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TITLE:

Assessing Binocular Central Visual Field and Binocular Eye Movements in a Dichoptic Viewing Condition

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Binocular eye movements, dichoptic viewing, 3D shutter glasses, EyeLink, Eye tracking, Binocular visual field, Macular degeneration

SUMMARY:

Presented here is a protocol for assessing binocular eye movements and gaze-controlled central visual field screening in participants with central vision loss.

ABSTRACT:

Macular degeneration typically results in heterogeneous binocular central visual defects. Currently available approaches to assess central visual field, like the microperimetry, can test only one eye at a time. Therefore, they cannot explain how the defects in each eye affect the binocular interaction and real-world function. Dichoptic stimulus presentation with a gaze-controlled system could provide a reliable measure of monocular/binocular visual fields. However, dichoptic stimulus presentation and simultaneous eye-tracking are challenging because optical devices of instruments that present stimulus dichoptically (e.g., haploscope) always interfere with eye-trackers (e.g., infrared video-based eye-trackers). Therefore, the goals were 1) to develop a method for dichoptic stimulus presentation with simultaneous eye-tracking, using 3D-shutter glasses and 3D-ready monitors, that is not affected by interference and 2) to use this method to develop a protocol for assessing central visual field in subjects with central vision loss. The results showed that this setup provides a practical solution for reliably measuring eye-movements in dichoptic viewing condition. In addition, it was also demonstrated that this method can assess gaze-controlled binocular central visual field in subjects with central vision loss.

INTRODUCTION:

Macular degeneration is generally a bilateral condition affecting central vision and the pattern of visual loss can be heterogeneous. The central visual loss could be either symmetrical or asymmetrical between two eyes¹. Currently, there are several techniques available to assess the central visual field in macular degeneration. The Amsler grid chart contains a grid pattern that can be used to manually screen central visual field. Automated perimeters (e.g., Humphrey visual field analyzer) present light flashes of varying brightness and sizes in a standardized ganzfeld bowl to probe the visual field. Gaze-contingent microperimetry presents visual stimulus on an LCD display. Micro-perimeters can compensate micro-eye movements by tracking a region of interest on the retina. Micro-perimeters can probe local regions in the central retina for changes in function but can test only one eye at a time. Consequently, micro-perimetric testing cannot explain how the heterogeneous defects in each eye affect the binocular interaction and real-world function. There is an unmet need for a method to reliably assess visual fields in a viewing condition that closely approximates real-world viewing. Such an assessment is necessary to understand how the visual field defect of one eye affects/contributes to the binocular visual field defect. We propose a novel method for assessing central visual field in people with central visual loss under dichoptic viewing condition (i.e., when visual stimuli are independently presented to each of the two eyes).

To measure visual fields reliably, fixation must be maintained at a given locus. Therefore, it is important to combine the eye-tracking and dichoptic presentation for binocular assessment. However, combining these two techniques can be challenging due to interference between the illuminating systems of the eye-tracker (e.g., infrared LEDs) and the optical elements of the dichoptic presenting systems (e.g., mirrors of haploscope or prisms of stereoscopes). Alternative options are to use an eye-tracking technique that does not interfere with the line of sight (e.g., scleral coil technique) or an eye-tracker that is integrated with goggles². Though each method has its own benefits, there are disadvantages. The former method is considered invasive and can cause considerable discomfort³ and the latter methods have low temporal resolutions (60 Hz)⁴. To overcome these issues, Brascamp & Naber (2017)⁵ and Qian & Brascamp (2017)⁶ used a pair of cold mirrors (which transmitted infrared light but reflected 95% of the visible light) and a pair of monitors on either side of the cold mirrors to create a dichoptic presentation. Infrared video-based eye-tracker was used to track eye movements in the haploscope setup^{7,8}.

However, using a haploscope-type dichoptic presentation has a drawback. The center of rotation of the instrument (haploscope) is different from the center of rotation of the eye. Therefore, additional calculations (as described in Appendix – A of Raveendran (2013)⁹) are required for proper and accurate measurements of eye movements. In addition, the planes of accommodation and vergence must be aligned (i.e., demand for accommodation and vergence must be the same). For example, if the working distance (total optical distance) is 40 cm, then the demand for accommodation and vergence is 2.5 diopters and 2.5-meter angles, respectively. If we align the mirrors perfectly orthogonal, then the haploscope is aligned for distant viewing (i.e., required vergence is zero), but the required accommodation is still 2.5D. Therefore, a pair of convex lenses (+2.50 diopters) must be placed between the eye and mirror arrangement of haploscope to push the plane of accommodation to infinity (i.e., required accommodation is zero). This arrangement necessitates more space between the eye and mirror arrangement of

haploscope is required, which takes us back to the difference in centers of rotation. The issue of aligning planes of accommodation and vergence can be minimized by aligning the haploscope to the near viewing such that both the planes are aligned. However, this requires measurement of inter-pupillary distance for every participant and the corresponding alignment of haploscope mirrors/stimulus presenting monitors.

In this paper, we introduce a method to combine infrared video-based eye-tracking and dichoptic stimulus presentation using wireless 3D shutter glasses and 3D-ready monitors. This method does not require any additional calculations and/or assumptions like those used with the haploscopic method. Shutter glasses have been used in conjunction with eye trackers for understanding binocular fusion¹⁰, saccadic adaptation¹¹, and eye-hand coordination¹². However, it should be noted that stereo-shutter glasses used by Maiello and colleagues¹⁰⁻¹² were the first-generation shutter glasses, which were connected through a wire to synchronize with the monitor refresh rate. Moreover, the first-generation shutter glasses are commercially unavailable now. Here, we demonstrate the use of commercially available second-generation wireless shutter glasses (**Table of Materials**) to present dichoptic stimulus and reliably measure monocular and binocular eye-movements. Additionally, we demonstrate a method to assess monocular/binocular visual fields in subjects with central visual field loss. While dichoptic presentation of visual stimulus enables monocular and binocular assessment of visual fields, binocular eye tracking under dichoptic viewing condition facilitates visual fields testing in a gaze-controlled paradigm.

PROTOCOL

All the procedures and protocol described below were reviewed and approved by the institutional review board of Wichita State University, Wichita, Kansas. Informed consent was obtained from all the participants.

1. Participant selection

1.1. Recruit participants with normal vision ($n=5$, 4 females, mean \pm SE: 39.8 ± 2.6 years), and with central vision loss ($n=15$, 11 females, 78.3 ± 2.3 years) due to macular degeneration (age-related/juvenile). Note that grossly different ages of the two groups was secondary to demographics of the subjects with central vision loss (age-related macular degeneration affects older subjects and is more prevalent in females). Further, the goal of this study was not comparing the two cohorts.

2. Preparation of the experiment

2.1. Use a wireless 3D active shutter glasses (**Table of Materials**) that can be synced with any 3D-ready monitor. For the shutter glasses to be active, there should be no interference between the infrared transmitter (a small pyramid-shaped black box) and the infrared receiver (sensor) on the nose bridge of the shutter glasses.

2.2. Display all the visual stimuli on a 3D monitor (1920 x 1080 pixels, 144 Hz). For the monitor and the 3D glasses to work seamlessly, ensure that appropriate drivers are installed.

2.3. Use a table-mounted infrared video-based eye-tracker (**Table of Materials**) that is capable of measuring eye movements at the sampling of 1000 Hz for this protocol. Separate the infrared illumination and camera of the eye-tracker and hold with a tripod. Place the camera at a distance of 20-30 cm from the participant and place the screen at a distance of 100 cm from the participant.

2.4. Use an infrared reflective patch (**Table of Materials**) to avoid the interference between infrared illumination of the eye-tracker and the infrared system of the shutter glasses (**Figure 1, Right**).

2.5. Use commercially available software (**Table of Materials**) to integrate shutter glasses and 3D ready monitor for dichoptic presentation of visual stimuli to control the eyetracker.

2.6. Use a tall and wide chin and forehead rest (**Table of Materials**) to stabilize the head movements and clamp it to an adjustable table. The wide dimension of the chin and forehead rest allowed comfortable positioning of participants with the shutter glasses on.

NOTE: **Figure 1** shows the setup for eye-tracking with dichoptic stimulus presentation using 3D shutter glasses and 3D-ready monitor. The infrared reflective patch was strategically placed below the infrared sensor on the nose bridge of 3D shutter glasses (**Figure 1, Right**).

2.7. Use the infrared eye-tracker in the table-mount format and therefore, place the infrared reflective patch below the sensor.

2.8. Minimize the leakage of luminance information by deactivating the light-boost option in the 3D ready monitor. The leakage of luminance information from one eye to the other eye is known as luminance leakage or crosstalk¹³. This is prone to occurring in the stereoscopic displays in the high luminance conditions.

2.9. Because of the shutters, the amount of infrared illumination (from the eye-tracking system) reaching the pupil can be significantly reduced¹³ – on an average, approximately 65% of luminance was reduced (**Supplementary Table 1**). To overcome this, increase the strength of the infrared LEDs of the eyetracker to 100% from the default 50%. Change this setting in the “Illumination power” settings in the left bottom screen as shown in **Figure 2**.

3. Running the experiment

NOTE: The main experiment of this study was binocular eye tracking and screening of the central visual field using dichoptic stimulus. The central visual field screening was comparable to the visual field testing of commercially available instruments (**Table of Materials**). The physical properties of the visual stimulus such as luminance of the target (~22 cd/m²), luminance of the

background (~10 cd/m²), size of the target (Goldmann III – 4 mm²), the visual field grid (3-12 polar grid with 28 points), and stimulus duration (200 ms) were identical to the visual field testing of commercially available instruments. Note that these luminance values were measured through shutter glasses when the shutter was ON (**Supplementary Table 1**). For the purposes of testing discussed here, the luminance of the stimulus was constant unlike visual field testing where the luminance of the stimulus is altered to obtain a detection threshold. In other words, the experiment employed supra-threshold screening and not thresholding. Therefore, the results of the screening were binary responses (stimuli seen or not seen) and not numerical values.

3.1. Pre-experiment checks

3.1.1. A couple of minutes before the participant arrives for the testing, ensure that both eye tracker and the host computer (that runs the experiment) is turned on and confirm that the host computer is connected to the eyetracker.

3.1.2. As a rule, confirm the synchronization accuracy (using platform specific commands) of the display before beginning the experiment.

NOTE: A homogeneous flickering screen indicates good synchronization.

3.2. Initiating the main experiment

NOTE: The main experiment of this study was binocular eye tracking and screening of the central visual field using dichoptic stimulus. The steps below are very platform specific and is contingent on the script that runs the main experiment. See supplementary files that contain the samples of the codes used to design and run the experiment.

3.2.1. Initiate the program (See **Supplementary Material** - 'ELScreeningBLR.m') that runs the main experiment from the appropriate interface. When and if prompted by the program, enter the participant information (such as participant ID, test distance) that is needed to save the output data file in the data folder with a unique filename.

3.2.2. A gray screen with instructions such as "Press Enter to toggle camera; Press C to calibrate, Press V to validate" will appear on the screen. At this stage, adjust the camera of the eye-tracker to align with the participant's pupil as shown in **Figure 2**.

3.3. Eye-tracker calibration and validation

3.3.1. Initiate the calibration of the eye-tracker. Instruct the participants to follow the target by moving the eyes (and not head) and to look at the center of the target.

3.3.2. After the successful calibration, initiate the validation. Provide the same instructions as the calibration: "follow the target by moving the eyes and look at the center of the target".

3.3.3. Read the results of the validation step (usually displayed on the screen). Repeat the calibration and validation until “good/fair” result is obtained.

3.4. Drift correction

3.4.1. Once the calibration and validation of the eye-tracker is done, initiate the drift correction.

3.4.2. Instruct the participants to “look at the central fixation target and hold their eyes as steady as possible”.

NOTE: After the calibration, validation, and drift correction, the eye-tracking will be initiated simultaneously with the main experiment.

3.5. Visual field screening

3.5.1. Re-instruct/remind the participant about the task that he/she must do during the experiment. Ask subjects to keep both eyes open during the entire testing.

3.5.2. For this visual field experiment, instruct them to hold the fixation at the central fixation target while responding to “any white light seen” by pressing the “enter” button in the response button (**Figure 1, Table of Materials**). Instruct them not to move the eyes and search for the new white lights. Also, remind them that the brief white lights can appear at any location on the screen.

NOTE: During visual field screening, the functioning of shutter glasses can be probed using monocular targets that can be fused to form a complete percept (See **Supplementary Figure 2** – catch trials).

3.5.3. Re-iterate the instruction to “hold fixation” several times throughout the experiment to ensure the fixation falls within the desired area.

NOTE: An audio feedback (like an error tone) can be used to alert loss of fixation (like eyes moved outside a tolerance window). When fixation lapses, reinstruct the participant to fixate only on the cross target. The visual stimuli presentation can be temporarily stopped until the participant brings the fixation back within the tolerance window (like central 2°).

3.5.4. At the end of the visual field experiment, the screen will display the result of the testing highlighting the seen and non-seen locations differently.

3.6. Saving the data file

3.6.1. All the visual field data (say saved as “. mat” file) and eye-movement data (say saved as “.edf” file) will be saved automatically for post-hoc analysis. However, ensure that the files have been saved before quitting the program/platform running the experiment.

4. Analysis

NOTE: The analysis of eye movement and visual field data can be performed in several ways and is contingent on the software used to run the experiment and data format of eye tracker's output. The steps below are specific to the setup and the program (See **Supplementary Materials**).

4.1. Eye movement analysis (post-hoc)

NOTE: The saved eye movements data file (EDF) is a highly compressed binary format, and it contains many types of data, including eye movement events, messages, button presses, and gaze position samples.

4.1.1. Convert EDF to ASC-II files using a translator program (EDF2ASC).

4.1.2. Run 'PipelineEyeMovementAnalysisERI.m' to initialize eye movement analysis and follow the instructions as noted in the code (See **Supplementary Materials** for the code script).

4.1.3. Run 'EM_plots.m', to extract horizontal and vertical eye positions and to plot as shown in **Figure 4** and **Figure 5**.

NOTE: Eye movement data can be further analyzed to compute fixation stability, detect microsaccades, etc. However, this is beyond the scope of the current paper.

4.2. Visual fields

4.2.1. To get the reports of visual field test, run 'VF_plot.m'.

NOTE: All datasets pertaining to the visual field experiment such as points seen/not seen will be plotted as a visual field map as shown in **Figure 6**. If a point was seen, then it will be plotted as "green" filled square, otherwise a red filled square will be plotted. No post-hoc analysis for visual field data will be required.

REPRESENTATIVE RESULTS

The representative binocular eye-movement traces of one observer with normal binocular vision during two different viewing conditions is shown (**Figure 4**). Continuous tracking of eye movements was possible when both eyes viewed the stimulus (**Figure 4A**), and when the left eye viewed the stimulus with the right eye under an active shutter (**Figure 4B**). As evident from these traces, the proposed method does not impact the quality of eye-movement measurement and can measure the eye movements for even long duration experiments. We then demonstrated that the method can be used to reliably measure eye movements even in challenging participants with central vision loss (**Figure 5**). An important application of the method is screening the central visual field in subjects with (**Figure 6**) and without (**Supplementary Figure 2**) central vision loss. The method provides a way to document the impact of central vision loss in real world viewing

with both eyes open. In this representative observer (S7 in **Supplementary Table 2**), binocular advantage was observed (i.e., seeing a greater number of points with both eyes compared to the right/left eyes). Preliminary analysis (**Supplementary Table 2**) of the visual field test results of all participants with central vision loss demonstrates the benefit of binocular viewing (compared to non-dominant eye viewing condition). One-way ANOVA revealed that there is a significant main effect of the viewing condition [$F(2,28) = 6.51, p = 0.004$]. Post-hoc (Tukey HSD) showed that participants with central vision loss saw greater number of points in the binocular viewing condition compared to non-dominant viewing condition ($p < 0.01$), but not dominant eye viewing condition ($p = 0.43$).

FIGURES

Figure 1: Eye tracking and dichoptic presentation setup. Left - Equipment setup showing (a) 3D-ready monitor, (b) chin/forehead rest, (c & d) EyeLink eyetracker camera and infrared illumination source (table mounted), (e & f) 3D shutter glasses and its IR transmitter and (g) response button. Right - 3D shutter glasses with (h) infrared sensor on the nose-bridge and (i) Infrared reflective patch strategically placed below the sensor and held in place by a thin wire.

Figure 2: Screen grab of the eye tracker settings. The figure shows that the infrared illumination power setting (bottom left corner) can be toggled between 50%, 75%, and 100%. This figure also shows the proper alignment of pupil.

Figure 3: Illustration of visual field test grid. Pictorial representation showing Polar 3 grid (N = 28, in 3 concentric rings of 2.3°, 6.6°, and 11° in diameter, respectively) visual field test design. Testing parameters were similar to commercially available instruments.

Figure 4: Binocular eye tracking in a subject with normal vision. Representative binocular eye-movement traces of a control participant: (A) horizontal and vertical eye positions of the left eye (top) and the right eye (bottom) when the visual stimuli were presented dichoptically to both eyes; and (B) horizontal and vertical eye positions of the left eye and the right eye when the visual stimuli were presented dichoptically only to the left eye. Each unit on the x-axis and y-axis represents one second and one degree, respectively.

Figure 5: Binocular eye tracking in a subject with central vision loss. Representative binocular eye movement traces of a participant with macular degeneration: (A) horizontal and vertical eye positions of the left eye (top) and the right eye (bottom) when the visual stimuli were presented dichoptically to both eyes, and (B) horizontal and vertical eye positions of the left eye and the right eye when the visual stimuli were presented dichoptically only to the left eye. Each unit on the x-axis and y-axis represents one second and one degree, respectively. It should be noted that despite larger fixational eye movements in the patient with central vision loss (compare it with **Figure 4**), reliable eye-tracking was feasible.

Figure 6: Visual field screening test results of a subject with central vision loss. Results of visual field screening (N=28) in a representative participant with central vision loss (S7 in **Supplementary Table 2**). Visual stimulus presented to both eyes (top), to the left eye only

(middle), and to the right eye only (bottom). Fixation cross is shown in the center and the visual field locations where the brief white stimulus was seen are shown as green filled squares. The locations that did not see the stimulus are shown as red filled squares. Proportion seen in the three viewing conditions were 0.50 (14/28, both eyes viewing, top); 0.29 (8/28, LE viewing, middle); and 0.14 (4/28, RE viewing, bottom).

Supplementary Figure 1: Visual field screening test results of a control subject. Results of visual field screening (N=28) in a representative control participant. Visual stimulus presented to both eyes (top), to the left eye only (middle), and to the right eye only (bottom). Fixation cross is shown in the center and the visual field locations where the brief white stimulus was seen are shown as green filled squares. The locations that did not see the stimulus are shown as red filled squares. Proportion seen in the three viewing conditions were 1.00 (28/28, both eyes viewing, top); 1.00 (28/28, LE viewing, middle); and 0.93 (26/28, RE viewing, bottom).

Supplementary Figure 2: Catch Trials - Probing the functioning of shutter glasses. Catch trials ascertained uninterrupted communication of stereoscopic glasses with IR emitter and synchronization with the stereo display. The central image illustrates a perception that should be reported by subject (red cross and a red/green/yellow square) if the synchronization works. The dimensions of the cross target (and the individual bars) were identical to the fixation cross used for visual field screening and the outer square border corresponds to the 4° tolerance window. Note that suppression of worse seeing eye, which is more likely in subjects with grossly dissimilar visual acuities, can confound the subjective perceptual reports. For the catch trials (every 10 trials), red horizontal bar enclosed in a red square seen only by the left eye and red vertical bar enclosed in a green square seen only by the right eye (2° x 0.4°) were used. The monocular targets could be fused to perceive a red central cross, if the stereoscopic mode was ON throughout and if the shutter glasses functioned properly. This step ascertained that the two infrared light sources did not interfere, and the shutter glasses were synchronized with the 3D-ready monitor.

Supplementary Table 1: Luminance of background and the stimulus. The luminance of the gray background and the white stimulus measured with and without the shutter glasses at the eye level of presumed subject. The shutter glasses reduce the luminance by approximately 65%. It is important to account for the transmission loss when presenting visual stimulus of set luminance and contrast. Note that the infrared illumination power of the eye tracker (always set to 100% in our testing) has no role in these measurements.

Supplementary Table 2: Summary of visual field testing in central field loss participants. Visual field performance by participants with central vision loss in dominant, non-dominant, and binocular viewing conditions. Abbreviations: DE – dominant eye; NDE – non-dominant eye; BE – both eyes. Binocular ratios for DE was calculated by finding the ratio between proportion of points seen during BE and DE viewing conditions. Similarly, the binocular ratio for NDE was also calculated. Ratio of >1 suggests binocular advantage (i.e., better performance under binocular viewing condition). Overall, a greater number of points was seen in BE viewing condition compared to NDE viewing condition.

DISCUSSION:

The proposed method of measuring eye movements in dichoptic viewing condition has many potential applications. Assessing binocular visual fields in participants with central vision loss that is demonstrated here is one such application. We used this method to assess binocular visual field in fifteen participants with central vision loss to study how binocular viewing influences the heterogeneous central visual field loss.

The most important step in the protocol is positioning (distance from eye and angle) the infrared source of the eye tracker for optimal illumination. This is critical for the eye tracker to capture both corneal reflex and pupil center consistently. Once this was achieved, the tracking should be continuous even in subjects with prescription glasses and in those with central vision loss. It is important to watch for postural changes in subjects, especially head tilts (with head and chin rested) during prolonged testing as it can interfere with eye tracking. Postural changes and fatigue can be minimized by reducing the overall test duration. In challenging subjects, the test duration is primarily driven by time taken to achieve a successful calibration/validation. The overall test duration for the procedure was about 45 minutes in subjects with macular degeneration. The positioning of the infrared reflective patch, emitter, and the infrared source of the eye tracker is critical for the uninterrupted functioning of the shutter glasses. The default calibration (like 9-point or HV 9) can be used for participants with normal vision. However, for assessing subjects with central vision loss it might be necessary to use alternatives (like 5-point calibration or HV 5), and/or large custom-made calibration targets (like black square $\approx 2^\circ$ in size). These changes to the calibration target can be handled in the scripts used to run the experiment (See **Supplementary Materials - 'ELScreeningBLR.m'**). For very challenging participants, calibration target can be pointed using fingers to help them find and point towards the target. Like the calibration process, drift check/correction can be performed using in-built target for participants with normal vision and custom-built larger target for participants with central vision loss. We followed the manufacturer recommendation to perform drift check at the beginning of each session. The gaze offset in degrees of visual angle (or pixels) can be accessed from final output file ('.edf' - eye movement data file). However, we did not apply any of these data for our analyses. As an in-built measure of quality, the EyeLink eye tracker repeats the calibration when the drift check fails.

The stimulus design, presentation, and control in the setup were through MATLAB based programs. Python or similar programs could be used for achieving the goals of our study. An important pre-requisite for running time-sensitive vision science experiments is good synchronization between the vertical retrace of the display and the stimulus onset. Before each session, we ran pre-experiment checks of synchronization using platform specific commands. A homogeneous flickering screen indicates good synchronization, whereas an inhomogeneous flicker implies poor synchronization, probably due to some bug or limitation of the graphics hardware or its driver. In addition to the flicker, an emerging pattern of yellow horizontal lines will also be seen in most computers. These lines should be tightly concentrated/clustered in the topmost area of the screen. Distributed yellow lines signal timing issues that can be due to background programs like anti-virus or others in the host computer. We recommend quitting all

unnecessary applications and turn on airplane mode (or turn the Wi-Fi off) to minimize timing related artefacts.

Similar to previous studies^{10,12} we used video-based high-resolution table-mounted eye tracker. However, we believe that the method described here should work equally well with other commercially available eye trackers. The quality of eye movement data for purposes of the method demonstrated in this study should not be impacted by the temporal resolution of the eye tracker. Even lower resolution eye trackers (as low as 60 Hz¹⁵) have been used to assess and train subjects with macular degeneration. The viewing distance is determined by several factors including the display resolution and stimulus parameters. Any practicable working distance within the range of wireless transmitter (<15 feet) can be used. The size of the visual field that can be assessed is contingent on the test distance and display size. In the setup here, the maximal possible was ~30°x17° (W x H). The standard visual field grid (Polar 3) used in this study tests central 11° (diameter) of visual field. The stereoscopic shutter glasses could be replaced with polarizing glasses. Suitable modifications in the setup (say higher resolution display or longer working distance) will be necessary to minimize the impact of reduced resolution secondary to use of polarizing glasses. Moreover, the current method is less expensive than building a haploscope for dichoptic presentation if researchers already have a video-based eye tracker.

We employed a 'gaze controlled' paradigm in this study. Gaze-controlled systems collect instantaneous information regarding gaze position (and hence discard trials where the gaze was not within a desired tolerance window) but do not compensate for it. However, the setup here can be used for a gaze contingent testing, where the instantaneous gaze position is not only monitored but also compensated by appropriate modification of stimulus presentation. For example, if the gaze moved from the desired location to the right by 'x' degree, then the stimulus can be offset by 'x' degree to the right. Studies of simulated vision loss and scotomas use gaze contingent paradigms^{16,17}. Such paradigms can be extremely time-sensitive and their effectiveness depends on several factors including the temporal resolution of the eye-tracker¹⁸. For example, an eye-tracker with a temporal resolution of 500 Hz (or one sample every 2 ms) will introduce a temporal delay of at least 2 ms. Although this is trivial, there are usually additional delays due to refresh rate of the stimulus display, computational delays of programming language, etc. Moreover, the proposed method can induce an additional delay due to temporal synchronization between 3D-monitors and 3D-shutter glasses.

Subjects with considerably asymmetric vision loss (say with large interocular differences in visual acuity or if the scotoma in one eye is relatively large) can be effectively monocular when viewing binocularly. Subjects with grossly dissimilar vision loss, nystagmus, high refractive error, and strabismus cannot be assessed using this setup. Subjects with systemic conditions like head tremors and Parkinson's disease will not be good candidates for eye tracking. Subjects with neck or back problems will need frequent breaks and briefer test protocols. The reduction in luminance through the active shutters necessitates use of displays with broader luminance range. Achieving optimal infrared illumination and continuous tracking of the corneal reflex and pupillary center can be challenging in subjects with prescription eyeglasses.

Several studies have used dichoptic stimulus presentation that is presenting two separate images to participant's two eyes to study the binocular functions such as stereopsis¹⁴, suppression¹⁸. However, these studies lack eye movements information because of the technical difficulties of combining dichoptic visual stimulus presentation and eye-tracking. Eye movements provide crucial insights about cognitive functions like covert/overt spatial attention. The proposed method of measuring eye movements in a dichoptic viewing condition will better the understanding of the binocular function in subjects with normal vision and in subjects with central vision loss. Amsler grid chart provides only qualitative information about the visual field and the retina-tracking perimeters cannot assess the binocular fields. The setup here incorporating eye tracking and dichoptic testing provides one way to reliably screen central visual field in macular degeneration. A potential application of the proposed method is in the field of virtual reality. All the commercially available virtual reality headsets use the concept of dichoptic presentation of visual stimulus. Many asthenopic symptoms have been associated with dysfunctional eye-movements (e.g., vergence eye-movements) while using virtual reality environment^{10,15}. The proposed method would help us to study eye-movements and visual function during dichoptic presentation, which can be related to virtual reality environment.

In summary, we detailed a method to assess 1) binocular eye movements and 2) monocular/binocular visual field while dichoptically presenting visual stimulus using wireless 3D-shutter glasses and 3D-ready monitor. We demonstrated that our method is feasible even in challenging participants such as those with central vision loss.

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DISCLOSURE

The authors have nothing to disclose. Parts of the study presented here were presented as abstract titled "Binocular Central Visual Function in Macular Degeneration" in the annual meeting of American academy of Optometry 2019.

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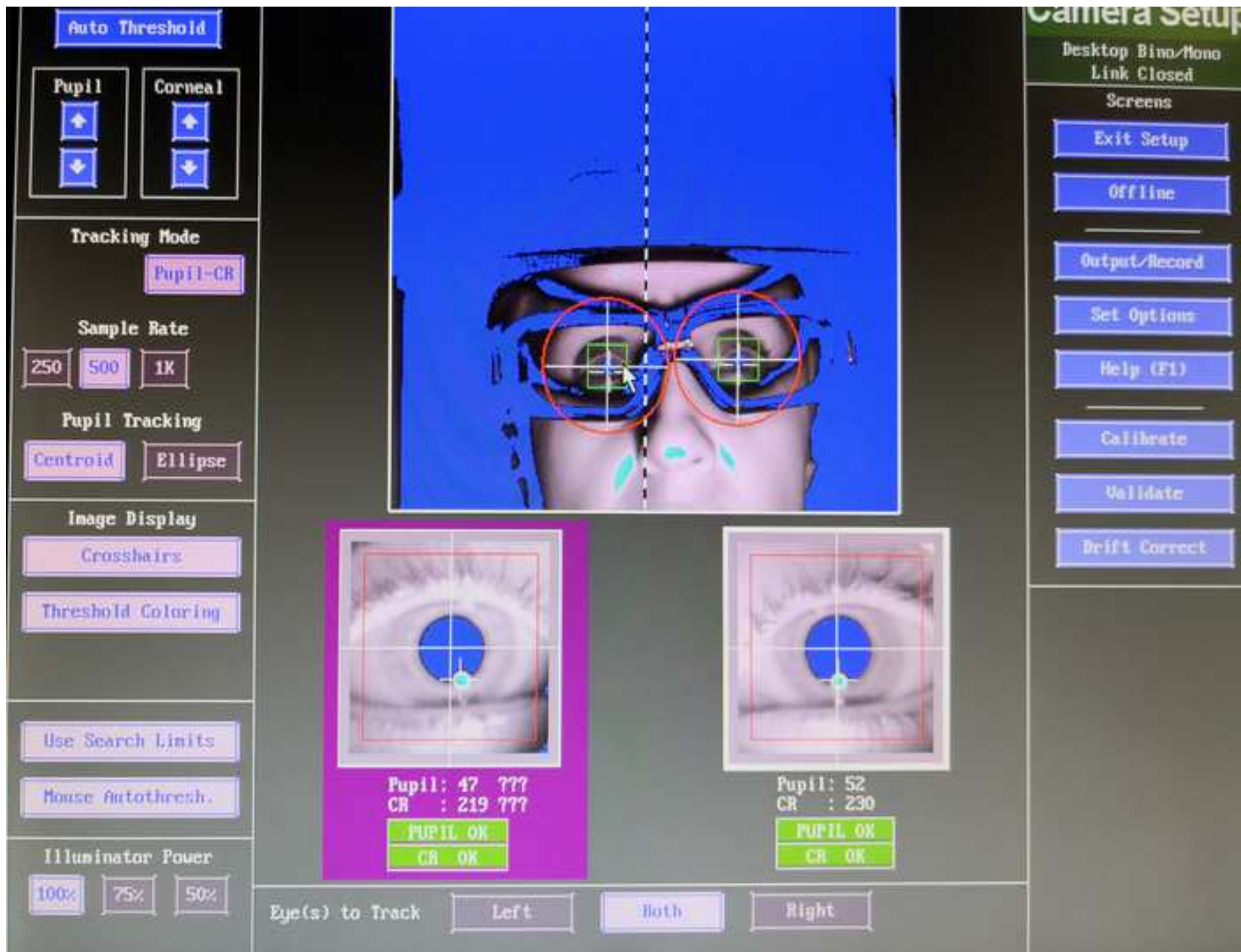
Figure 1

[Click here to access/download;Figure;Fig 1a-1b merged.psd](#)



Figure 2

[Click here to access/download;Figure;Figure 2.psd](#)



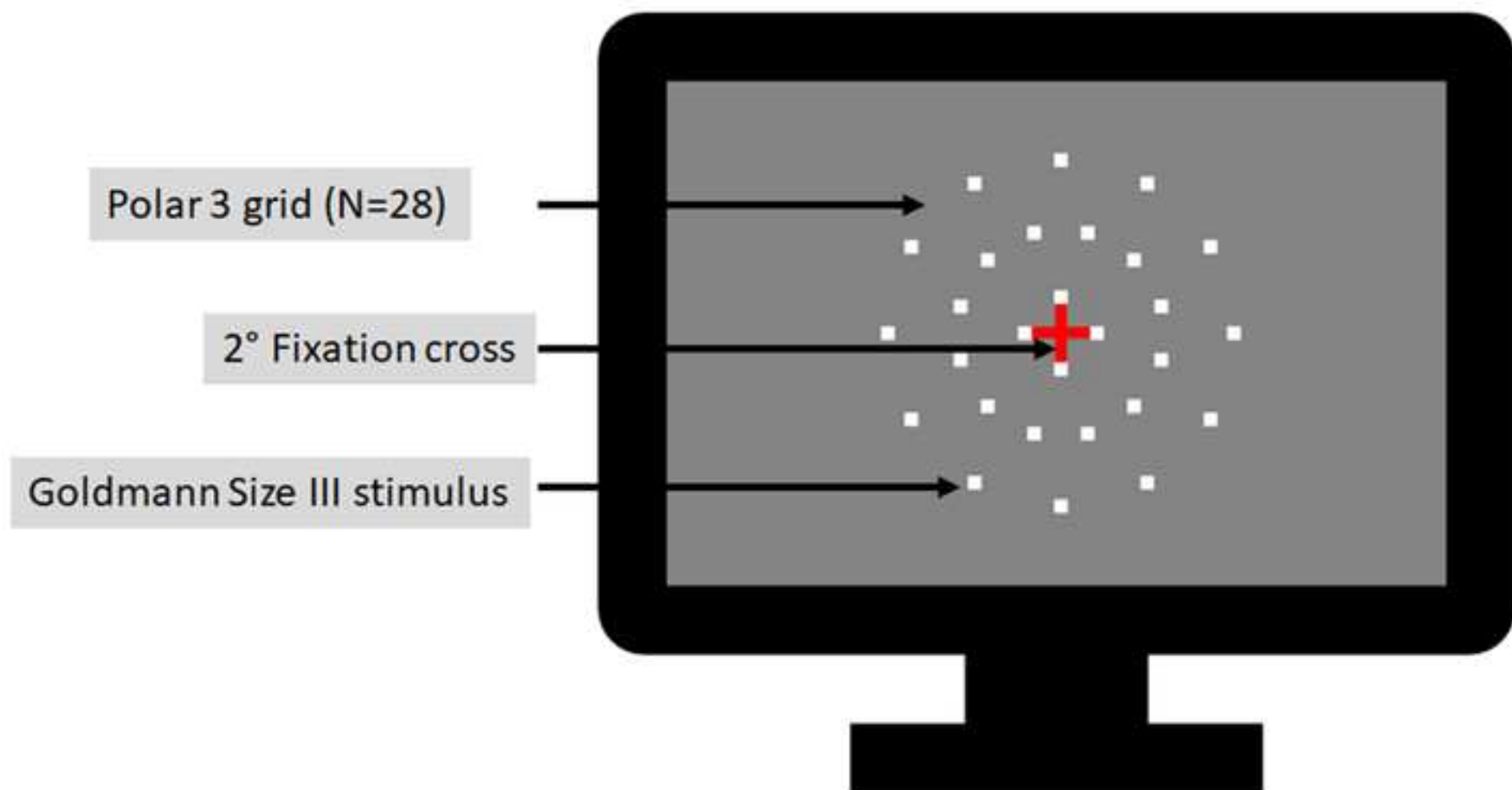
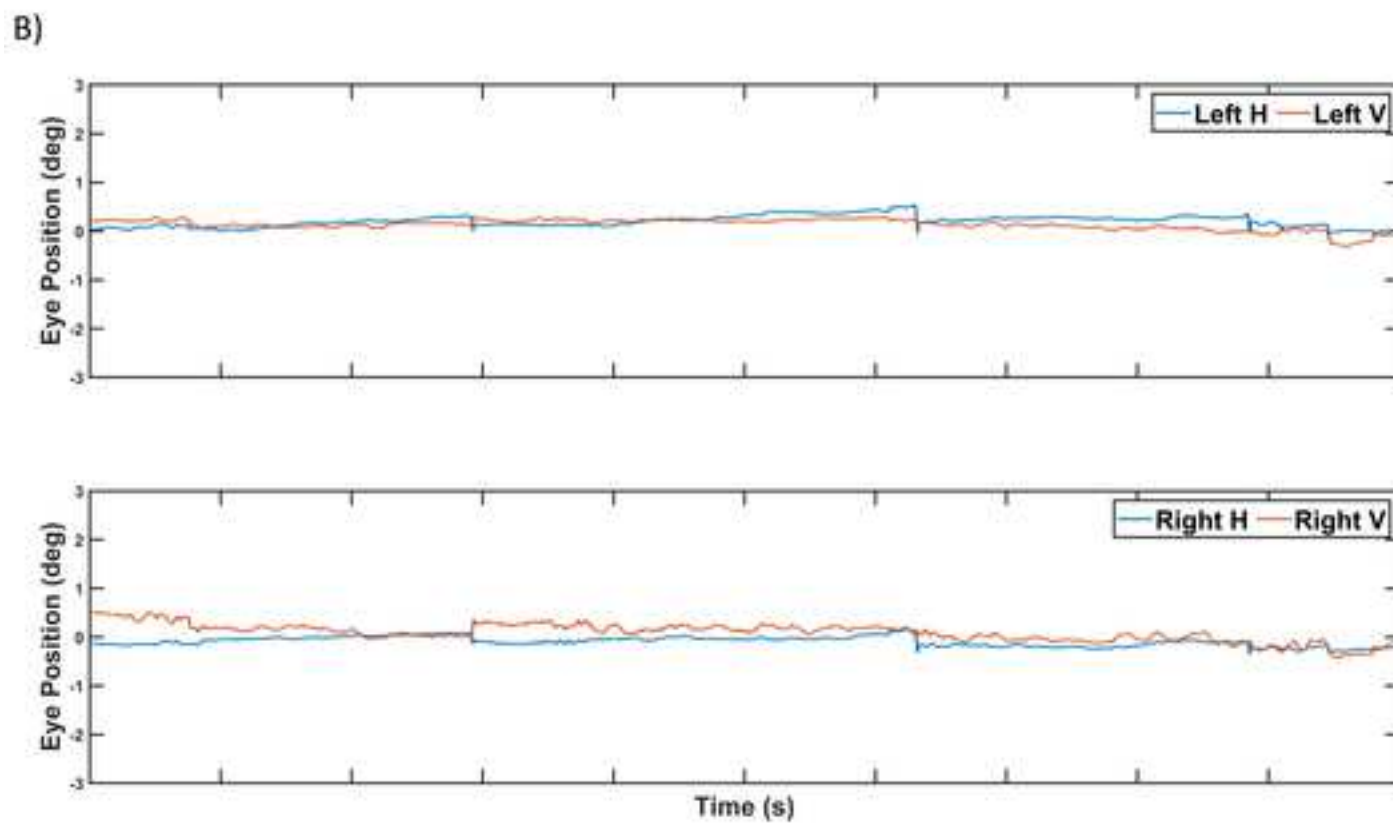
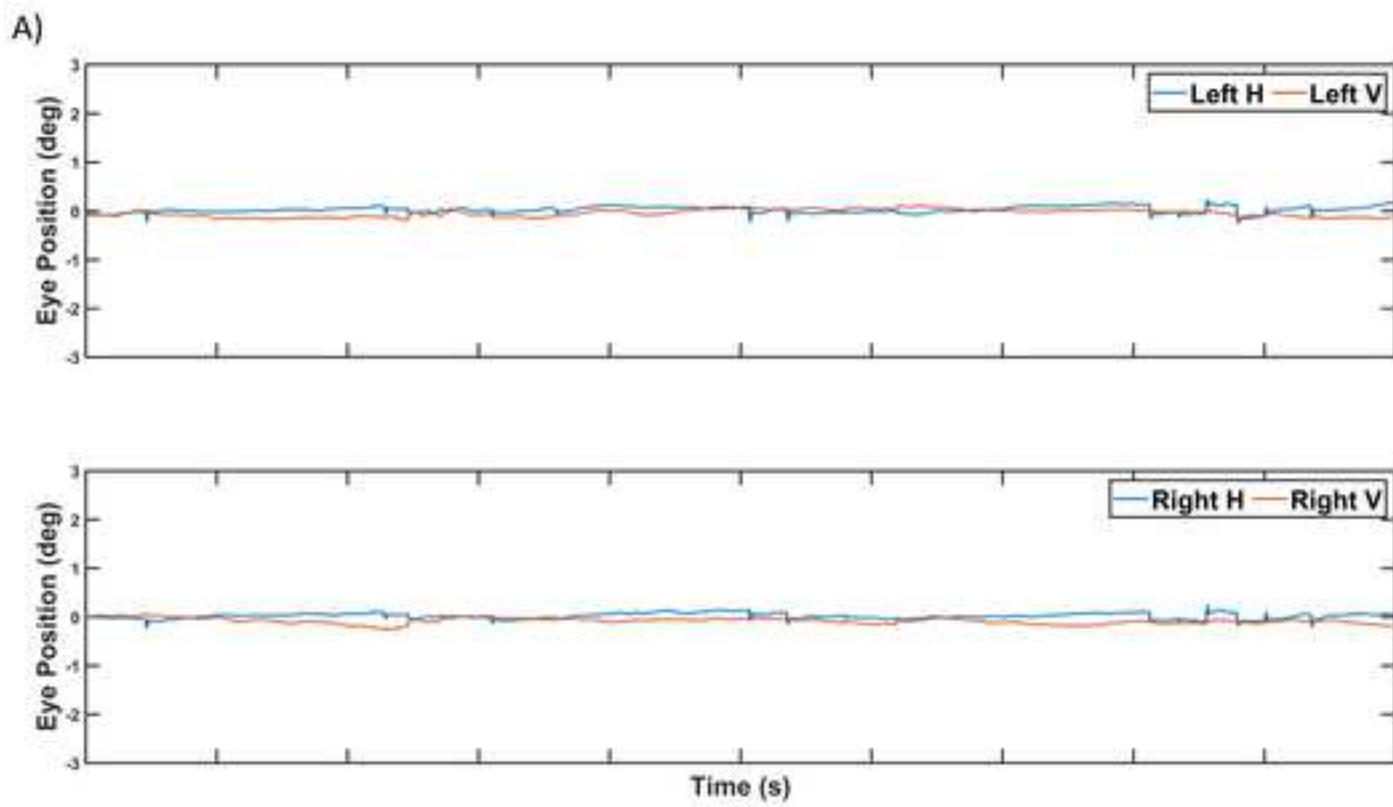
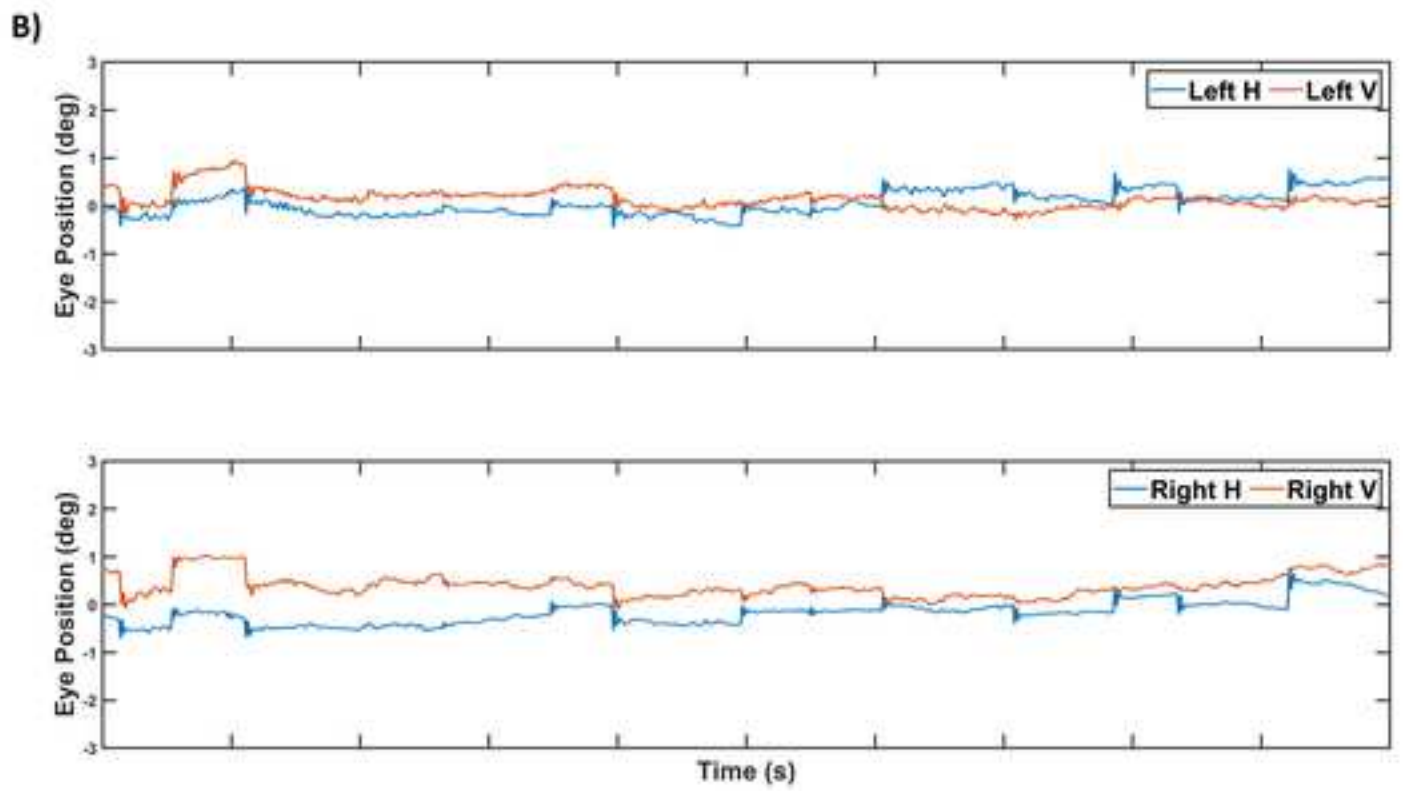
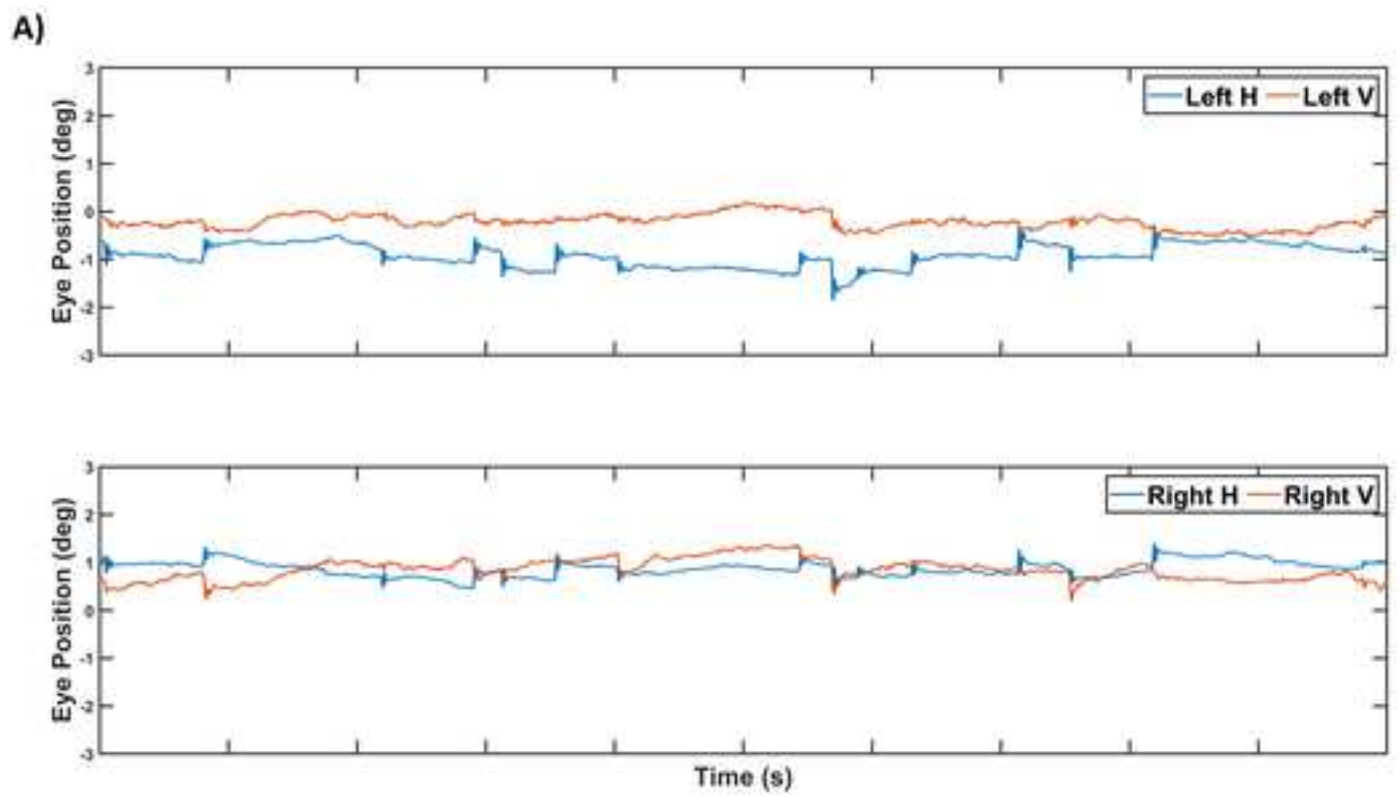
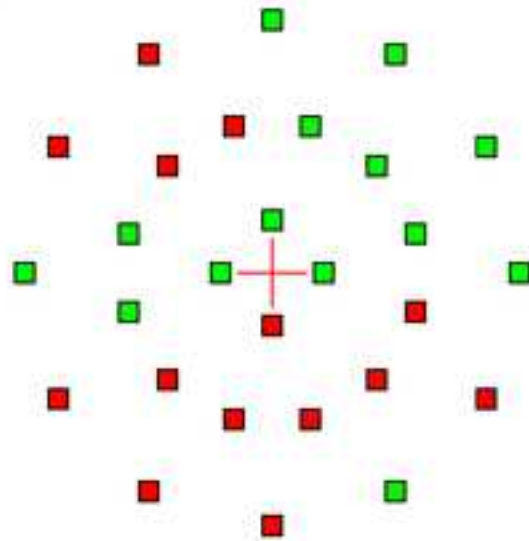


Figure 4

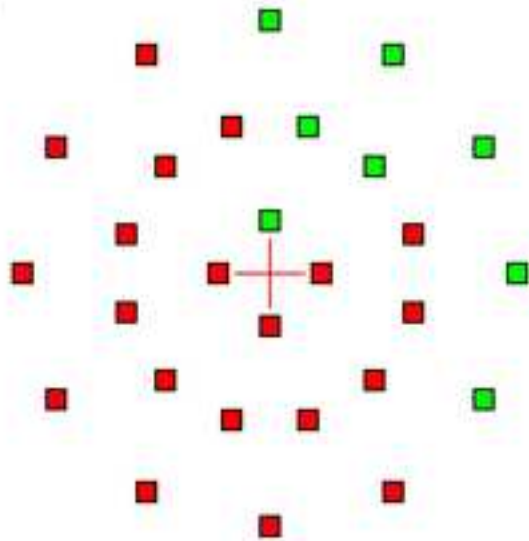




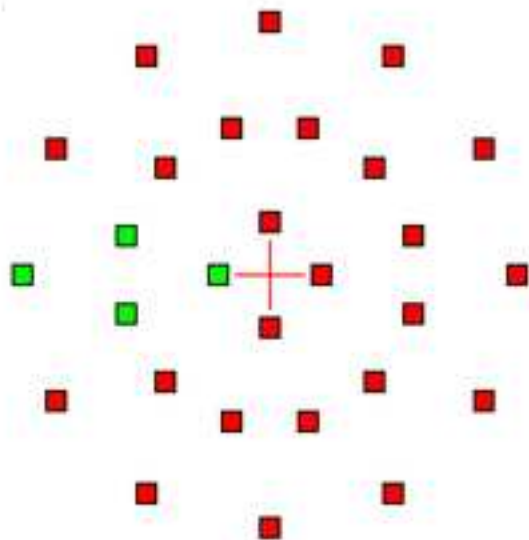
A)



B)



C)



S. No	Material/Item	Company	Catalog Number
1	3D monitor	Benq	NA
2	3D shutter glass	NVIDIA	NA
3	Chin/forehead rest	UHCO	NA
4	Eyetracker	SR Research	NA
5	IR reflective patch	Tactical	NA
6	MATLAB Software	Mathworks	NA
7	Numerical Keypad	Amazon	CP001878 (model), B01E8TTWZ2 (ASIN)
8	Psychtoolbox - Add on	Freeware	NA
9	Tripod (Dekstop)	Manfrotto	MTPIXI-B (model), B00D76RNLS (ASIN)

Comments/Description
https://zowie.beng.com/en/product/monitor/xl/xl2720.html
https://www.nvidia.com/object/product-geforce-3d-vision2-wireless-glasses-kit-us.html
https://www.opt.uh.edu/research-at-uhco/uhcotech/headspot/
https://www.sr-research.com/eyelink-1000-plus/
https://www.empiretactical.org/infrared-reflective-patches/tactical-infrared-ir-square-patch-with-velcro-hook-fastener-1-inch-x-1-inch
https://www.mathworks.com/pricing-licensing.html
https://www.amazon.com/Numeric-Jelly-Comb-Portable-Computer/dp/B01E8TTWZ2
http://psychtoolbox.org/download.html
https://www.amazon.com/dp/B00D76RNLS

Approximate Cost (in USD)
500
300
750
27,000
10
2150
15
FREE
30

June 23, 2020

Dear Editor and Reviewers:

Thank you very much for the second round of reviews for our manuscript. Our point by point responses to the individual comments are provided below. This manuscript is not under consideration for publication elsewhere. All authors reviewed the manuscript and approved for submission to the journal. We have no conflicts of interest or any financial relationship to disclose.

Thank you for considering the manuscript.

Yours sincerely,

Rajkumar Raveendran

Arun Krishnan

Editorial comments:

1. The Protocol should contain only action items that direct the reader to do something. Please move the discussion about the protocol to the Discussion (about the large paragraphs in step 3).

[Thank you for the suggestion. We amended the manuscript as per the comments.](#)

2. When referring to supplemental material, please specify the specific file.

[Thank you. We have amended the manuscript as per the suggestion.](#)

3. Please restart the numbering for supplemental figures. Supplemental Figure 7 should be Supplemental Figure 1, etc.

[We have modified it as per the suggestion.](#)

4. Please highlight 2.75 pages of protocol text for inclusion in the protocol portion of the video. This is a hard production limit to ensure that videography can occur in a single day.

[We have highlighted the lines \(127-170, 187-266\) in gray to indicate the protocol text.](#)

5. Figure 1 left: The labels are very hard to see due to the color. Please revise.

[We have changed the font color. Thank you for the suggestion.](#)

Reviewers' comments:

Reviewer #1:

Manuscript Summary:

The authors present an updated method for dichoptic stimulus presentation and binocular eye-tracking using 3D-shutter glasses and 3D-ready monitors. The main application of this technology is the measurement of binocular central visual fields in people with central vision loss. I believe this is a useful paper, especially considering that the eye movements of people with central field loss are difficult to record.

The authors have made all the required improvements to their paper.

[Thank you for your constructive comments.](#)

Reviewer #2:

The authors had made significant progress in the manuscript. They acknowledged previous work on this topic, provided more results, and improved the delivery of the methods.

Considering that, I recommend the publication of the paper. Besides, there are a few minor points that the authors could consider incorporating in the manuscript.

Minor :

1. [line 434] I assume the authors' method is less expensive than using commercially available eye trackers, especially for researchers who already have both 3D ready monitor and video-based eye tracker. I think the authors can add this in the manuscript to make it a better method.

Thank you for this wonderful comment. Yes, we have amended the manuscript to add this information. (Line 437-439)

2. Figure quality: the authors claimed that they increased the figure quality. However, many figures look rather blurred to me.

We made sure that the quality of the figures was 600dpi. However, we assume that poor quality may be due to the converting to pdf (as you have suggested).

a. Figure 2 is a lower resolution than the eye tracker monitor screen. The buttons in the interface look very blurry.

We have taken a new screen shot now.

b. Figure 4 has yellow artefacts along the data. This could be due to the transformation from the figure to pdf.

Yes, you are correct. The artefacts are due to conversion of the documents to pdf.

c. The figure caption and the actual figure are not consistent in how many panels there are. For example, the caption of Figure 4 described a-d four panels but the actual figure only denoted panel A and B. The same is true for Figure 5.

We have made it clear now. Sorry for not being consistent.

3. [line 195] Greyish is not a technical description of the luminance. Could the author change the wording and provide the luminance level?

Thank you for the suggestion. We have amended this in the manuscript.

Reviewer #3:

Manuscript Summary:

The authors of the "Assessing binocular central visual field and binocular eye movements in a dichoptic viewing conditions" had significantly changed the manuscript. It describes better now the main idea and procedure. There is enough information to make the same procedure and to apply the described method. However, there are some changes that still can be made.

Thanks for your feedback.

Major Concerns:

1. Give explanation why so high frequency (1000 Hz) eye tracker was used. Later in discussion, the authors mentioned that the method will work even with other commercially available eye trackers. What are the opportunities of high-resolution eye trackers in such procedures? Will the lower resolution eye trackers give the same quality data? What accuracy is required in such procedures? How the longer or shorter working distance will change the accuracy of the procedure?

The choice in our case was dictated by resources available at our disposal. Like previous studies (Maiello et al. 2014, 2018) we used video-based high-resolution table-mounted eye tracker. However, we believe that the method described here should work equally well with other commercially available eye trackers. The quality of eye movement data for purposes of the method demonstrated in this study, should not be impacted by the temporal resolution of the eye tracker. Infact lower resolution eye trackers (as low as 60Hz, Seiple et al. IOVS 2005) have been used to assess and train subjects with macular degeneration. The viewing distance is determined by several factors including the display resolution and stimulus parameters. Any practicable working distance within the rage of wireless transmitter (<15 feet) can be used. Both issues are now included in the discussion.

2. The luminance was evaluated in two conditions - without and with shutter glasses and presented in Supplementary Table 1. It is not clear was this evaluation performed with 50%, 75%, or 100% illumination power? If the authors suggest to increase the strength of the infrared LEDs to 100%, it should be specified what illumination power was used to demonstrate data in Supplementary Table 1? What would be the size of improvement if 100% illumination power is used?

The luminance of the background and the stimulus were measured at the eye level both with and without shutter glasses and the results are summarized in the supplementary table. The illumination power of the eye tracker (which was set to 100%) has no role/relevance in these measurements. A note clarifying the same was added to the supplementary table legend.

3. Why the drift correction should be performed and how and where these data can be applied? Is there any quality measurement for drift correction?.

Below is the excerpt from the eye tracker's manual about drift correction.

".... The Drift Check/Drift Correct screen displays a single target to the participant and then measures the difference between the computed fixation position and the current target. For the EyeLink 1000, the default configuration leaves the calibration model unmodified. The purpose, therefore, is to check whether the model has become grossly invalidated. If the error is large, the experimenter is prompted to acquire another sample. If the error remains large (i.e., the prior sampling error was reproduced), the drift check will fail, and another calibration will be required...."

Source: <http://sr-research.jp/support/EyeLink%201000%20User%20Manual%201.5.0.pdf>

We followed the recommendation to perform drift check at the beginning of each session. The gaze offset in degrees of visual angle (or pixels) can be accessed from final output file ('.edf' - eye

movement data file). However, we did not apply any of these data for our analyses. As an in-built measure of quality, the EyeLink eye tracker repeats the calibration when the drift check fails. This is now clarified in the discussion section.

4. What is duration of the procedure? If it is used as a screening it should be less time-consuming procedure compared to the clinical one.

Our test duration is contingent on time taken to achieve successful calibration/validation. The overall test duration for our procedure was about 45 minutes and is slightly longer mainly because the clinical testing does not test both eyes. We use the word 'screening' because we are not thresholding the visual sensitivity at each locus, but rather screen with supra-threshold stimulus.

5. In discussion, please include the application (indications) of such visual field screening in the clinical examinations and not only for the experimental use.

We discuss few potential applications in our concluding section of the discussion (See lines 525-530).

Minor Concerns:

1. What is the size of visual field that can be tested?

This is contingent on test distance and display size. In our setup the maximal possible was ~30°x17° (WxH). The polar grid used in this study tests central 11° of visual field.

2. Lines 273-276: Is the tolerance window and desired area the same? Please use the same terminology.

Thank you. Yes, they are the same and the specified lines have been rephrased.

3. Lines 321-323: The description in the text do not correspond to one given in the description of the Figure 4. The same is about Figure 5. Correct the Figure 4 and Figure 5 (incorrect letters are given in the figures).

The in-text reference error was fixed.

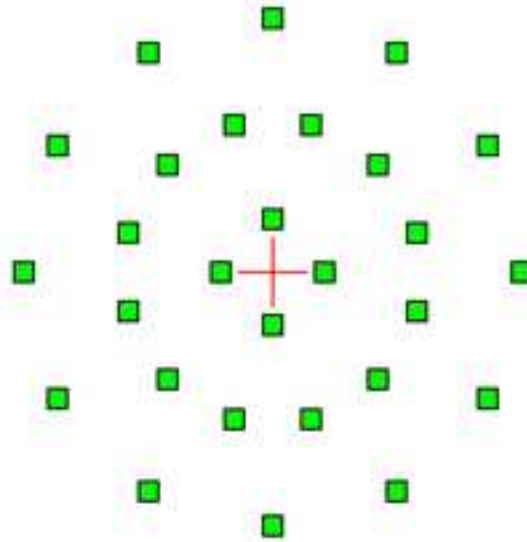
4. Figure 1: Please include detail presentation (either with arrows or letters) in the image on the right side (similar as for one on the left).

Added letter references to the image on the right.

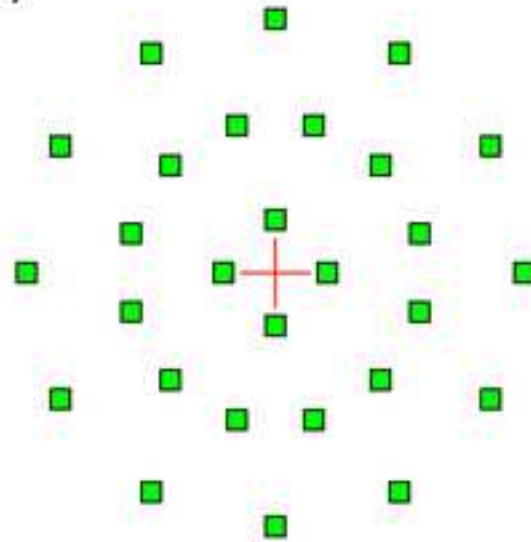
5. Lines 419-421: Why the reference is given at the end of the sentence that describes the authors' experiment?

The wrong reference was removed and added a line in disclosure section regarding conference presentation of the work discussed in this manuscript.

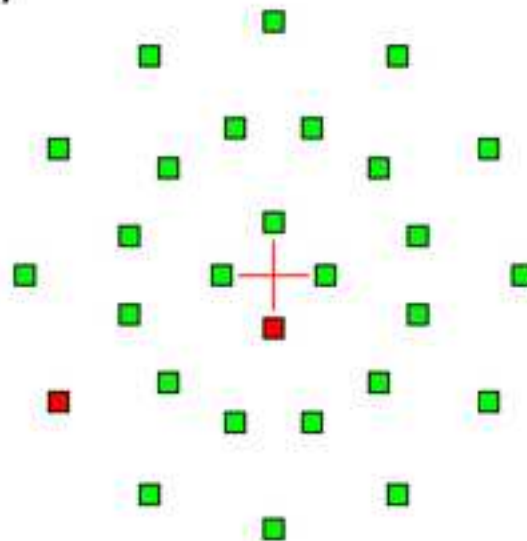
A)

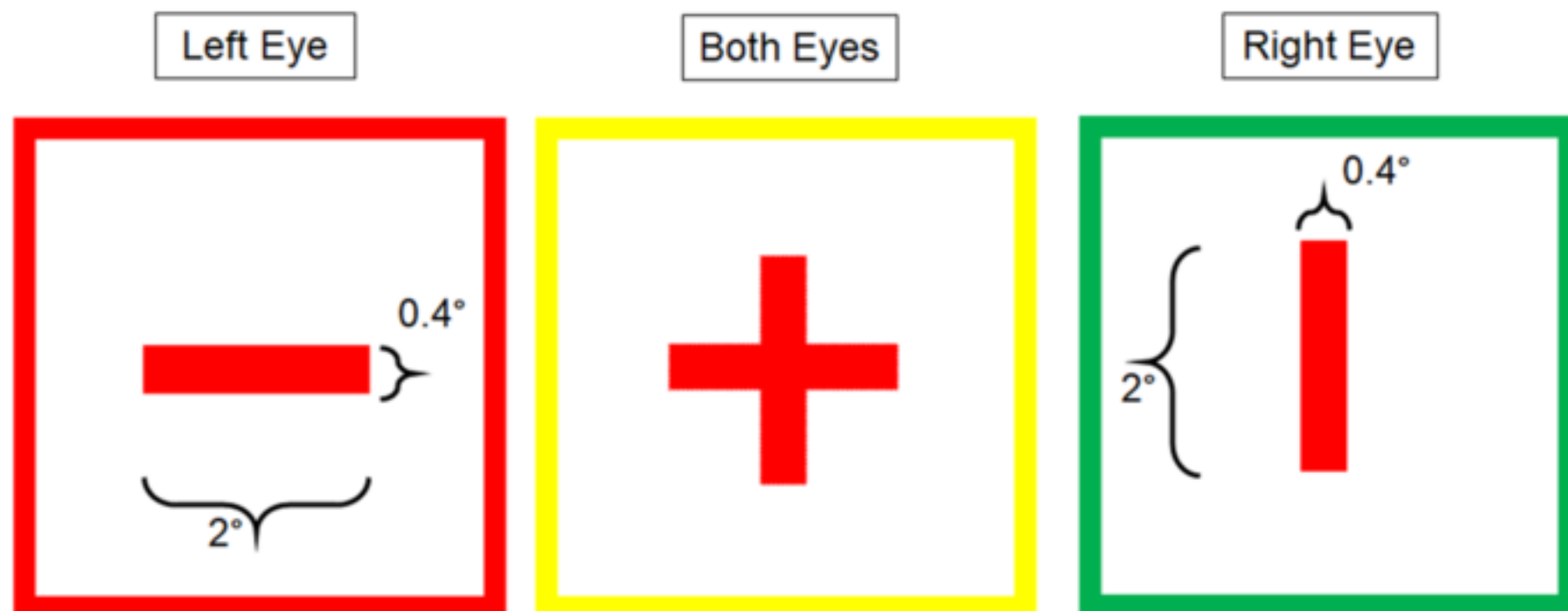


B)



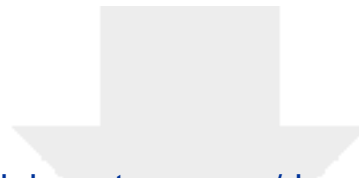
C)





	BG Luminance (R=G=B =132)		Stimulus Luminance (R = G= B = 216)	
	(in cd/ m ²)		(in cd/ m ²)	
Run	No Shutter Gl.	With Shutter Gl.	No Shutter Gl.	With Shutter Gl.
1	28.03	9.95	60.63	22.04
2	28.05	9.87	60.66	22.1
3	28.07	10.16	60.69	22.28
4	28.5	10.22	60.72	22.35
5	28.59	10.4		
6	28.4	10.2		
Avg	28.27	10.13	60.68	22.19
SD	0.25	0.19	0.04	0.15
% Transmn	35.84		36.58	
% Light Loss	64.16		63.42	

Subject	Age	Gender	Proportion Seen			Binocular ratio	
	Yrs	M/F	DE	NDE	BE	BE/DE	BE/NDE
S1	58	M	0.04	0.04	0.04	1.00	1.00
S2	86	F	0.36	0.07	0.39	1.10	5.50
S3	77	F	0.18	0.18	0.32	1.80	1.80
S4	70	F	0.61	0.71	0.54	0.88	0.75
S5	85	M	0.61	0.32	0.39	0.65	1.22
S6	84	F	0.75	0.75	0.79	1.05	1.05
S7	86	F	0.14	0.29	0.50	3.50	1.75
S8	80	F	0.61	0.32	0.57	0.94	1.78
S9	74	F	1.00	1.00	1.00	1.00	1.00
S10	84	F	0.79	0.43	0.93	1.18	2.17
S11	90	F	0.14	0.04	0.14	1.00	4.00
S12	62	M	0.21	0.14	0.61	2.83	4.25
S13	79	M	0.38	0.53	0.54	1.41	1.02
S14	79	F	0.64	0.49	0.73	1.13	1.49
S15	80	F	0.71	0.65	0.81	1.14	1.24
Average	78.31		0.48	0.40	0.55	1.37	2.00
SE	2.33		0.07	0.08	0.07	0.20	0.37



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Supplemental Coding Files

Supplementary Material_MATLABscripts.rar

