differences in the 0 - 4 dB range decreased to a mean of 87% (versus 91% in the Dark Room and Lit Room Studies), but there are still no threshold differences in the >10 dB range. Looking at the histograms will provide more insight into why there is this decrease in accuracy.

Figure 4.18 plots the details of the differences in thresholds for a) between the two HFA-Exp sessions and b) between MP-HeadMovement-NoPatch-CY-2 and HFA-Exp-CY-2. There appears to be a negative skew in the curve in the graph comparing the MP to HFA, with the mean being 1.54 dB (s.d. 2.57 dB). The shape of the curve is reasonable, so the skew is the reason for the 5% difference in threshold differences in the 0 - 4 dB range compared to the previous studies. The difference is not because of less accuracy in the perimeter, but the skew needs to be investigated.

This brings us to the older control group to see if the same trend occurs. Table 4.13



(a) HFA-Exp-CY-2 vs. HFA-Exp-CY-1

(b) MP-HeadMovement-NoPatch-CY-2 vs. HFA-Exp-CY-2

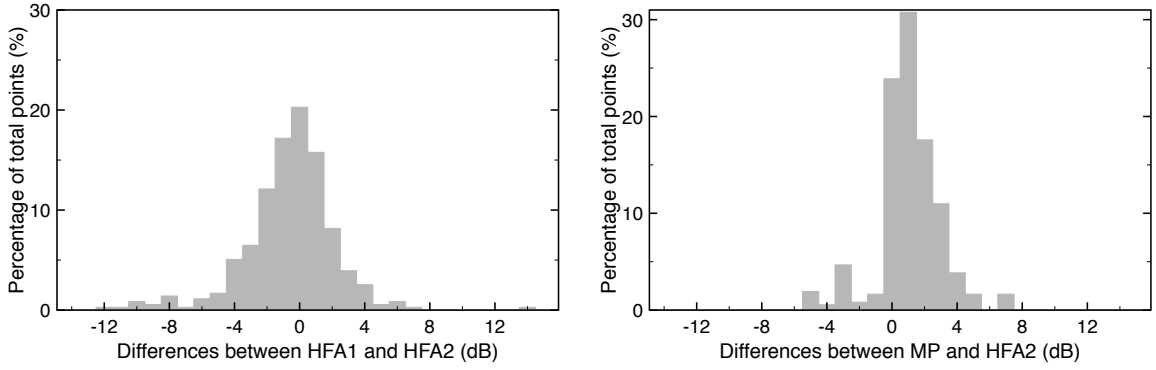
Figure 4.18: Histogram of differences in differential light sensitivities for the Head Movement Compensation Study for Group CY.

shows the categorized threshold differences for Group CO. The percentage of threshold differences in the 0 - 4 dB range is very close between the two comparisons (84% vs 90%), and there are only slightly more threshold differences in the >10 dB range. From only looking at this table, it does not look like there are major differences between the two comparisons.

However, when we take a look at the histograms in Figure 4.19, the negative skew is very obvious in the second graph (comparing MP to HFA). The mean of it was 1.05 dB (s.d. 1.94 dB), while the mean of the first graph was -0.62 dB (s.d. 2.83 dB). The shape of the curve does not suggest any other discrepancies between the HFA and the head compensating MP. Other than the skew seen in both control groups, the head compensation appears to be working as expected. The skew will be investigated in a later section.

Table 4.13: Head Movement Compensation Threshold Differences for Group CO

	MP-HeadMovement-NoPatch-CO-2 vs. HFA-Exp-CO-2			**HFA-Exp-CO-1 vs. HFA-Exp-CO-2**		
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**>10 dB (%)**
CO-1	98	1.9	0	100	0	0
CO-2	81	19.2	0	85	15.4	0
CO-3	88	11.5	0	77	19.2	3.8
CO-4	81	12	0	92	0	0
CO-5	90	9.6	0	94	5.8	0
CO-6	56	29	7.7	79	10	1.9
CO-7	88	11.5	0	94	5.8	0
CO-8	92	7.7	0	98	1.9	0
Mean	**84**	**13**	**1.0**	**90**	**7.2**	**0.7**



(a) HFA-Exp-CO-2 vs. HFA-Exp-CO-1

(b) MP-HeadMovement-NoPatch-CO-2 vs. HFA-Exp-CO-2

Figure 4.19: Histogram of differences in differential light sensitivities for the Head Movement Compensation Study for Group CO.

4.5.2.2 Mean Sensitivity

The mean sensitivities for perimeter sessions MP-HeadMovement-NoPatch-CY-1, MP-HeadMovement-NoPatch-CY-2, and HFA-Exp-CY are outlined in Table 4.14. Each row contains the MS measurements for all sessions for each subject. The fourth column is the average of the MS measurements of HFA-Exp-1 and HFA-Exp-2.

Table 4.14: Mean Sensitivity of Control Group CY with Head Movement Compensation and No Eye-Patch

	Mean Sensitivity (dB)		
	MP-HeadMovement-NoPatch-CY-1	**MP-HeadMovement-NoPatch-CY-2**	**HFA-Exp-CY**
CY-1	32.16	31.81	31.88
CY-2	32.19	32.61	30.89
CY-3	32.23	32.48	30.17
CY-4	33.10	33.52	30.34
CY-5	33.29	33.48	32.88
CY-6	31.32	31.61	29.13
CY-7	31.65	31.77	29.77
CY-8	32.48	32.23	30.54
CY-9	31.81	31.61	31.63
CY-10	31.84	33.10	31.02
Mean	**32.21**	**32.42**	**30.83**

The mean sensitivities of MP-HeadMovement-NoPatch-CY are somewhat larger than what was measured by HFA-Exp-CY, with an average of 1.49 dB increase over HFA-Exp-CY. This is an expected result due to the skew seen in the histograms of the previous subsection.

Again, a two-tailed paired t-test and a scattergram of the differences in measurements are used to evaluate the agreement between the two perimeters. The two-tailed paired t-test indicates that MP-HeadMovement-NoPatch-CY did measure a statistically-significant different mean MS than HFA-Exp-CY ($p < 0.05$), which was also expected because the skew was almost 2 dB.

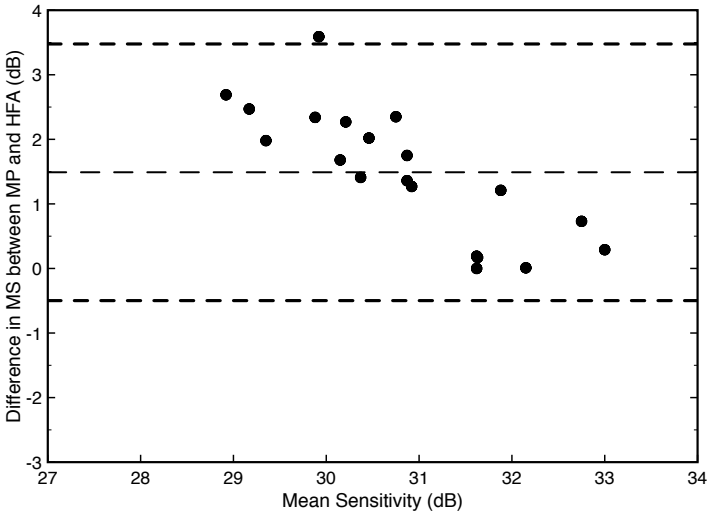


Figure 4.20: Scattergram of MS for Group CY MP-HeadMovement-NoPatch-CY vs HFA-Exp-CY

Figure 4.20 presents the differences in MS between the MP-HeadMovement-NoPatch-CY and HFA-Exp-CY. For MP-HeadMovement-NoPatch-CY, the mean of the differences between the two perimeters was 1.49 dB (s.d. 1.01 dB). The 95% interval (-0.50 dB - 3.48 dB) would be reasonable if the mean was shifted back down to 0 and has a range close to the previous studies. Again, we see that the differences in MS for the higher mean sensitivities (>31.5 dB) tend to cluster around 0.

Now we will examine the mean sensitivities of Group CO. The mean sensitivities for perimeter sessions MP-HeadMovement-NoPatch-CO-1, MP-HeadMovement-NoPatch-CO-2, HFA-Exp-CO-1, and HFA-Exp-CO-2 are outlined in Table 4.15. The expected increase in MS for MP-HeadMovement-NoPatch-CO is observed, with an average of 1.11 dB increase over HFA-Exp-CO. The two-tailed paired t-test also indicates that MP-HeadMovement-NoPatch-CO did measure a statistically-significant different mean MS than HFA-Exp-CO ($p < 0.05$). Note that two subjects in Group CO appeared to undergo a sharp learning curve during the HFA-Exp-CO tests, increasing their MS by more than 2 dB between tests. Even artificially increasing CO-2 and CO-3's HFA-Exp-CO-1 measurements result in a MP-HeadMovement-NoPatch-CO increase of almost 0.9 dB, and the means are still significantly different.

Figure 4.21 presents the differences in MS between the MP-HeadMovement-NoPatch-CO and HFA-Exp-CO. For MP-HeadMovement-NoPatch-CO, the mean of the differences between the two perimeters was 1.11 dB (s.d. 1.57 dB). The 95% interval (-1.96 dB to

Table 4.15: Mean Sensitivity of Control Group with Head Movement Compensation and no patch (oc)

	Mean Sensitivity (dB)			
	MP-HeadMovement-NoPatch-1	**MP-HeadMovement-NoPatch-2**	**HFA-Exp-1**	**HFA-Exp-2**
CO-1	32.10	32.19	32.48	32.19
CO-2	29.02	28.81	25.90	28.13
CO-3	30.77	30.26	25.85	28.44
CO-4	29.90	30.19	27.83	28.00
CO-5	27.06	27.61	27.65	27.63
CO-6	25.61	26.23	24.65	24.47
CO-7	29.39	30.42	30.69	30.46
CO-8	30.74	30.84	29.27	29.79
Mean	**29.32**	**29.57**	**28.04**	**28.64**

4.17 dB) is a very large interval, but if we artificially increase the results of the two anomalous subjects again in Group CO on their first HFA-Exp-CO test, the interval reduces to -1.41 - 3.09 dB. This adjusted interval would be reasonable if the mean was shifted back down to 0. We also see that the differences in MS for the higher mean sensitivities (>31.5 dB) cluster around 0.

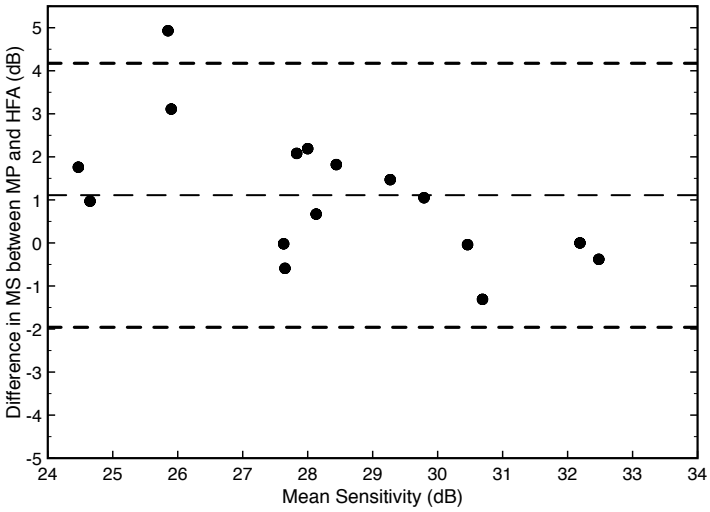


Figure 4.21: Scattergram of MS for CO MP-HeadMovement-NoPatch vs HFA-Exp

4.5.2.3 Test Repeatability

The short-term (SF), long-term heterogeneous (LF-he), long-term homogeneous (LF-ho) fluctuations for MP-HeadMovement-NoPatch-CY and MP-HeadMovement-NoPatch-CO are summarized in Tables 4.16 and 4.17 respectively. Each row of the table contains the test repeatability metrics for both perimeters for each subject. The last two rows are the mean and standard deviation for each metric. In general, we would not expect the test repeatability metrics to have the same increase as the other metrics if there is simply a skew in the data because we are comparing two of the same tests.

Table 4.16: Test Repeatability Metrics for MP-HeadMovement-NoPatch-CY vs. HFA-Exp-CY for Group CY

	SF	**LF-he**		**LF-ho**	
	MP	**MP**	**HFA**	**MP**	**HFA**
CY-1	1.82	0.76	1.10	0.21	0.41
CY-2	1.18	0.85	0.89	0.27	-
CY-3	1.22	0.87	1.15	0.13	0.38
CY-4	0.55	0.90	0.93	0.27	0.58
CY-5	0.95	0.70	1.06	0.09	0.38
CY-6	1.52	0.96	0.82	0.14	0.28
CY-7	1.30	1.22	1.26	-	0.82
CY-8	0.95	1.35	0.92	-	0.44
CY-9	1.82	0.96	0.91	-	-
CY-10	1.30	1.28	1.32	0.87	1.25
Mean	**1.26**	**0.99**	**1.04**	**0.28**	**0.57**

Table 4.17: Test Repeatability Metrics for MP-HeadMovement-NoPatch-CO vs. HFA-Exp-CO for Group CO

	SF	**LF-he**		**LF-ho**	
	MP	**MP**	**HFA**	**MP**	**HFA**
CO-1	1.14	1.24	0.68	-	0.18
CO-2	3.39	1.73	1.75	-	1.56
CO-3	1.18	1.23	2.16	0.32	1.81
CO-4	1.45	1.06	0.83	0.13	0.04
CO-5	2.97	1.03	1.09	0.34	-
CO-6	2.76	2.08	1.86	0.30	-
CO-7	2.17	1.52	1.08	0.69	0.14
CO-8	1.87	0.92	0.84	-	0.35
Mean	**2.12**	**1.35**	**1.29**	**0.36**	**0.68**

From the two tables, we can confirm that the test repeatability metrics were again quite low, showing low variability between tests. In fact, the SF of MP-HeadMovement-NoPatch-CY decreased compared to the previous two studies, and the SF for Group CO is similar to the SF of Group CY for the Dark Room Study (2.12 dB vs 1.94 dB). This decreasing SF seen in Group CY could be a result of learning. For the long-term fluctuation metrics, the means were very similar between the MP and HFA for both groups.

From a two-tailed paired t-test, there is no significant difference in the LF-he between the MP and the HFA ($p < 0.05$) for both groups. The scattergrams in Figures 4.22 and 4.23 display the differences in LF-he between the MP and HFA for Group CY and CO respectively. For Group CY, the mean was -0.05 db (s.d. 0.24 dB), and for Group CO, the mean was 0.06 dB (s.d. 0.46 dB). Both groups have a small 95% interval and demonstrate acceptable levels of long-term heterogeneous fluctuation.

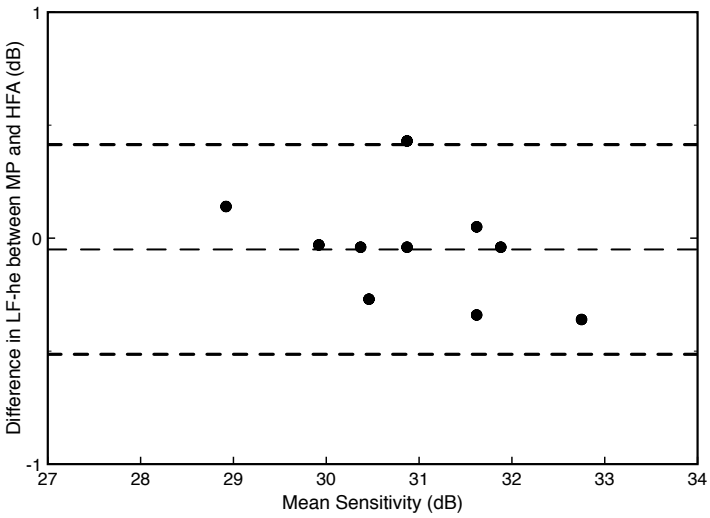


Figure 4.22: Scattergram of LF-he for Group CY - MP-HeadMovement-NoPatch-CY vs HFA-Exp-CY

From a two-tailed paired t-test, there is also no significant difference in the LF-ho between the MP and the HFA ($p < 0.05$) for both groups. The scattergrams in Figure 4.24 and 4.25 display the differences in LF-ho between the MP and HFA for Group CY and CO respectively. For Group CY, the mean was -0.26 dB (s.d. 0.089 dB), and for Group CO, the mean was -0.28 dB (s.d. 1.07 dB).

Group CY has 95% intervals with the top bound near the 0 dB point, meaning it had lower LF-ho measurements than HFA-Exp-CY, which again is likely a result of learning

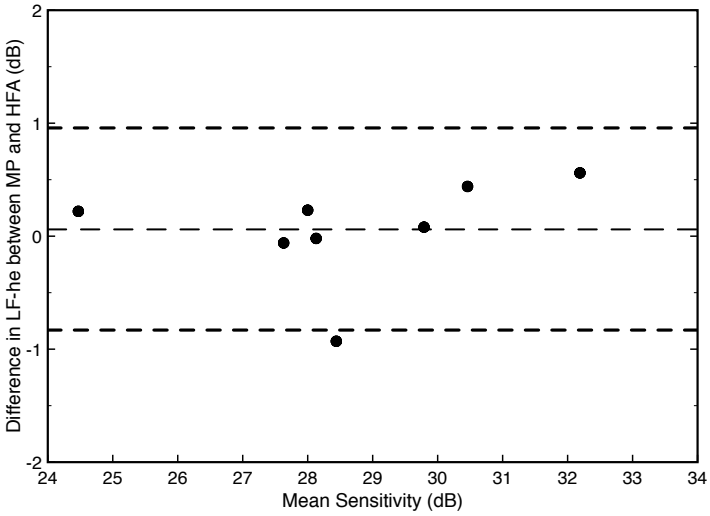


Figure 4.23: Scattergram of LF-he for Group CO - MP-HeadMovement-NoPatch-CO vs HFA-Exp-CO

and getting more consistent results. Group CO did not have this effect (this group did not complete nearly as many tests as Group CY), but the 95% interval was in an acceptable range and this shows good agreement between the two perimeters.

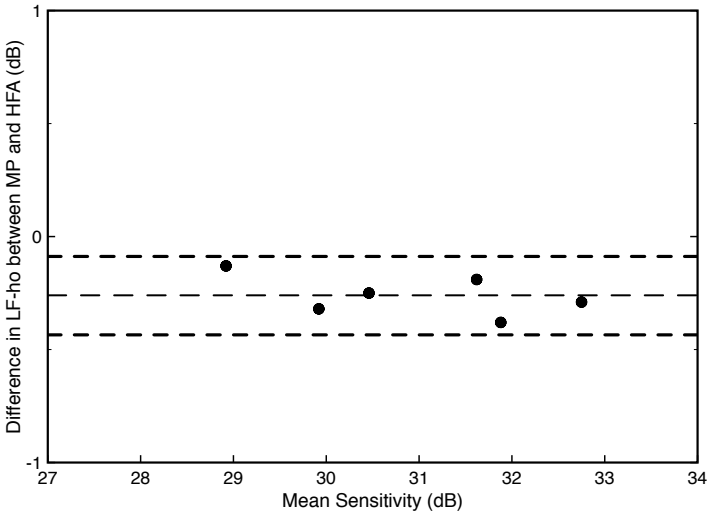


Figure 4.24: Scattergram of LF-ho for CY MP-HeadMovement-NoPatch-CY vs HFA-Exp-CY

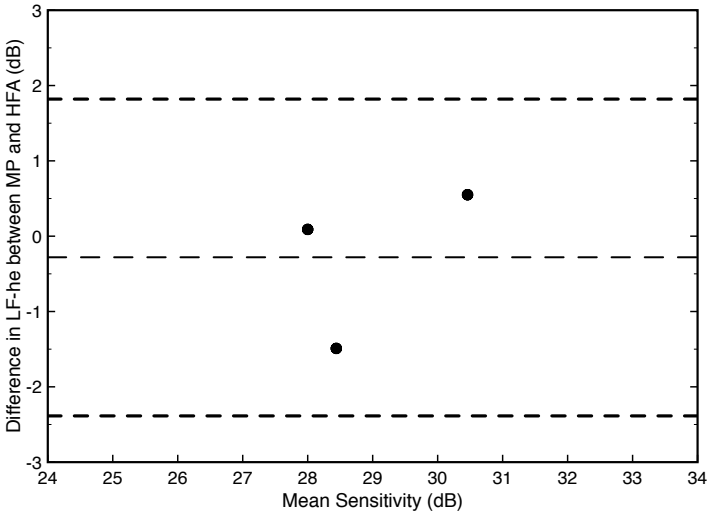


Figure 4.25: Scattergram of LF-ho for CO MP-HeadMovement-NoPatch-CO vs HFA-Exp-CO

4.5.2.4 Skew Investigation

This subsection investigates the negative skew found in the differential light sensitivity thresholds and the mean sensitivities measured in both control groups. The only differences between the Lit Room Study and the Head Movement Compensation Study were 1) Allowing for head movements and 2) Using only the asymmetrical circle grid as a patch, and omitting a complete opaque black eye-patch. The second difference seemed to be more likely to create an increase in thresholds measured and so a few experiments were conducted to look into this.

Four subjects performed the same head-movement experiment, but with the opaque eye-patch on: MP-HeadMovement-Patch. Two subjects had experienced an increase in mean sensitivity (CY-2 and CY-4), and two subjects did not (CO-1 and CO-7).

Table 4.18 contains the results. With the opaque eye-patch, the mean sensitivity matches the Lit Room results for the subjects that were affected and the mean sensitivity stays the same for the subjects that did not experience an increase when using a "translucent" patch, seen in Figure 4.26. The lack of an opaque eye-patch seems to be the cause of this skew.

The increase in thresholds is explained by the Ganzfeld Effect, which occurs when there is a large difference between the light entering the right and left eye. The brain attempts to merge the two images, resulting in an image with lowered brightness. A

Table 4.18: Mean Sensitivity Comparisons between Opaque Eye-Patch and 'Translucent' Eye-Patch

	Mean Sensitivity (dB)			
	MP-HeadMovement-NoPatch	**MP-HeadMovement-Patch**	**MP-Lit-Compd**	**HFA-Exp**
CY-2	32.40	31.19	30.81	30.89
CY-4	33.31	31.78	31.50	30.34
CO-1	33.26	32.14		32.34
CY-7	29.48	29.90		30.63

(a) A translucent eye-patch (b) An opaque eye-patch

Figure 4.26: Different eye-patches

black opaque eye-patch would result in an image with lowered brightness and therefore lowered threshold measured. Fuhr et al. found that there was approximately 0.7 dB increase in mean sensitivity when using a translucent eye-patch compared to an opaque eye-patch [40]. Interestingly, subjects in the study found the translucent eye-patch more comfortable as it did not create a 'fog-effect', which could only be eliminated through blinking. The results when using a translucent eye-patch were also more consistent. In addition, some subjects did not appear to be affected by the Ganzfeld Effect, which explains why some subjects in our study also did not have an increase in mean sensitivity.

With the benefits of using a translucent eye-patch, it is interesting as to why it is not being used for the standard visual field test. It would benefit most subjects by lessening the fatigue experienced and greatly decrease the discomfort felt during the test. One possible reason why the current perimeter still uses an opaque eye-patch even though

the benefits of a translucent one could be due to tradition. Visual field tests have always used opaque patches and people are unwilling to change.

Because the results were quite consistent across all subjects, it is clear that using a black opaque eye-patch would have resulted in measurements that agreed well with the HFA. From the studies on the control groups, the mobile perimeter appears to do quite well and be very comparable to the HFA. Now it is tested on real patients with glaucoma and the results are presented in the next chapter.

Chapter 5

Comparison between Perimeters in Glaucoma Patients

In this chapter, the MP is evaluated against the HFA in a study involving patients with glaucoma or at risk of glaucoma. The visual field results of both tests are compared.

5.1 Study Procedure

Recall the different methodologies described in Chapter 3. This study makes use of the methodologies in Section 3.1, 3.2.3, and 3.3. The purpose of this study is to compare patients' visual field results on the HFA to the MP.

The study tested each subjects in a single session due to time constraints. There were two parts to this study. The procedure for the first part was as follows: Subjects first underwent HFA-Exp-2, which was a regularly scheduled appointment with their opthalmologist for the purpose of monitoring their vision. After HFA-Exp-2, subjects were relocated to a hallway/waiting area in the hospital where the tablet measured an environmental illumination of approximately 7 lux. All subjects underwent MP-HeadMovement-Patch-Demo1 to acclimate themselves to the MP and minimize the effect of the influence of learning [41]. If the blindspot was properly detected during the demonstration, MP-HeadMovement-Patch was then run, otherwise, the demonstration was repeated. At the end, subjects were asked to fill out a questionnaire and talk about what they liked or disliked about the MP and how it compared to the HFA.

For the second part of the study, the only difference was that the subjects went to a lab in the hospital (instead of a hallway) before HFA-Exp-2 to perform the test on the mobile perimeter (instead of after), and instead of undergoing a demonstration of MP-HeadMovement-Patch-Demo1, they underwent MP-HeadMovement-Patch-Demo2.

In order to measure long-term fluctuations, we took their past test results, which will be referred to as HFA-Exp-1. On average, HFA-Exp-1 had been performed 7 months prior to HFA-Exp-2.

To compare the results, the mean sensitivity (MS), short-term fluctuation (SF), long-term heterogeneous fluctuation (LF-he), long-term homogeneous fluctuation (LF-ho), the number of false positives and false negatives, the distance measured from the pose estimation, and the differences in the differential light sensitivities were analyzed between the two perimeters.

5.2 Subjects

A total of 38 subjects (16 males and 22 females, ages 30 to 92: mean age 67) were tested on the MP and HFA perimeters. Twelve (12) subjects were at risk of glaucoma, while twenty-six (26) subjects had glaucomatous visual fields. For Part 1 of the study, subjects were selected if they fit the following criteria: Subjects had their own reading glasses or the prescription calculated by the HFA was available in pre-fabricated reading glasses. However, many subjects were unreliable and additional criteria were added for Part 2 of the study (the first criteria was slightly altered for other reasons and this will be discussed later on) to the following:

1. Subjects' prescriptive lens (calculated by the HFA) was available in pre-fabricated reading glasses.
2. Subjects had reliable results according to the HFA test results.
3. Subjects did not show signs of progression of glaucoma.

The subjects were split into four different groups. Each group contains subjects from both parts of the study, specified in the list below in the square brackets as (total number of subjects) [# of subjects from Part 1 of study / # of subjects from Part 2 of study].

1. Unreliable subjects at risk of glaucoma (group RU (3) [2/1])

2. Reliable subjects at risk of glaucoma (group RR (9) [3/6])
3. Unreliable subjects with glaucoma (group GU (12) [11/1])
4. Reliable subjects with glaucoma (group GR (14) [6/8])

Unreliable subjects were those who were reported as having unreliable results on the HFA or were reported as having possible glaucoma progression or were observed to struggle with the bluetooth button used for the MP. Unreliable results on the HFA are classified as those subjects that have more than 20% fixation losses, false positives or false negatives. Reliable subjects were those who had reliable results on the HFA and were reported as not having glaucoma progression and did not struggle with the bluetooth button.

The difference between subjects at risk of glaucoma and those who have glaucoma were based on the gold standard of glaucomatous visual field loss as follows: the standard 24-2 test on the HFA reports the subject as "Outside Normal Limits" and there is a cluster of three points at the 5% level on the pattern deviation plot, the subject is classified to have glaucoma [42]. The pattern deviation plot is a plot that shows the chances of each threshold being the number that it is when taking into account their age and other diseases that could cause a lowered threshold.

Within groups GU and GR, there are also subjects who have mild, moderate, and severe glaucoma, classified using the Hoddap-Parrish-Anderson method [43]. Of the glaucoma patients, 12 are in the severe category, 7 in the moderate category and another 7 are classified as mild cases.

Tables 5.1, 5.2 and 5.3 list all the patients according to their group. Their age, the eye that was tested, the refractive lens used, the level of glaucoma, the false positives, false negatives, fixation losses, and general comments about their test are listed in the tables. The comments involve information about a patient's possible progression or if they had trouble with the bluetooth button. Asterisks beside a subject indicate that they participated in Part 2 of the study.

Table 5.1: Summary of at-risk subjects (both unreliable [RU] and reliable [RR]). FP stands for false positives, FN stands for false negatives, and FL stands for fixation losses.

Subject	**Age**	**Eye Tested**	**Refractive Lens**	**Level of Glaucoma**	**FP (%)**	**FN (%)**	**FL (%)**
RU-1	67	Left	+2.00 DS	At-risk	0	0	83
RU-2	64	Right	+2.50 DS	At-risk	5	0	36
RU-3 (*)	64	Left	+2.25 DS	At-risk	4	0	31
RR-1	30	Right	+0.00 DS	At-risk	2	0	0
RR-2	52	Right	+2.50 DS	At-risk	0	0	19
RR-3	82	Right	+4.00 DS	At-risk	0	5	6.7
RR-4 (*)	58	Right	+2.50 DS	At-risk	0	0	0
RR-5 (*)	32	Right	+0.00 DS	At-risk	1	0	15
RR-6 (*)	66	Right	+0.00 DS	At-risk	5	11	14
RR-7 (*)	47	Right	+2.00 DS	At-risk	0	1	0
RR-8 (*)	56	Right	+3.00 DS	At-risk	1	0	6.7
RR-9 (*)	77	Right	+3.00 DS	At-risk	1	0	6.2

Table 5.2: Summary of unreliable subjects with glaucoma [GU]. FP stands for false positives, FN stands for false negatives, and FL stands for fixation losses.

Subject	**Age**	**Eye Tested**	**Refractive Lens**	**Level of Glaucoma**	**FP (%)**	**FN (%)**	**FL (%)**	**Comments**
GU-1	77	Right	+3.25 DS	Mild	42	16	77	
GU-2	57	Right	+0.00 DS	Mild	6	0	23	
GU-3	77	Left	+2.75 DS	Mild	1	4	19	Possible Progression
GU-4	80	Right	+2.00 DS	Moderate	5	0	0	Trouble with button
GU-5	73	Right	+3.25 DS -1.25DC x 73	Severe	7	0	0	Likely Progression
GU-6	65	Right	+2.75 DS -0.75 DC x 122	Severe	20	59	25	
GU-7	92	Right	+3.25 DS	Severe	1	0	5.9	Trouble with button
GU-8	75	Right	+3.50 DS	Severe	22	0	29	
GU-9	75	Right	+3.25 DS	Severe	0	13	18	Trouble with button
GU-10	83	Left	+3.25 DS	Severe	1	15	0	Likely Progression
GU-11	71	Right	+2.25 DS	Severe	0	20	5.6	Likely Progression
GU-12 (*)	51	Right	+1.25 DS	Moderate	13	0	50	

Table 5.3: Summary of reliable subjects with glaucoma [GR]. FP stands for false positives, FN stands for false negatives, and FL stands for fixation losses.

Subject	**Age**	**Eye Tested**	**Refractive Lens**	**Level of Glaucoma**	**FP (%)**	**FN (%)**	**FL (%)**
GR-1	66	Right	+3.25 DS	Moderate	1	8	0
GR-2	76	Right	+3.25 DS	Severe	3	6	6.7
GR-3	82	Right	+3.25 DS	Severe	0	0	5.9
GR-4	74	Right	+3.25 DS	Severe	2	13	6.3
GR-5	55	Left	+2.50 DS	Mild	7	6	13
GR-6	85	Right	+2.25 DS	Mild	2	11	13
GR-7 (*)	43	Right	+1.00 DS	Moderate	0	3	5.9
GR-8 (*)	78	Left	+3.25 DS	Severe	1	4	0
GR-9 (*)	67	Right	+2.50 DS	Severe	0	13	0
GR-10 (*)	79	Right	+3.25 DS	Moderate	9	0	6.7
GR-11 (*)	80	Left	+3.25 DS	Moderate	1	0	0
GR-12 (*)	70	Right	+1.25 DS	Mild	4	0	6.2
GR-13 (*)	62	Left	+1.75 DS	Moderate	0	13	0
GR-14 (*)	61	Right	+2.25 DS	Mild	3	11	6.7

5.3 Results

5.3.1 Differential Light Sensitivity Thresholds

An example of the test results for subject GR-4 on the MP, the HFA, and the differences between the tests are shown in Figure 5.1. Overall, the MP is able to detect the scotoma in the same area as the HFA. There are some errors in the thresholds measured along the boundaries of the scotoma, but this kind of error is also evident between the two HFA tests. These errors could be due to patient variability.

Processing the results from all 38 subjects, each of their thresholds at all 54 points measured by session HFA-Exp-2 were subtracted from the thresholds measured by MP-HeadMovement-Patch, yielding 54 differences in thresholds. These differences were calculated for each of the 38 subjects and categorized into absolute differences between a) 0 - 4 dB, b) 5 - 10 dB, and c) >10 dB. This was repeated for differences between the thresholds calculated by HFA-Exp-1 and HFA-Exp-2.

Tables 5.4a-5.4d show the categorized threshold differences for each of the four groups. The second to fourth columns show the percentage of points that had differences within each category for each subject (identified in the first column) between the MP-HeadMovement-Patch and HFA-Exp-2. The fifth to seventh columns show the same, but between HFA-Exp-2 and HFA-Exp-1. The last row contains the averages of the group. Again, asterisks beside a subject indicate that they participated in Part 2 of the study.

Table 5.4: Differences in thresholds measured between MP and HFA

(a) Unreliable At-risk Group [RU]

	MP-HeadMovement-Patch vs. HFA-Exp-2			**HFA-Exp-1 vs. HFA-Exp-2**		
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**>10 dB (%)**
RU-1	98	1.9	0.0	98	1.9	0.0
RU-2	88	12	0.0	56	33	12
RU-3 (*)	71	29	0.0	92	7.7	0.0
Avg	**86**	**14**	**0.0**	**82**	**14**	**3.8**

				24	18	14 (24)	22		
			28	24 (22)	24	22	22	22	
		18	24	26	26	22	18	26	34
	4	14	14 (6)	18	32	30	28	26	26 (30)
0 (0)	0	0	0	0	0	30 (30)	30	0	30
	0	2	0 (0)	0	0	0	0	26	18
		6	0	16	16	28	20 (24)		
			10	12 (24)	24	26 (26)			

(a) Mobile Perimeter Visual Field

		20	21	24	26			
	25	24	27	26	26	23		
7	15	28	27	26	28	22	26	
0 6	15	23	29	28	28	25	28	
0 0	0	0	3	30	31	0	28	
0	0	0	0	0	2	25	26	
	6	12	0	13	24	21		
		19	21	21	25			

(b) Humphrey Field Analyzer Visual Field 1 (Past test)

		18	21	18	21			
	24	25	26	24	25	23		
25	26	27	26	26	26	26	27	
0 7	27	27	27	28	25	25	27	
0 0	0	0	4	30	29	0	28	
0	0	0	0	0	2	28	23	
	12	12	13	4	27	13		
		11	8	21	26			

(c) Humphrey Field Analyzer Visual Field 2 (Most recent test)

		6	-3	-4	1			
	4	-1	-2	-2	-3	-1		
-7	-2	-1	0	-4	-8	0	7	
4 7	-13	-9	5	2	3	1	-1	
0 0	0	0	-4	0	1	0	2	
0	2	0	0	0	-2	-2	-5	
	-6	-12	3	12	1	7		
		-1	4	3	0			

(d) Difference between HFA and MP

		-2	0	-6	-5			
	-1	1	-1	-2	-1	0		
18	11	-1	-1	0	-2	4	1	
0 1	12	4	-2	0	-3	1	-1	
0 0	0	0	1	0	-2	0	0	
0	0	0	0	0	0	3	-3	
	6	0	13	-9	3	-8		
		-8	-13	0	1			

(e) Difference between HFA-1 and HFA-2

Figure 5.1: Comparison of Visual Fields for Subject GR-4 between the HFA and MP.

(b) Reliable At-risk Group [RR]

	MP-HeadMovement-Patch vs. HFA-Exp-2			**HFA-Exp-1 vs. HFA-Exp-2**		
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**>10 dB (%)**
RR-1	69	31	0.0	69	21	9.6
RR-2	90	7.7	1.9	98	1.9	0.0
RR-3	71	27	1.9	94	5.8	0.0
RR-4 (*)	87	13	0.0	98	1.9	0.0
RR-5 (*)	92	7.7	0.0	98	1.9	0.0
RR-6 (*)	71	27	1.9	98	0.0	1.9
RR-7 (*)	90	9.6	0.0	87	13	0.0
RR-8 (*)	88	12	0.0	98	1.9	0.0
RR-9 (*)	92	7.7	0.0	98	1.9	0.0
Avg	**80**	**19**	**1.0**	**93**	**5.4**	**1.9**

(c) Unreliable Glaucomatous Group [GU]

	MP-HeadMovement-Patch vs. HFA-Exp-2			**HFA-Exp-1 vs. HFA-Exp-2**		
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**>10 dB (%)**
GU-1	63	27	9.6	48	46	5.8
GU-2	73	27	0.0	98	1.9	0.0
GU-3	79	15	5.8	94	3.8	1.9
GU-4	65	31	3.8	87	13	0.0
GU-5	63	17	19	88	12	0.0
GU-6	60	12	29	25	19	56
GU-7	62	29	9.6	65	25	9.6
GU-8	58	17	25	65	21	13
GU-9	58	23	19	60	23	17
GU-10	58	29	13	54	31	15
GU-11	54	33	13	63	25	12
GU-12 (*)	54	37	10	88	7.7	3.8
Avg	**62**	**25**	**13**	**70**	**19**	**11**

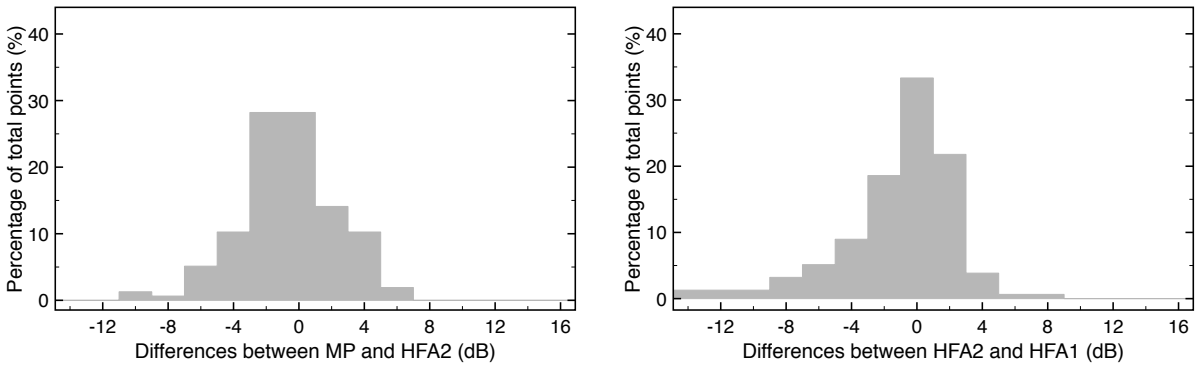
(d) Reliable Glaucomatous Group [GR]

	MP-HeadMovement-Patch vs. HFA-Exp-2			HFA-Exp-1 vs. HFA-Exp-2		
	0-4 dB (%)	**5-10 dB (%)**	**>10 dB (%)**	**0-4 dB (%)**	**5-10 dB (%)**	**>10 dB (%)**
GR-1	73	19	7.7	75	15	9.6
GR-2	67	21	12	81	10	9.6
GR-3	58	33	9.6	77	15	7.7
GR-4	75	15	5.8	79	12	9.6
GR-5	75	23	1.9	94	5.8	0.0
GR-6	60	35	5.8	100	0.0	0.0
GR-7 (*)	73	21	5.8	83	13	3.8
GR-8 (*)	73	21	5.8	79	17	3.8
GR-9 (*)	56	29	15	63	23	13
GR-10 (*)	67	23	9.6	75	21	3.8
GR-11 (*)	77	17	5.8	87	12	1.9
GR-12 (*)	79	5.8	15.4	83	13	3.8
GR-13 (*)	69	21	9.6	85	10	5.8
GR-14 (*)	63	29	7.7	94	5.8	0.0
Avg	**69**	**24**	**6.7**	**83**	**11**	**5.5**

In general, the mobile perimeter had slightly less consistent results when comparing to the HFA than the two HFA test results, with the 0-4 dB category having a lower percentage of thresholds within that range for all groups except Group RU (which only has 3 subjects). The glaucoma groups were also less consistent than the at-risk groups, with the percentage of the threshold differences being in the 0-4 dB range in the 60's, while the at-risk groups had percentages in the 80's. This is likely due to the large scotomas in the glaucoma groups causing large variations in the thresholds measured near scotoma edges.

Group GR, the more reliable group, also showed more consistent results over Group GU (69% vs. 62% in the 0-4 dB difference range). The more reliable groups also showed more consistent results than the unreliable groups on the HFA, with 80-90% of the threshold differences being in the 0-4 dB range, in contrast to the 70-80% for the unreliable groups.

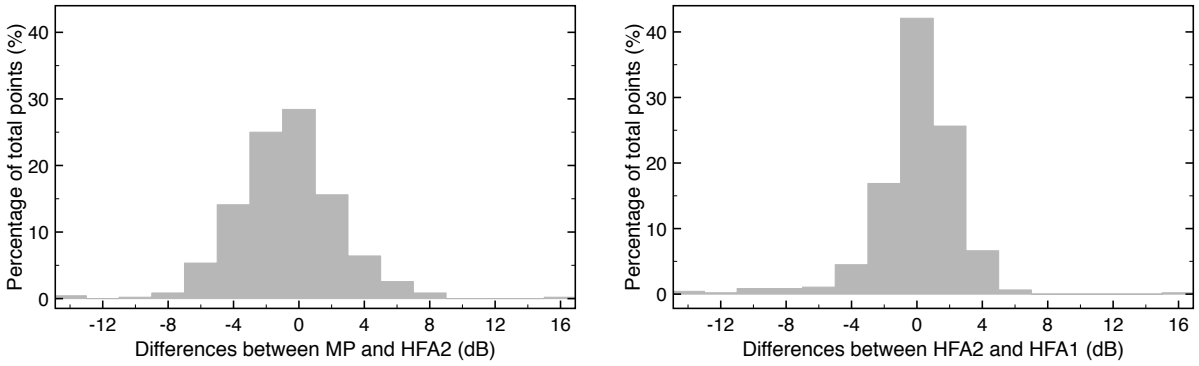
The threshold differences that were greater than 10 dB did not differ much between the MP and HFA, with the MP having 2% more than the HFA at the worst. This indicates that there are no more egregious errors in the thresholds measured by the MP than you would find between two regular HFA tests. However, the two HFA tests being compared are performed with many months in between, so it is expected that there would be some errors.



(a) (b)

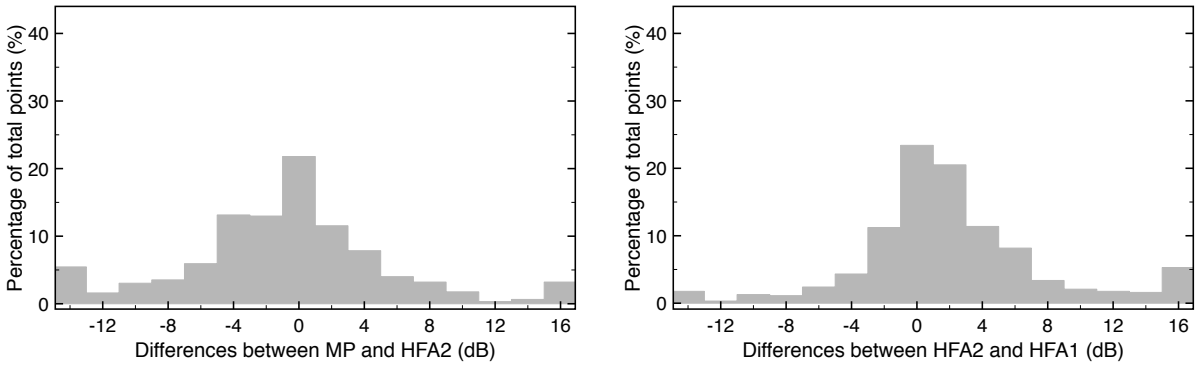
Figure 5.2: Histogram of differences in differential light sensitivities for group RU. a) between MP-HeadMovement-Patch and HFA-Exp-2, and b) between HFA-Exp-1 and HFA-Exp-2.

The histograms in Figures 5.2-5.5 represent the range of threshold differences in a visual manner and display outlier behaviour. The x-axis shows the threshold differences between two visual field tests. The y-axis is the percentage of points for all subjects in



(a) (b)

Figure 5.3: Histogram of differences in differential light sensitivities for group RR. a) between MP-HeadMovement-Patch and HFA-Exp-2, and b) between HFA-Exp-1 and HFA-Exp-2.

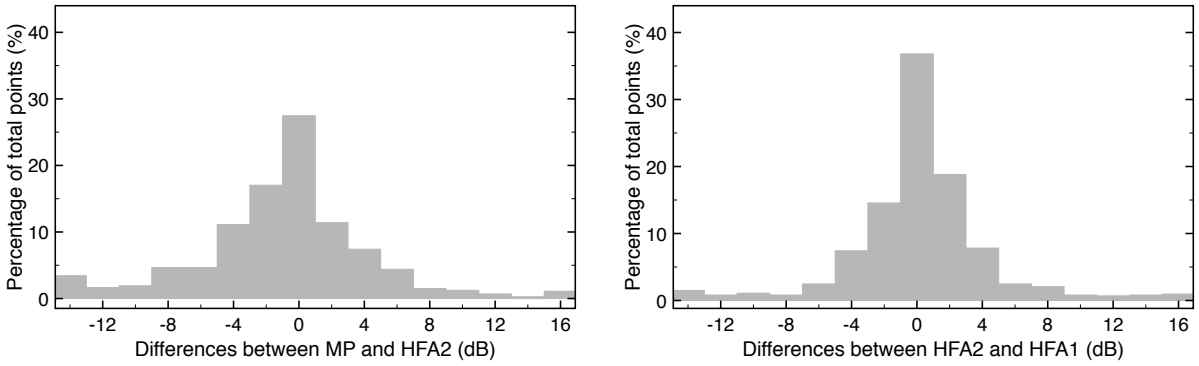


(a) (b)

Figure 5.4: Histogram of differences in differential light sensitivities for group GU. a) between MP-HeadMovement-Patch and HFA-Exp-2, and b) between HFA-Exp-1 and HFA-Exp-2.

that group that have a specific threshold difference.

There is a clear difference between the at-risk and glaucoma groups. For both the MP and HFA, groups GU and GR had wider spreads in their differences than groups RU and RR, showing that large differences in thresholds are more common with glaucoma patients. In general, the histograms between the two perimeters looked relatively similar for all groups, with the MP having fewer threshold differences in the middle (0 dB, indicating same threshold measured). Group GU, the unreliable glaucomatous group, had very clear histograms that illustrated the unreliability of the measurements for both the HFA and MP. There were markedly more differences spread out along the entire range of differences, with many differences even at the 16 dB+ mark. The shape of the



(a) (b)

Figure 5.5: Histogram of differences in differential light sensitivities for group GR. a) between MP-HeadMovement-Patch and HFA-Exp-2, and b) between HFA-Exp-1 and HFA-Exp-2.

curve of Group GU's histograms were also less smooth than all the other graphs.

Table 5.5 shows the means and standard deviations of the threshold differences. A mean closer to 0 represents a better match between the two tests being compared, and a smaller standard deviation represents a smaller spread of differences. The standard deviations of groups RU and RR are almost half of groups GU and GR, showing that the at-risk groups have smaller deviations, as expected. Group GR also has smaller standard deviations compared to Group GU, which is expected because Group GR contains the reliable subjects.

Table 5.5: Mean and Standard Deviations of differences in thresholds.

	MP-HeadMovement-Patch vs HFA-Exp-2		**HFA-Exp-1 vs HFA-Exp-2**	
	mean	*stdev*	*mean*	*stdev*
RU	-0.65	2.97	-1.08	3.57
RR	-0.71	3.16	0.03	2.68
GU	-0.82	6.27	2.07	5.72
GR	-0.98	5.20	0.21	4.30

The means when comparing MP-HeadMovement-Patch and HFA-Exp-2 are all negative, indicating that the MP measured lower thresholds than the HFA. This consistent negative difference will be discussed later on, in Section 5.3.2. In contrast, the means

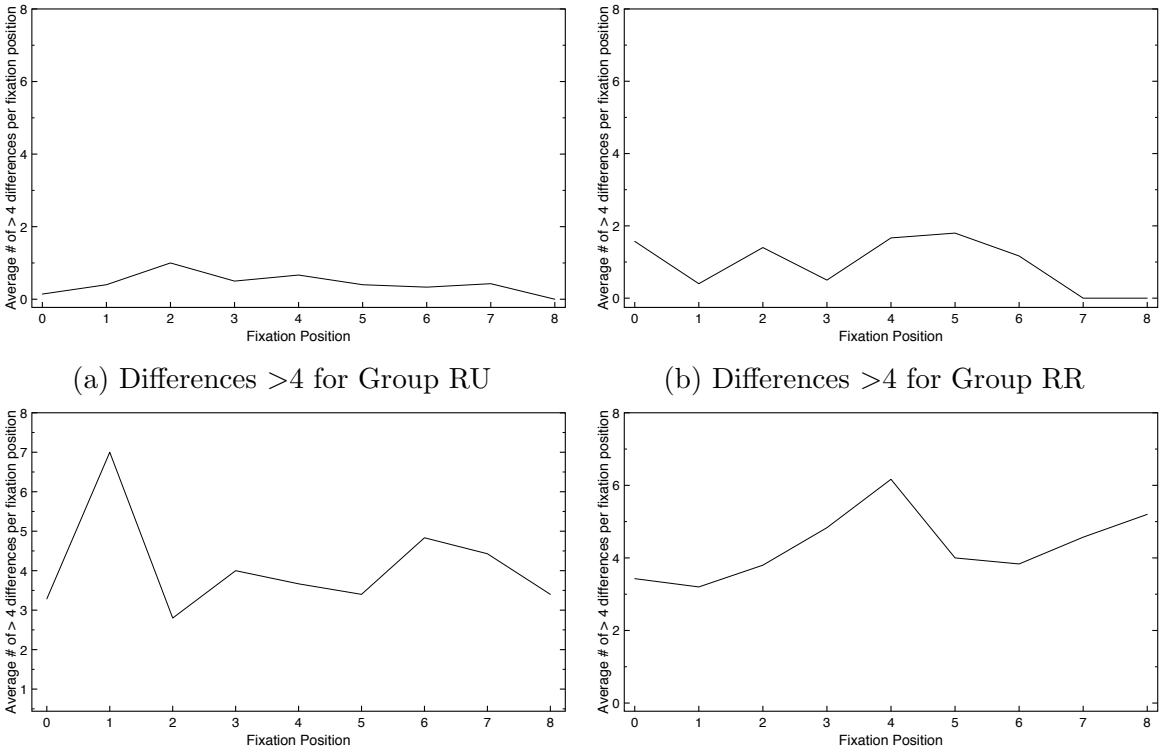
when comparing HFA-Exp-1 and HFA-Exp-2 are generally closer to 0. However for group GU, the mean was 2.07, indicating that HFA-Exp-1 measured higher thresholds than HFA-Exp-2. This is expected as group GU contains subjects that have a possible progression in their disease and therefore, their results in HFA-Exp-2 will be slightly lower.

5.3.1.1 Differences in Thresholds over Time

Because the MP tests all stimuli using nine different fixation points, it would be instructive to see if there is a correlation between the differences and time or fixation point position. The fixation positions are tested in order from 0 through to 8, the orientation of the tablet is flipped between fixation positions 4 and 5, and subjects are told during fixation point 8 that it is the last section of the test. Certain positions could be causing larger number of differences or the length of the test could be tiring out the subjects.

Figure 5.6 shows the average number of differences over all subjects in each group per visual field point in each fixation position. The x-axis are the fixation points from 0 to 8, which are tested in chronological order. The y-axis is the average number of differences that are greater than 4 that a single stimulus point will have for a certain fixation point. For example, if fixation point 4 for group GU has an average of 2, that means each stimulus point tested during fixation point 4 will have on average two differences greater than 4 over all subjects. If there are 8 stimulus points tested during fixation point 4, then this means there are roughly 16 differences greater than 4 over all subjects.

Groups RU, and RR have fewer threshold differences larger than 4, so the limited data does not suggest any correlation with fixation point or time. Group GU shows a significant increase going from fixation point 0 to 1, then a sharp decrease going to fixation point 2. This suggests that the first movement of the fixation point (0 to 1) causes confusion and increases the differences dramatically, and there is a learning curve involved. We attempted to mitigate this effect with MP-HeadMovement-Patch-Demo2, a short demo that would move the fixation point during the demonstration. Most of Group RR and GR performed the moving fixation point demo prior to the mobile perimeter test and this effect seems to have been eliminated. In Group GR, there seems to be a steady increase in threshold differences until the switch in tablet orientation from fixation point 4 to 5. Here the average threshold differences greater than 4 decreases temporarily, but increases again as the test continues. This suggests that fatigue is playing a role in the



(a) Differences >4 for Group RU

(b) Differences >4 for Group RR

(c) Differences >8 for Group GU

(d) Differences >8 for Group GR

Figure 5.6: Average number of differences per point tested at each fixation position.

number of threshold differences that occur. The MP visual field test is at least double the length of the HFA (15 minutes vs. 7 minutes), but it appears that even a small break in the test helps with combating fatigue.

5.3.2 Mean Sensitivity

The mean sensitivities for all four groups are summarized in Tables 5.6a-5.6d for MP-HeadMovement-Patch, HFA-Exp-1, and HFA-Exp-2. Each table contains every subject's mean sensitivity measured by all three tests in columns 2-4. The last column is the difference between the MP results and the second HFA results (HFA-Exp-2). The last row contains the averages of all the subjects in that group.

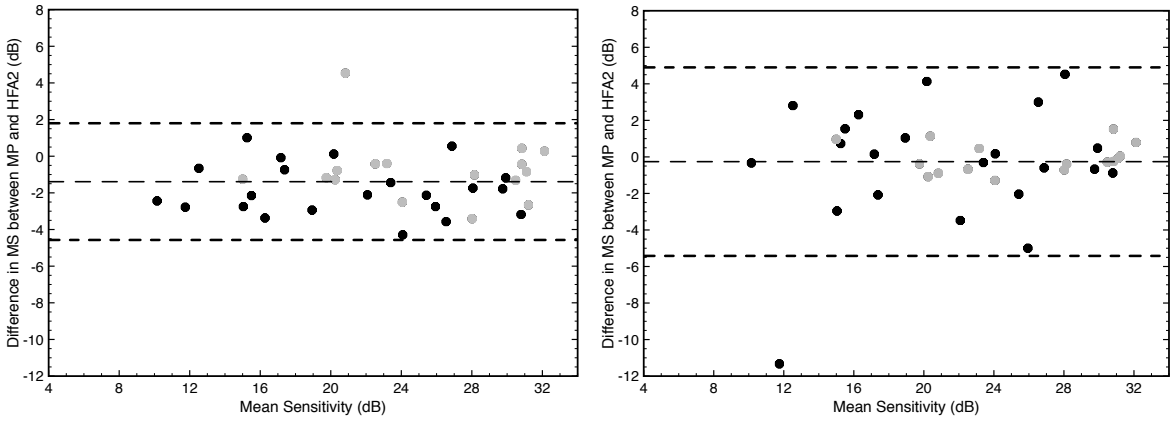
To analyze the differences and investigate the agreement between two clinical measurements, we examine the differences to see if they are within a set interval ($\pm 1.96 \times$ s.d. of differences) around the mean difference, which is the 95% interval referred to in Section 3.6.4. Each point in Figure 5.7 represents the difference between the mean sensitivities

Table 5.6: Mean Sensitivities measured on the MP and HFA

(a) Unreliable At-risk Group [RU]

	Mean Sensitivity (dB)			
	MP-HeadMovement-Patch	**HFA-Exp-1**	**HFA-Exp-2**	**Difference**
RU-1	28.74	29.44	29.92	-1.18
RU-2	26.32	23.54	28.06	-1.74
RU-3 (*)	30.26	31.17	31.10	-0.84
Avg	**28.44**	**28.05**	**29.69**	**-1.25**

measured by the specified perimeter sessions for each subject. They are plotted against the mean sensitivity measured by HFA-Exp-2. The middle dashed line represents the mean of the differences between two perimetry tests. The two dashed lines surrounding the middle one are the boundaries of the interval. The lighter coloured points are the subjects that were tested in Part 2 of the study.



(a) (b)

Figure 5.7: Scattergrams a) between MP-HeadMovement-Patch and HFA-Exp-2, and b) between HFA-Exp-1 and HFA-Exp-2.

From Figure 5.7a, the mean of the differences between the two perimeters was -1.39 dB (s.d. 1.62 dB). The 95% interval (-4.6 dB to 1.8 dB) is quite large as well. However, if we look at only the subjects from Part 2 of the study, this changes to a mean of -1.12 dB (s.d. 1.06), with a 95% interval of -3.19 dB to 0.95 dB, which is much more acceptable. Part 2 of the study changed the procedure to call subjects before their appointment

(b) Reliable At-risk Group [RR]

	Mean Sensitivity (dB)			
	MP-HeadMovement-Patch	**HFA-Exp-1**	**HFA-Exp-2**	**Difference**
RR-1	22.97	23.54	26.54	-3.57
RR-2	27.97	30.42	29.75	-1.78
RR-3	23.29	27.46	25.42	-2.13
RR-4 (*)	28.55	31.17	31.21	-2.66
RR-5 (*)	32.39	31.33	32.12	0.27
RR-6 (*)	31.26	31.08	30.83	0.43
RR-7 (*)	30.39	29.31	30.83	-0.44
RR-8 (*)	29.16	30.77	30.48	-1.32
RR-9 (*)	27.13	28.56	28.15	-1.02
Avg	**28.12**	**29.29**	**29.48**	**-1.36**

(c) Unreliable Glaucomatous Group [GU]

	Mean Sensitivity (dB)			
	MP-HeadMovement-Patch	**HFA-Exp-1**	**HFA-Exp-2**	**Difference**
GU-1	23.19	30.94	25.94	-2.75
GU-2	27.61	31.67	30.79	-3.18
GU-3	21.97	23.71	23.40	-1.44
GU-4	16.00	17.90	18.94	-2.94
GU-5	16.26	14.52	15.25	1.01
GU-6	8.97	23.08	11.75	-2.78
GU-7	12.29	18.00	15.04	-2.75
GU-8	20.29	16.04	20.17	0.12
GU-9	12.90	13.96	16.27	-3.37
GU-10	13.35	13.96	15.50	-2.15
GU-11	16.65	19.46	17.38	-0.74
GU-12 (*)	25.35	21.73	20.83	4.53
Avg	**17.23**	**20.30**	**19.13**	**-1.91**

(d) Reliable Glaucomatous Group [GR]

	Mean Sensitivity (dB)			
	MP-HeadMovement-Patch	**HFA-Exp-1**	**HFA-Exp-2**	**Difference**
GR-1	19.97	25.56	22.08	-2.11
GR-2	11.85	9.71	12.52	-0.66
GR-3	7.71	10.48	10.15	-2.44
GR-4	17.10	17.02	17.17	-0.08
GR-5	27.42	27.46	26.87	0.55
GR-6	19.79	23.90	24.08	-4.29
GR-7 (*)	18.58	20.13	19.75	-1.17
GR-8 (*)	22.77	22.71	23.17	-0.40
GR-9 (*)	13.74	14.04	15.00	-1.26
GR-10 (*)	19.58	19.23	20.37	-0.78
GR-11 (*)	22.10	23.19	22.52	-0.42
GR-12 (*)	21.55	25.35	24.06	-2.51
GR-13 (*)	18.97	21.33	20.25	-1.28
GR-14 (*)	24.61	28.73	28.02	-3.41
Avg	**18.15**	**19.62**	**19.47**	**-1.32**

for agreement to participate. It also narrowed down the subjects chosen for the study to only reliable subjects. It also changed the location of the test to a quiet laboratory room *before* the HFA test, and give a demonstration that reflected the moving fixation point that would happen in the MP test. This was done because the results from Part 1 showed significantly worse results, with a mean of -1.84 dB (s.d. 1.4 dB) with a 95% interval of -4.6 dB to 0.91 dB. We believed that the noise of the hallway that Part 1's tests were located in was damaging subjects' concentration, causing them to miss stimuli they would have otherwise seen. We also believed that calling the subjects ahead of time gave the study more credence and resulted in subjects taking it more seriously. In addition, performing the test before the HFA meant that any fatigue they experienced from waiting for their appointment and going through multiple eye tests (usually at least three) would be mitigated. Of course, the reverse could happen, where the HFA tests would be affected due to fatigue, but because the HFA has metrics to determine how accurate the results are, this can be monitored.

In the end, the changes in Part 2 of the study greatly improved the results measured by the MP, but there was still a significant decrease in mean sensitivity measured by the MP. In contrast, the differences in mean sensitivity between the two HFA tests were roughly 0. In Figure 5.7b, the mean of the differences is very close to 0 at -0.26 dB (s.d. 2.63 dB) with a 95% interval of -5.4 dB to 4.9 dB. This interval is quite large, but decreases to -2.8 dB to 2.7 dB when only looking at reliable subjects. This is still quite a large interval, but there is a gap of many months between the two tests, which could account for the difference. The 95% interval is acceptable for the MP, but the mean is around 1 dB lower than it should be, which indicates there is a specific effect within the MP test that causes this difference.

In addition, when looking at all subjects and at individual groups, a two-tailed paired t-test indicates that MP-HeadMovement-Patch measures a statistically-significant lower MS than HFA-Exp-2 ($p < 0.05$).

One hypothesis as to why the MS is lower across almost all subjects is that the reading glasses used to correct for near distance affected the perception of the stimuli. The HFA uses a circular dome ensuring that all stimuli displayed are 30 cm away from the subject's eye and correct for this distance by using a lens that accomodates for 30cm. This experiment has been using the same correction for the MP even though head movements are allowed and the subject is directed to start out closer to the tablet at around 25-28cm. The wrong refractive correction can cause around a 1.25 dB/diopter

decrease in MS [44] [45].

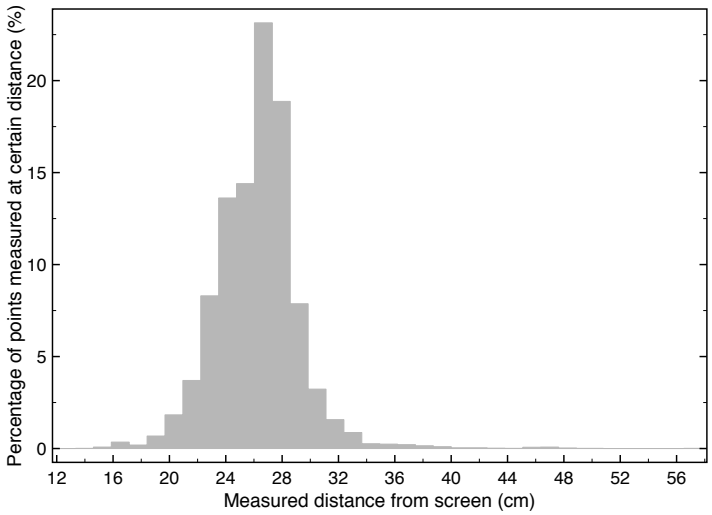


Figure 5.8: Histogram of distances calculated by pose estimator over all subjects

Figure 5.8 shows the percentage of times the pose estimator (described in Section 2.2) calculated various distances from the subject's head to the tablet. The mean was 26.25 cm, and the standard deviation was 3.0. This means that on average the subjects were approximately 26 cm away from the tablet while using a pair of reading glasses that would correct for 30 cm away. A person who is unable to compensate for close distances would require 3.25 diopters to focus at 30 cm, and 3.75 diopters to focus at 26.25 cm. Using these numbers, the MS would be lowered by around 0.6 dB due to using the wrong refractive correction.

To measure, experimentally, if refractive correction was in fact affecting the MS, we performed a small study to confirm the results of the refractive correction study. Two subjects performed half of the visual field test on the MP at a distance of 18 cm and a distance of 28 cm. The same refractive correction was provided to them as specified by the HFA for both distances, and their heads were fixed at those positions using a chinrest to prevent movements. The mean sensitivities for this small experiment are outlined in Table 5.7.

The difference in refractive correction required between 18 and 28 cm is approximately 2 diopters. From the refractive correction study, this would mean a 1.2 dB difference in mean sensitivity. The results from the small experiment reflect these numbers relatively well, with one subject above the expected difference and the other below. This accounts for the difference seen in mean sensitivity and test results.

Table 5.7: Mean Sensitivities for Refractive Correction Experiment

	Mean Sensitivity (dB)		
	@ 18 cm	**@ 28 cm**	**Difference**
CO-1	33.2	33.8	-0.6
CO-7	26.7	28.9	-2.2

5.3.3 Test Repeatability

The short-term (SF), long-term heterogeneous (LF-he), long-term homogeneous (LF-ho) fluctuations are summarized in Tables 5.8a-5.8d. The fluctuations are split into four different tables for each group. The first column of the table identifies each subject. The second column contains the short-term fluctuations of the MP-HeadMovement-Patch test. The ten double-determination points of the test were used to determine the SF. Unfortunately, the short-term fluctuations were not available for the HFA sessions so only the MP values are documented.

The second and third columns contain the LF-he, while the fourth and fifth contain the LF-ho. Because there is only one MP-HeadMovement-Patch test, to calculate the LF-he and LF-ho of the MP, MP-HeadMovement-Patch is compared against HFA-Exp-2. For the HFA, HFA-Exp-1 is compared against HFA-Exp-2. The LF-he and LF-ho metrics of the MP are no longer comparing the repeatability between two tests on the MP, they are comparing the repeatability between a test on the MP and a test on the HFA. The LF-ho columns are blank for some subjects, meaning the mean sensitivities between the two tests being compared are very small.

In general, the at-risk groups had lower numbers for all three indices, while the reliable glaucoma group had lower numbers than the unreliable glaucoma group. Overall, the MP had a slightly higher LF-he index than the HFA for all groups, the largest difference seen in Group GU, which is likely a cause of the unreliability of the subjects. The MP also had a substantially lower mean LF-ho than the HFA for the glaucoma groups, but this could be accounted for by the two HFA sessions being completed months apart.

The mean of the SF for all subjects is 3.03 dB, while only 2.68 dB for subjects from Part 2. Both these values are slightly higher than the mean SF of a group of patients tested on the HFA (2.39 dB) [2]. This could be due to the ambient light creating

Table 5.8: Test repeatability comparison between MP and HFA

(a) Unreliable At-risk Group [RU]

	SF	**LF-he**		**LF-ho**	
	MP	**MP**	**HFA**	**MP**	**HFA**
RU-1	1.18	1.15	0.78	0.82	0.32
RU-2	2.49	1.58	3.03	1.21	3.17
RU-3 (*)	2.19	1.90	1.13	0.53	-
Avg	**1.95**	**1.54**	**1.64**	**0.86**	**1.75**

(b) Reliable At-risk Group [RR]

	SF	**LF-he**		**LF-ho**	
	MP	**MP**	**HFA**	**MP**	**HFA**
RR-1	1.00	2.15	2.82	2.52	2.08
RR-2	1.55	2.07	0.60	1.23	0.47
RR-3	3.10	2.08	1.10	1.49	-
RR-4 (*)	1.18	1.70	0.83	1.88	-
RR-5 (*)	2.28	1.15	0.93	0.11	0.75
RR-6 (*)	2.28	2.06	1.42	0.11	-
RR-7 (*)	3.32	1.42	1.32	0.24	1.18
RR-8 (*)	1.48	1.36	0.86	0.92	0.18
RR-9 (*)	1.73	1.29	0.88	0.71	0.26
Avg	**1.99**	**1.70**	**1.20**	**1.02**	**0.82**

(c) Unreliable Glaucomatous Group [GU]

	SF	**LF-he**		**LF-ho**	
	MP	**MP**	**HFA**	**MP**	**HFA**
GU-1	2.24	2.88	2.58	1.91	3.52
GU-2	1.95	2.07	0.92	2.24	0.61
GU-3	2.24	2.47	1.53	0.96	2.81
GU-4	2.97	2.61	1.40	2.06	5.57
GU-5	2.19	5.17	1.42	0.72	2.84
GU-6	6.48	5.70	7.33	1.81	11.24
GU-7	4.88	3.09	3.67	1.90	6.76
GU-8	2.65	5.02	2.80	-	2.90
GU-9	7.28	4.27	3.93	2.31	6.92
GU-10	6.88	3.41	3.86	1.45	3.72
GU-11	3.19	4.15	3.52	-	7.34
GU-12 (*)	2.83	4.01	2.13	3.17	1.90
Avg	**3.81**	**3.74**	**2.92**	**1.85**	**4.68**

(d) Reliable Glaucomatous Group [GR]

	SF	**LF-he**		**LF-ho**	
	MP	**MP**	**HFA**	**MP**	**HFA**
GR-1	3.19	2.98	3.05	1.45	6.44
GR-2	5.52	3.64	3.10	-	1.69
GR-3	2.45	3.14	2.24	1.68	2.87
GR-4	4.15	2.32	2.49	-	4.40
GR-5	1.84	1.79	1.06	0.30	2.16
GR-6	3.03	2.73	0.77	3.02	1.56
GR-7 (*)	2.28	2.66	2.18	0.74	1.51
GR-8 (*)	1.34	2.97	1.76	-	1.35
GR-9 (*)	3.44	3.71	3.10	0.73	5.43
GR-10 (*)	5.87	2.74	2.09	0.41	4.84
GR-11 (*)	3.92	3.02	2.17	-	5.16
GR-12 (*)	2.19	3.84	2.45	2.64	3.96
GR-13 (*)	3.71	2.93	2.46	1.62	4.49
GR-14 (*)	2.83	2.78	1.19	2.90	1.66
Avg	**3.27**	**2.95**	**2.15**	**1.55**	**3.39**

reflections on the screen, or the use of incorrect refractive correction (described in Section 5.3.2) because the subject was positioned closer to the MP than the HFA and was able to change their positioning throughout the test.

The mean LF-he for all subjects was 2.79 dB for the MP and 2.13 dB for the HFA. Only looking at subjects from Part 2, the mean LF-he drops to 2.47 dB for the MP and 1.68 dB for the HFA. From a two-tailed paired t-test, there is a significant difference in the LF-he between the MP and the HFA ($p < 0.05$). This is expected because of the significant difference in the MS that was accounted for partly by the flawed study procedure (described in Section 5.1) and partly by incorrect refractive correction (described in Section 5.3.2).

From the scattergram in Figure 5.9, the mean of the differences in LF-he between the two perimeters was 0.69 dB (s.d. 1.02 dB), with a 95% interval of -1.3 dB to 2.7 dB. The mean is higher again, which is expected because of the difference in MS found earlier. The absolute size of the interval itself is acceptable and the scattergram would show good agreement between the two perimeters if the means were aligned.

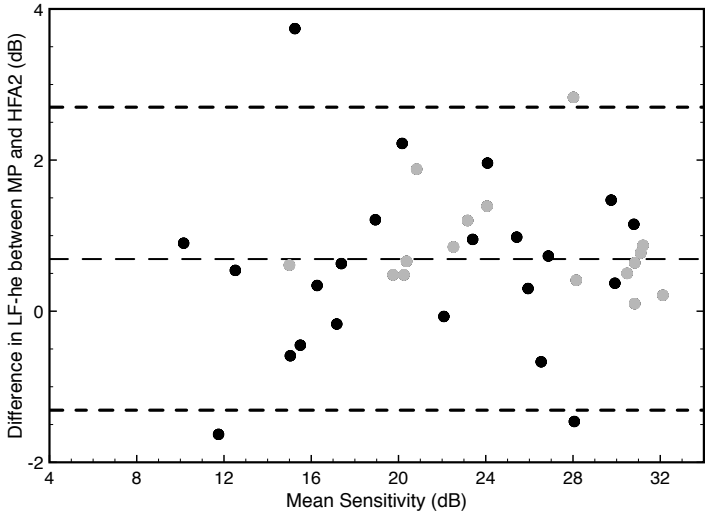


Figure 5.9: Scattergram of LF-he

The mean LF-ho over all subjects was 1.49 dB for the MP and 3.19 dB for the HFA. In addition, a two-tailed paired t-test indicates a statistically significant difference ($p < 0.05$). However, both of these results are likely because the LF-ho for the HFA sessions were higher due to the large amount of time between the tests. The higher LF-ho numbers are also mostly seen in the glaucoma patients, which also lends credence to the idea that the time gap between tests results in larger differences in patients who could have possible

progresion. From the scattergram in Figure 5.10, the mean of the differences in LF-ho between the two perimeters was -1.64 dB (s.d. 2.65 dB) with a 95% interval of -6.8 dB to 3.6 dB. Because this is not a fair comparison, we cannot conclude that the MP performs better than the HFA between two tests, but at least it provides results that differ less than two tests that are completed months apart.

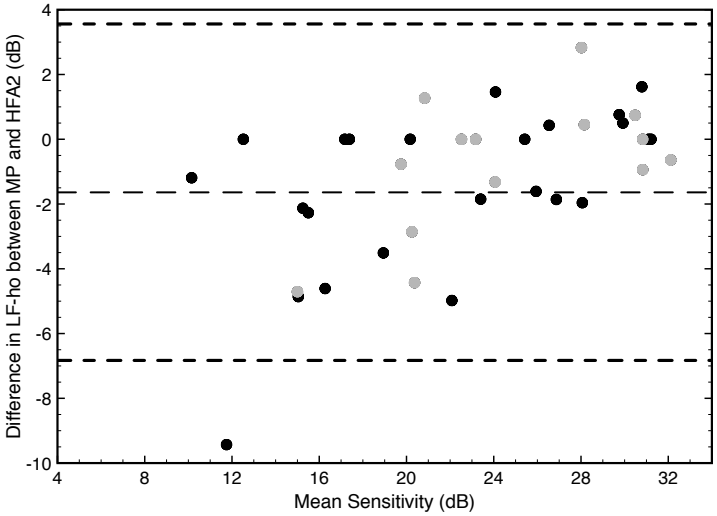


Figure 5.10: Scattergram of LF-ho

5.3.4 False Positives and Negatives

An important metric in creating a test for the general public is false positives. If a person with normal vision takes the test and the test wrongly predicts that there is something wrong, this would cause unnecessary time wasted for everyone involved. This could potentially become a hindrance to doctors if there are too many patients coming in who do not actually have glaucoma. Another important metric is false negatives. Telling a person who has glaucoma they do not would hinder their ability to treat themselves properly. Ophthalmologists will look for two main things when assessing if a patient has glaucomatous visual fields. One is a nasal step, which is when there is a reduced threshold in the nasal visual field on one side of the horizontal raphe (the horizontal physiological boundary that separates the upper and lower retina) and normal thresholds on the other side, seen in Figure 5.11. The other is a cluster of 3 threshold points depressed below normal in the visual field.

To look at this metric, the at-risk and mild glaucoma subjects' results were inspected. The at-risk subjects were examined to see if the MP test results showed any of these two

signs. The mild glaucoma subjects were examined to see if the MP would properly show that they had glaucoma.

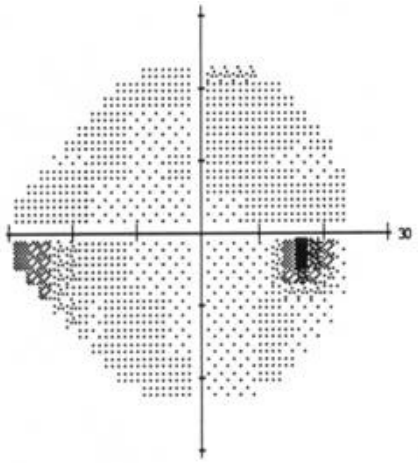
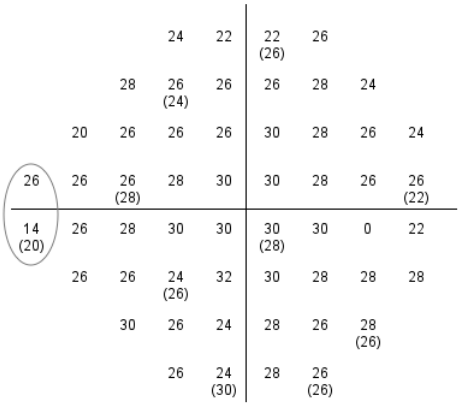


Figure 5.11: Example of a small inferior nasal step, picture taken from [46]

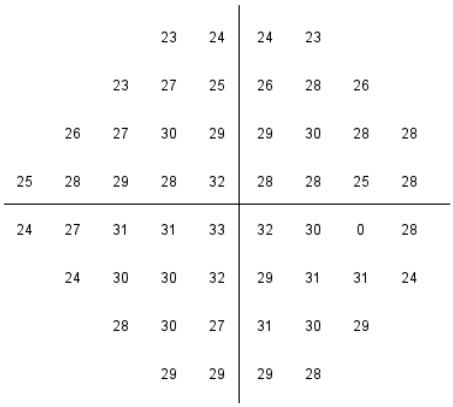
There were 12 at-risk subjects in total; one of the mobile perimeter fields would have been flagged as a possible case of glaucoma with a slight nasal step detected by the MP, but not by the HFA. This subject's results are shown in Figure 5.12. However, this subject was unreliable and had 36% fixation losses on the HFA. There was one subject with depressed fields overall, but this was likely due to distractions during the test causing an overall decrease in mean sensitivity. There was another subject where a nasal step and a single depression in the central visual field was found, but this was also detected on the HFA. This subject was not classified as having glaucomatous fields because they did not satisfy the Hoddap-Parrish-Anderson criteria.

Of the 6 mild glaucoma subjects, the MP was unable to produce results indicating glaucoma for just one subject, as seen in Figure 5.13.

Of course, this is a very small sample size, and multiple tests are required before a diagnosis can be made. With a mobile device, this would be much more feasible in a short amount of time. Subjects could perform parts of the test over a period of time, reducing fatigue and increasing accuracy. With the ability to do the test more often, re-learning the test will be much easier every time, which will also increase accuracy of the test. All of these factors would be able to reduce the amount of false positives and false negatives in the detection of glaucoma.

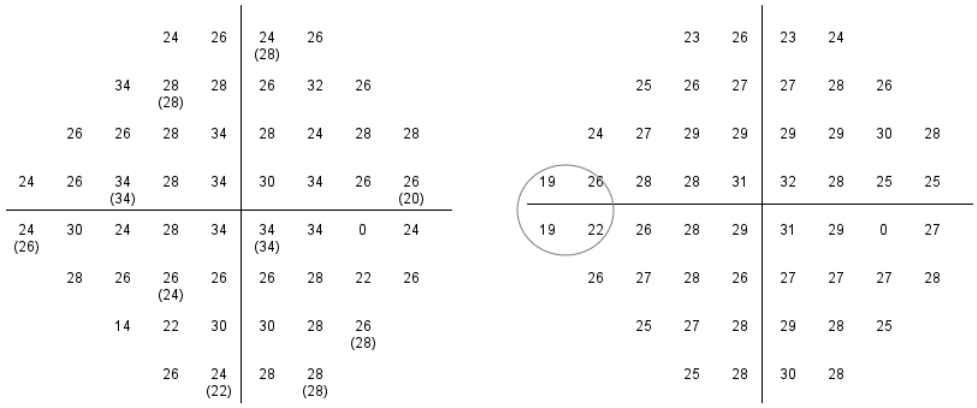


(a) Mobile Perimeter Visual Field



(b) Humphrey Field Analyzer Visual Field 2 (Most recent test)

Figure 5.12: Visual Fields for Subject RU-2. The MP detected a nasal step that the HFA did not.



(a) Mobile Perimeter Visual Field

(b) Humphrey Field Analyzer Visual Field 2 (Glaucomatous defect is circled)

Figure 5.13: Visual Fields for Subject GR-5. The MP was unable to detect a depressed cluster of thresholds in the nasal visual field.

5.3.5 Qualitative Feedback

All subjects were asked which perimeter they preferred and to provide feedback on what they liked and disliked about the mobile perimeter and how it could be improved. Twenty subjects said they preferred the MP, six said they found the two to be equivalent, and twelve preferred the HFA.

Some subjects preferred the HFA because it was more comfortable as it provided a chin-rest, while others stated that the MP was more comfortable because it was less claustrophobic. Most of the feedback involved improving the calibration of the MP and having a better button or better feedback to indicate that they had seen a stimulus. Other suggestions included having a way to track fixation. People generally liked the moving fixation points, but some found it disorienting and caused them to be dizzy. There were also a few comments about the lack of noise on the MP improving concentration. The HFA has mechanical parts that change where the stimulus will be projected on the dome and is constantly making noises throughout the entire test, whereas the MP is completely silent. There were also some comments on reflections on the screen that looked like stimulus points.

Overall, the reception was relatively good for an unpolished perimeter that did not have much user experience in mind. Some of the subjects that preferred the HFA would

likely not prefer the MP even if the user experience was improved, but these are promising results nonetheless.

Chapter 6

Conclusion

Glaucoma is one of the leading causes of blindness in the world, and is difficult to detect in the beginning stages without proper visual field testing instrumentation. It is estimated that there are currently 1.5 million people undiagnosed with glaucoma in only the U.S.A. Currently, glaucoma is caught through testing using specialized and expensive instruments in controlled environments and under the supervision of trained technical staff. In this research we have developed a portable perimeter that, with further development, could be used by patients at home or be used to screen for visual field defects, especially in areas of the world in which access to the more expensive equipment is limited, and this quality of result is acceptable.

The key contributions of this work are:

1. The development of a basic visual field test that uses the limited screen space of a mobile device, making it possible for people to screen for glaucoma due to the proliferation of mobile devices in the present day. This demonstrates that a clinically useful device can be created using inexpensive components that many people all over may already own, or have easy access to.

2. The development of compensation techniques that can automatically adjust the intensities displayed for various background illuminations and the placement of the stimuli by monitoring head movements of a subject. This increases accuracy of the test, which means the mobile perimeter could then be used to monitor the progression of glaucoma instead of simply screening. It also introduces more novel

ways to improve the visual field test itself because of the compensating nature of the test.

3. The testing of the mobile permiter's capabilities (light, head position compensation) on both subjects with normal vision and subjects with glaucoma. The result of the mobile perimeter was compared with the results from the Humphrey Field Analyzer by comparing the visual fields obtained from each test. Several indices were examined, such as the mean sensitivity, the long and short-term fluctuations, and found that reasonable agreement between the two perimeters for subjects with glaucoma, and very good agreement for subjects with normal vision.

6.1 Future Work

There are many ways in which the mobile perimeter can be improved. The technical aspects and especially user experience need to be improved so that it is feasible for real people with and without glaucoma to perform the test on their own.

6.1.1 Lens Compensation

There was a significant problem with the lens compensation while allowing for free head movements. Having a range of lenses for a subject to use depending on their distance from the screen is unrealistic, especially because the distance to the screen can vary by 10 cm or more in one test session. Something to look into is to have a way to dynamically adjust the test according to the distance the subject is from the screen. This could be done in a variety of ways, including changing stimulus size, as we know changing the size can change the perceived luminance. The stimulus intensities or scale could be adjusted as well. If the subject is closer to the screen, the perceived luminance could be calculated for using their age and real prescription. The intensity of the stimulus can be adjusted to follow the new scale.

6.1.2 Head Calibration

Many subjects expressed doubt at their ability to be able to test themselves at home without someone to help them. Currently, the head calibration is very crude as the current version of the mobile perimeter was created as a proof-of-concept. A future version of the head calibration could include improved instructions to provide a better user experience. The current version has text on the screen telling the subject how to position themselves, but over the course of the study, this proved to be a bad idea due to glaucoma and presbyopia preventing subjects from being able to read the text clearly. There are many ways this could be improved. Voice instructions is a possibility, as well as a better way to visually guide subjects to the appropriate position. The current head calibration also has trouble tracking the subject when it is placed in the vertical position. This is due to the limited field of view of the front-facing camera. This could be improved in the future with better cameras or better patttern placement.

6.1.3 Self-Calibration

Currently, the mobile perimeter's light calibration is calibrated for that specific lightmeter and screen. These two vary with every device, so a self-calibration method needs to be investigated. This self-calibration has to be feasible for a technologically-illiterate person. Because of this constraint, the self-calibration will likely be relatievly simple and crude. The effect of having a rough calibration will need to be investigated to ensure that reliability of the test does not drop a significant amount.

6.1.4 Light Spectrum Effects

Further investigations need to be made on the effect of different spectra of light and what the lightmeter on the tablet measures. The effects on the perceived luminance and contrast ratio should be investigated to see if there are significant variances in measured versus actual thresholds.

6.1.5 Visual Field Test Algorithm

Many subjects also expressed frustration at the length of the test. The mobile perimeter uses the simplest algorithm, which tests every single point on the visual field, and takes around twice the amount of time as the Humphrey Field Analyzer's SITA algorithm. This algorithm can be easily changed to reduce the amount of time required for the test.

6.1.6 Fixation Loss

With no technician to supervise the subject during the test, fixation loss can become a large problem. People, especially patients with glaucoma, have a desire to do well on the test as they are hoping their disease is not progressing and their vision is okay. A way to track or promote fixation would greatly improve the reliability of the results. A simple eye tracker can be used to monitor fixation. This would be feasible as it only needs to ensure the subject is maintaining fixation, and there is no need to monitor fine eye movements.

6.1.7 Feedback Mechanism

Another frustration expressed by some subjects was the button used to indicate a "seen" stimulus. The button was difficult to press and the physical feedback was low. Either another more improved button could be found (although it would have to be relatively cheap and easy to find to allow for more accessibility), or a different method of indicating "seen" could be developed. With a short test in mind, this method could be vocal, or involve tapping a surface. With these kinds of methods (and even the current button), there needs to be a way to reassure the subject that their confirmation was recorded properly. This could be as simple as the colour of the fixation point changing.

6.1.8 Translucent Eye-Patch

More research needs to be done on using a translucent eye-patch instead of an opaque eye-patch to reduce the Ganzfeld Effect. It could possibly lessen the disdain and annoyance of the visual field test, which would make a frequent short test a real possibility.

6.2 Conclusion

In conclusion, we were able to develop a mobile perimeter that is able to provide clinically useful results. Many of the subjects liked the idea and found it more comfortable to use. There are also many ways the test can be improved upon and having it feasible on a mobile device opens up many avenues to pursue.

Bibliography

[1] Glaucoma research foundation. [Online]. Available: http://www.glaucoma.org/

[2] A. D. Chan, "Head-mounted perimetry," Master's thesis, University of Toronto, 1999.

[3] S. R. Drance and D. R. Anderson, *Automated perimetry in glaucoma: A practical guide*. Gruen and Stratton Inc., 1985.

[4] A. of Optiks. Technology is the cornerstone of art of optiks. [Online]. Available: http://www.artofoptiks.com/technology/

[5] L. L. Sloan, "Area and luminance of test object as variables in examination of the visual field by projection perimetry." *Vision Research*, vol. 1, pp. 121–138, 1961.

[6] H. I. Inc., *Humphrey Field Analyzer II - User's Guide*. San Leandro, CA, 1994.

[7] B. Damato and C. Groenewald, "Multifixation campimetry on line: a perimeter for the detection of visual field loss using the internet," *The British Journal of Ophthalmology*, vol. 87, no. 10, pp. 1296–1298, 2003.

[8] ——. (2014) Visual field test. [Online]. Available: http://testvision.org

[9] EyesAge.org. (2015) Free visual field test of your eyes for pc. [Online]. Available: http://www.eyesage.org/

[10] EyeLab. (2010, April) Vuscope - visual field screener. [Online]. Available: http://www.vutest.com/visual-fields/index.php

[11] P. Vision. (2015) Professional eye exams from your smartphone. [Online]. Available: http://www.peekvision.org/

[12] A. Bastawrous, M. E. Giardini, N. M. Bolster, and et al, "Clinical validation of a smartphone-based adapter for optic disc imaging in kenya," *JAMA Ophthalmology*, pp. 1–8, 2015.

[13] Haag-Streit. Octopus 900. [Online]. Available: http://www.haag-streit.com/product/perimetry/octopusr-900.html

[14] Asus. Nexus 7 (2013). [Online]. Available: https://www.asus.com/ca-en/Tablets/Nexus_7_2013/

[15] Google. Android. [Online]. Available: https://www.android.com/

[16] T. Instruments. The sensortag story. [Online]. Available: http://www.ti.com/sensortag

[17] A. L. Lewis, S. Kelly, and J. J. Thimons, "Comparison of the dicon tks 4000 with the allergan humphrey field analyzer," *Clinical Eye Vision Care*, vol. 3, no. 4, pp. 161–165, 1991.

[18] Y. Li and R. P. Mills, "Kinetic fixation improves threshold sensitivity in the central visual field," *Journal of Glaucoma*, vol. 1, no. 2, pp. 108–116, 1992.

[19] P. Cheng, "Control of eye movements during eccentric fixation," Master's thesis, University of Toronto, 1989.

[20] G. E. Trope, M. Eizenman, and E. Coyle, "Eye movement perimetry in glaucoma," *Canadian Journal of Ophthalmology*, vol. 24, no. 5, pp. 197–199, 1989.

[21] H. Collewijn, J. VanderSteen, L. Ferman, and T. C. Jansen, "Human ocular counterroll: assessment of static and dynamic properties from electromagnetic scleral coil recordings," *Experimental Brain Research*, vol. 59, pp. 185–196, 1985.

[22] T. Pansell, "Ocular counter-rolling during head tilt," Ph.D. dissertation, Karolinska Institutet, 2003.

[23] HowStuffWorks. [Online]. Available: http://static.howstuffworks.com/gif/vr-gear-8.jpg

[24] Visage. Visage technologies face tracking and analysis. [Online]. Available: http://www.visagetechnologies.com/

[25] OpenCV. Camera calibration and 3d reconstruction. [Online]. Available: http://docs.opencv.org/2.4/modules/calib3d/doc/camera_calibration_and_3d_reconstruction.html

[26] G. Medioni and S. B. Kang, *Emerging Topics in Computer Vision*. Prentice Hall Professional Technical Reference, 2004.

[27] J. Y. Bouguet. Matlab calibration tool. [Online]. Available: http://www.vision.caltech.edu/bouguetj/calib_doc/

[28] Z. Zhang, "A flexible new technique for camera calibration," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 22, no. 11, pp. 1330–1334, 2000.

[29] A. de la Escalera and J. M. Armingol, "Chessboard detection for intrinsic and extrinsic camera parameter calibration," *Sensors*, vol. 10, no. 3, pp. 2027–2044, 2010.

[30] F. Fankhauser, "Problems related to the design of automatic perimeters," *Documenta Ophthalmologica*, vol. 47, no. 1, pp. 89–138, 1979.

[31] D. K. Heuer, D. R. Anderson, W. J. Feuer, and M. G. Gressel, "The influence of decreased retinal illumination on automated perimetric threshold measurements," *American Journal of Ophthalmology*, vol. 108, no. 12, pp. 643–650, 1989.

[32] E. L. Greve, "Single and multiple stimulus static perimetry in glaucoma; the two phases of perimetry," *Documenta Ophthalmologica*, vol. 36, pp. 1–355, 1973.

[33] M. E. Wilson, "Spatial and temporal summation in impaired regions of the visual field," *Journal of Physiology*, vol. 189, no. 2, pp. 189–208, 1967.

[34] K. Teunissen, S. Qin, and I. Heynderickx, "A perceptually based metric to characterize the viewing-angle range of matrix displays," *Journal of the Society for Information Display*, vol. 16, no. 1, pp. 27–36, 2008.

[35] C. A. Poynton, *Digital Video and HDTV: Algorithms and Interfaces*. Morgan Kaufmann Publishers, 2003.

[36] Digi-Key. Ambient light sensors. [Online]. Available: http://dkc1.digikey.com/ca/en/tod/VishaySemiconductor/AmbientLightSensors/AmbientLightSensors.html

[37] A. Field, J. Miles, and Z. Field, *Discovering Statistics Using R*. Sage Publications, 2012.

[38] J. M. Bland and D. G. Altman, "Statistical methods for assessing agreement between two methods of clinical measurement," *Lancet*, vol. 1, no. 8476, pp. 307–310, 1986.

[39] J. N. Carroll and C. A. Johnson. Visual field testing: From one medical student to another. [Online]. Available: http://www.eyerounds.org/tutorials/VF-testing/index.htm

[40] P. S. Fuhr, T. A. Hershner, and K. M. Daum, "Ganzfeld blankout occurs in bowl perimetry and is eliminated by translucent occlusion," *Archives of Ophthalmology*, vol. 108, pp. 983–988, 1990.

[41] A. Heiji and B. Bengtsson, "The effect of perimetric experience in patients with glaucoma," *Archives of Ophthalmology*, vol. 114, no. 1, pp. 19–22, 1990.

[42] P. J. Foster, R. Buhrmann, H. A. Quigley, and G. J. Johnson, "The definition and classification of glaucoma in prevalence surveys," *British Journal of Ophthalmology*, vol. 86, no. 2, pp. 238–242, 2002.

[43] R. S. Jr. and R. M. Vessani, "Staging glaucoma patient: Why and how?" *The Open Ophthalmology Journal*, vol. 3, pp. 59–64, 2009.

[44] D. K. Heuer, D. R. Anderson, W. J. Feuer, and M. G. Gressel, "The influence of refraction accuracy on automated perimetric threshold measurements," *Ophthalmology*, vol. 94, no. 12, pp. 1550–1553, 1987.

[45] P. H. House, S. M. Drance, M. Schulzer, and K. Wijsman, "The effect of refractive blue on the visual field using the ring perimeter," *Acta Ophthalmologica (Copenh)*, vol. 68, no. 1, pp. 87–90, 1990.

[46] J. Rixen and Y. H. Kwon. Normal tension glaucoma. [Online]. Available: http://www.eyerounds.org/cases/86-Normal-Low-Tension-Glaucoma.htm

Appendix A

System Design

This describes the design of the mobile perimeter system. The mobile perimeter is developed on the Nexus 7 tablet and uses the lightmeter and the front-facing camera of the device. The application is developed on the Android operating system.

There are 6 main components to the system, which are shown in Figure A.1:

1. Perimetry Algorithm: This controls the flow of the visual field test and takes in inputs from the ambient light compensation, head movement compensation, and bluetooth service and determines what the next stimulus intensity should be displayed and where it should be displayed on the screen. It also outputs the next intensity level to the ambient light compensation to obtain the rgb value required.

2. Ambient Light Compensation: This takes in the positioning of the eye, the lightmeter sensor value and the wanted stimulus threshold and outputs the rgb value that will result in the correct contrast ratio required.

3. Head Movement Compensation: This takes in the front-facing camera input and uses OpenCV libraries to find the extrinsic parameters to determine the location of the eye in space relative to the tablet. The location of the eye is fed into the perimetry algorithm and the ambient light compensation component.

4. Bluetooth Service: This obtains a connection to the bluetooth button and receives alerts when the button is clicked. This then lets the perimetry algorithm know that a stimulus has been seen so the algorithm can be adjusted accordingly.

5. Database Storage: This receives the test results from the perimetry algorithm and stores the data in a database.

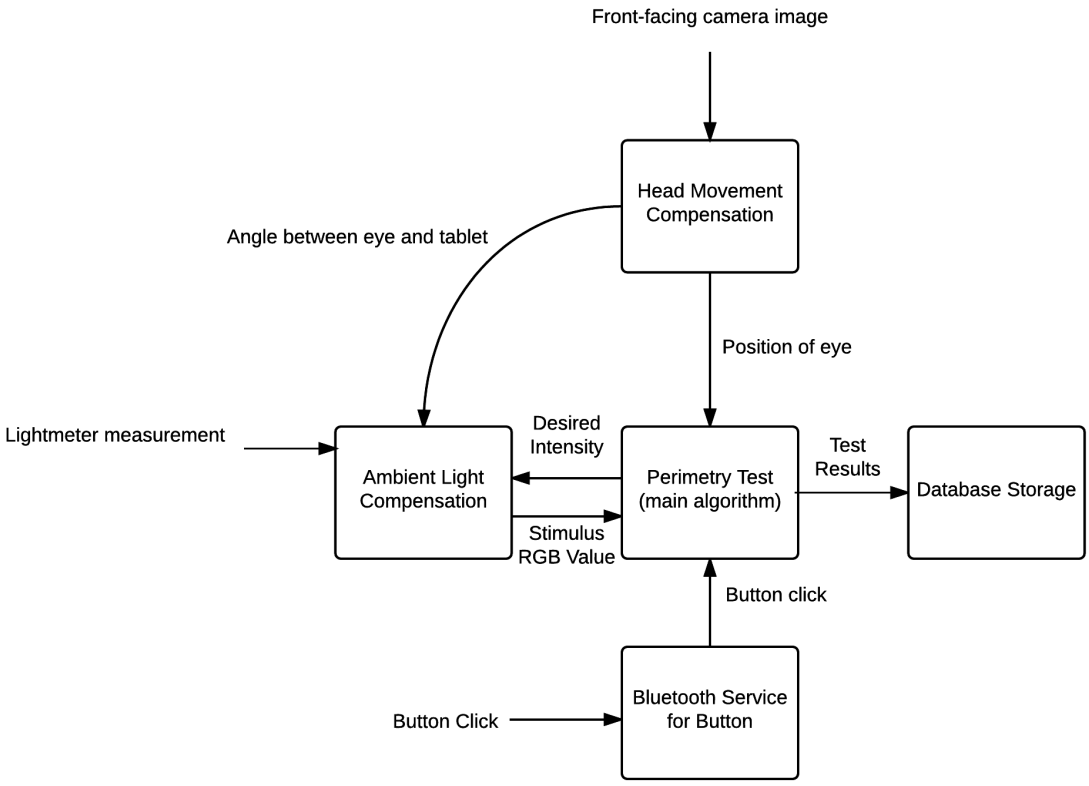


Figure A.1: Design of Mobile Perimeter