Binocular and Monocular Assessment of Eye Movements – Does Dominance Confer a Performance Advantage?

Thesis

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Abstract

Eye dominance is the preference for the use of one eye over the fellow eye when prompted to perform a given task. Eye dominance can vary depending on the task assigned to the subject. Sensory eye dominance (SED) is determined by presenting one eye with one stimulus and the fellow eye with a contradictory stimulus; the sensory dominant eye is determined to be the eye that saw the stimulus that was more strongly perceived. Motor (or sighting) eye dominance (MED) is determined by which eye is used when asked to look through a small aperture at a distant object. The eye that does so successfully is named the motor dominant eye. Given the preference for one eye over the other in certain scenarios, does this preference confer any advantages? This study aims to ascertain if these preferences result in increased performance on a variety of eye movements. Eye movements including pursuits, saccades, and fixation were measured using the RightEye System, a commercially available eye tracking system. The RightEye system also labels a "likely dominant" eye (RED), and this dominance was similarly analyzed. Subjects performed these movements under monocular conditions, with an IR pass filter over the fellow eye. Movements were also recorded under binocular conditions. Data were analyzed via paired T-test and repeated measures ANOVA. The dominant eye did not display increased ability to perform eye movements in comparison to the non-dominant eye, across the eye movements measured. This was determined by comparing the performance of the dominant eye when viewing under monocular conditions to the performance of non-dominant eye when viewing under monocular conditions. Similar comparisons were made when each eye was behind a filter (non-viewing under binocular conditions) and under binocular conditions. This was true of SED, MED, and RED. However, significant differences were found when comparing the open eye to the eye behind the filter. Viewing condition was found to have a significant impact on performance, leading to the conclusion that eye movement performance is much more likely to be impacted by the ability to view the stimulus rather than the preference for the use of one eye over the other.

Dedication

For Jen and Kirk

For Mary and Dick

For Jinny and Ron

For Mackinaw

For Nicole

-*PMM*

"…hard work, determination, and an enthusiasm unknown to mankind."

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Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

Eye Dominance

Eye dominance is the preference for the use of one eye over another. While there are many examples of how to measure this preference, Coren and Kaplan (1973)[1] demonstrate three main categories of dominance: motor or sighting dominance, sensory dominance, and acuity dominance. In healthy individuals the first of these categories often manifests in a preference for one eye when precision is required and only one eye is permitted to be used by nature of a small aperture. This dominance is commonly known by the public and is determined by asking observers to look through a small opening at a distant object.[2] The motor dominant eye is said to be the eye selected to view the target when the fellow eye is closed or unable to be used. Favoring the image perceived by one eye on sighting tasks serves to eliminate potential diplopia that would result if suppression of the non-dominant eye was unable to be accomplished. Examples of activities requiring use of the motor dominant eye include photography, shooting, monocular telescope or microscope use, billiards, etc. Motivations for this preference remain unclear and is even considered force of habit by some such as Mapp et al.[3] The strength of this innate preference is, as of yet, unresolved.

Less known to the general public is the notion of sensory eye dominance (SED). This eye dominance is the preference for one eye over the other when opposing stimuli are presented to the observer and must be reconciled into a single image. SED can be attained in two ways. One method is to vary the contrast of the stimuli to balance sensory input. This is termed the binocular rivalry balancing method[4,5] and is the method used to evaluate SED in this study. Another method to assess SED is to record the proportion of time a stimulus is perceived by one eye compared to the other. This is termed the binocular rivalry tracking method. In the former, the eye with less sensory input necessary to bring percepts into balance is the sensory dominant eye, in the latter it is the eye corresponding to the image seen for the majority of the trial. These two measures of SED have been shown to select the same eye as the sensory dominant eye.[5]

Both the lateral geniculate nucleus[6], and the primary visual cortex[7] have been shown to play a role in localization of SED within the brain. Beyond the gray matter of the brain, SED differences have been shown to correlate with differences in optic radiations and occipital corpus collosum, main highways of visual information.[8]

SED plays a role in the preference for the healthy eye over that of a fellow eye in ocular disease or in an eye that is underdeveloped. Extreme cases of SED can be seen in patients with amblyopia and vision threatening ocular disease, demonstrating preference for the percept that is of the best quality and exhibiting increased inhibition of the amblyopic eye. Patients with amblyopia have been shown to have larger SED preferences than their normally sighted counterparts.[5] Beyond patients with amblyopia, within the binocularly "normal" population patients can still demonstrate high levels of SED.[9] The goal of amblyopia treatment is to reduce this disparity and decrease the preference of one eye over the other.[10]

It has been widely demonstrated that MED is not indicative of SED.[2] Nevertheless, it is important to understand eye dominance in order to know in what aspects the dominant eye outperforms the non-dominant eye. That is, what purpose does the preference serve beyond selecting the single, highest quality image? What is the impact of a strong bias towards one eye on other abilities of the fellow eye? This study seeks to answer the question does eye dominance confer increased ability to make basic eye movements?

Eye Movements

Eye movements investigated in this study include pursuits, saccades, and fixation.

Pursuits are smooth continuous eye movements in which the target and the subject's eyes are moving at similar rates. Observers have been reported to successfully follow stimuli moving at angular velocities ranging from 30[11] to 100[12] degrees/second without significant intrusion of catch-up saccades. For sinusoidal stimuli, pursuit eye movements demonstrate reasonable gain (eye velocity/target velocity) at frequencies up to 1Hz. Catch-up saccades are defined below. Pursuits allow one to track a moving target as it moves across one's visual scene.[13] Smooth pursuit eye movements are mediated by cortex (middle temporal visual area), pons (dorsal pontine nuclei and nucleus reticularis tegmenti pontis), and cerebellum (the flocculus–paraflocculus complex and the posterior vermis).[14] Elbaum et al. has presented evidence that a cyclopean tracking of a target in smooth pursuit results in less deviation from the stimuli.[15]

Saccades refer to quick eye movements made as an observer switches fixation from one target to another. These voluntary eye movements are said to be ballistic as once they are initiated, they will not stop until complete. Saccades have a latency of 200ms, and their duration varies linearly with their amplitude; this relationship is known as the main sequence. Saccades can reach peak velocities of 500-700 degrees per second.[16] Saccades play a vital role in the ability to foveate a target that is falling on the subject's retina outside the foveal region.[13]

Saccades are controlled by a number of discrete centers in the cortex, including the parietal eye fields, frontal eye fields, and supplemental eye fields.[17] Saccadic amplitude to a target presented in the contralateral hemifield to the dominant eye was shown to be more accurate in comparison to saccadic amplitude when the target was presented to the ipsilateral hemifield.[18] In addition to amplitude, saccade trajectory tends to curve more towards distractors in the contralateral hemifield than the ipsilateral hemifield of the dominant eye.

Fixational eye movements allow the subject to continuously hold the image of a given stationary target on their fovea.[19] These eye movements consist of drift movements: slow oscillations around the target. These drift movements are interrupted 1-3 times per second by microsaccades, named such due to their smaller size (<1 degree). When viewing freely, microsaccades occur at a rate of 0.6hz[19]. The main sequence for microsaccades is somewhat similar to the main sequence of larger saccades,[20] which in turn results in saccades of average duration between 8 and 30ms[21]. While the precise role of microsaccades is unknown, fixational eye movements serve to counteract the Troxler effect, the fading of an image if held stable at a constant point on the retina. [13]

RightEye

Founded in 2012, RightEye has produced the RightEye System, a widely available eye tracking system that allows practitioners to assess eye movements quickly in a clinical setting. The Right Eye System pairs an eye tracker with a computer monitor that can track patients' eye movements as they perform different tasks. The RightEye System has modules to assess reading eye movements, basic eye movements (Dynamic Vision Assessment used in this study)[22], and concussion identification and recovery.[23]

With each completion of the Dynamic Vision Assessment the RightEye System designates a "Likely Dominant Eye" (RED) based on the results of the Fixation Stability task. The RightEye System quantifies the amount of variability in the gaze location of each eye as the subject fixates on a series of targets, including an "x," circles in a diamond configuration, and a single filled circle. Further details can be found below. The RightEye system then designates the more precise and stable eye as the RightEye "Likely Dominant Eye." Evidence of increased performance in fixation stability by the dominant eye is mixed. Serpa et al. have presented evidence in children between the ages of 7-8 of dominant eyes exhibiting better fixation stability[24], similar to the findings of Horgen and Langaas,[25] who found eye position to be more stable in the sighting dominant eye, but this advantage disappears with age[24], in line with the findings of Raveendran et al. [26]

Research Question

Given the potential role of visual cortex in both dominance and eye movements in combination with the demonstrated preference for one eye over the other, the natural question follows: "Does dominance as assessed with either SED, MED or RED confer increased ability to perform eye movement tasks?" Not only does the grey matter of cortex represent a difference in those with imbalanced eye dominance[6], but the density of the circuitry itself [8] can be imbalanced in those with imbalanced eye dominance. If an imbalance in eye dominance could be established in those experiencing eye movement difficulties, perhaps addressing the dominance imbalance[10] could lead to more successful eye movements. The first step to addressing this question lies in establishing a connection between eye dominance and eye movements. This was investigated by evaluating each subjects' ability to perform eye movements under three viewing conditions: These were: dominant eye viewing – viewing the stimulus with the dominant eye only, non-dominant eye viewing – viewing the stimulus with the non-dominant eye only, and binocular viewing, viewing the stimulus with both eyes. Given the preference innate to the subject and shared locus of influence in visual cortex, eye dominance might be related to visual cortical loci and connections that are partially responsible for eye movement control. We therefore predict that for at least one form of dominance examined, either SED, MED, or RED, the dominant eye would exhibit a performance advantage and outperform the non-dominant eye. The dominant eye might be related to cortical connections and the cortex is partially responsible for eye movement control.

Chapter 2. Materials and Methods

Subject Selection

Thirty-five (35) subjects participated in this study. Subjects were undergraduate and graduate-age adults of varying refractive and binocular vision status. The majority of subjects were recruited from an existing subject pool established during the work of Coleman (2023)[27] and Weatherford (2023).[28] A minority were recruited by word of mouth. While not the topic of this study, the overlap in subjects was intentional as part of a multi-part effort, so that in the future this subject base could be evaluated to investigate not only the relationship between eye movements and eye dominance but accommodation as well. For any subject not part of the original work of Coleman and Weatherford, data was acquired as part of this study according to their methodology in pursuit of this larger goal. No exclusion criteria were applied to subjects. Spherical refractive error ranged from +3.50D to -7.50D with a maximum of -2.25D of cylinder. Visual acuity was high across subjects ranging from -0.28 to -0.16 logMAR. Contrast sensitivity ranged from 1.5 to 2.1. Ocular alignment at distance ranged from 12pd esophoria to 16pd exophoria while near ocular alignment ranged from 30pd intermittent alternating esotropia to 20pd exophoria.

Equipment

The refractive and binocular vision status of the subjects were evaluated as part of the work of Coleman(2023)[27] and Weatherford(2023)[28] or according to their protocol using an illuminated Revised ETDRS chart, Grand Seiko WAM-5500 autorefractor, Reichert ML1 manual lensometer, RANDOT and Frisby stereopsis testing, a Wesson card, manual phoropter with Risley prism, near point/accommodative rule, +/-2.00DS flippers, and 12BO/3BI flippers. While correlations were not evaluated, these data serve to characterize the binocular vision of the subjects used in the present study. Although we did not exclude based on this finding, this allowed knowledge of subjects' binocular vision status to be available when analysis of eye movements was conducted.

MED was evaluated using a round cup with a small opening to sight through, and a computer display as a target for subjects to view as part of the work of Coleman[27] and Weatherford[28] or according to their protocol.

SED was evaluated using vertical and horizontal gratings overlaid through the use of a haploscopic mirror system as described by Han et al[4] (2018). Details are provided below in the section "Eye Dominance Evaluation". [27,28]

Subject's eye movements were evaluated using the RightEye Vision System which consists of a display for the eye movement stimuli, and an eye tracker that records the resultant movements. The RightEye Vision System utilizes a Tobii Dynavox I-15 eye tracking system. The Tobii Dynavox I-15 makes use of a 15" LED display. The RightEye System incorporates an infrared eye tracker with a sampling rate of 90Hz. Measures of gaze accuracy within this system have an error of <1.9 degrees and measures of gaze precision have and error of <0.4 degrees across 95% of the population according to Tobii.[29]

Eye Movement Evaluation

Subjects completed the Dynamic Vision assessment available on the RightEye system. The Dynamic Vision assessment requires completion of seven (7) unique tasks, circular smooth pursuit, horizontal smooth pursuit, vertical smooth pursuit, horizontal saccades, vertical saccades, fixation stability, choice reaction time, and discriminate reaction time. Each of these tasks will be described in more detail below, except choice reaction time and discriminate reaction time, as they were not analyzed in this study.

Because the dominant eye was unknown prior to evaluation, subjects performed the Dynamic Vision assessment under three viewing test conditions in random order: the right eye viewing test condition – viewing the stimulus with the right eye only, the left eye viewing test condition – viewing the stimulus with the left eye only, and the binocular viewing test condition – viewing the stimulus with both eyes. Once testing was complete and the dominant eye was known, subject data could be sorted according to whether the dominant or non-dominant eye was viewing. Therefore, data were sorted into the following categories: dominant eye viewing, non-dominant eye, and binocular viewing. This process is described in detail below in the "Analysis" section. An Optical Cast IR Longpass Filter (Edmund Optics) was used to achieve monocular viewing while simultaneously ensuring that the RightEye system could measure the subject's gaze for the eye behind the filter (that is, under the right eye viewing test condition, the left eye was covered with the IR filter so the RightEye system could "see" the subject's eye, but that eye could not see the screen).

Subjects completed the Dynamic Vision Assessment under each of the three viewing test conditions (right eye viewing/left eye viewing/binocular) to constitute one block of testing. Each subject completed four (4) total testing blocks. The order in which subjects completed the Dynamic Vision Assessment under the different viewing test conditions (right eye viewing/left eye viewing/binocular) within each block was randomized.

Results from each block were averaged by viewing test condition (right eye viewing/left eye viewing/binocular) for each subject. A five (5) minute break was given after the first block of testing, a ten (10) minute break was given after the second block of testing and an additional (5) minute break was given after the third block of testing. Each Dynamic Vision Assessment took 5-7 minutes to complete; giving breaks ensured attention to the task at hand throughout the somewhat monotonous and repetitive testing.

Each subject was required to complete RightEye's calibration module prior to beginning each Dynamic Vision Assessment under each viewing test condition (right eye viewing/left eye viewing/binocular). Prior to completing the calibration module and before each subsequent task, subjects used live guidance from the RightEye System to position themselves 56 cm from the device to ensure they were positioned optimally within the headbox of the system. Once positioned properly, subjects looked from a central target on screen to eight peripheral targets. Accurate eye tracking from the RightEye Vision System of at least 7 out of 9 targets was required to start the Dynamic Vision Assessment. If this was not achieved, calibration was repeated until adequate tracking was attained.

Included in the Dynamic Vision Assessment is the Circular Smooth Pursuit task. Subjects were instructed to track a white dot on a black background as it moved in a circle using instructions provided by RightEye. At the distance of 56cm, the target is 0.2 degrees of visual angle in diameter and traverses a circle 10 degrees of visual angle in diameter. The target moves at a rate of 0.4 Hz for 15 seconds in a clockwise fashion as summarized from Murray et al (2019).[22] A predictable target moving circularly at a frequency of 0.4Hz is expected to result in efficient smooth pursuit.

The Dynamic Vision Assessment also includes the Horizontal Smooth Pursuit task. Subjects were instructed to track a white dot on a black background as it moved back and forth sinusoidally. At the distance of 56cm the target is 0.2 degrees in diameter. The target moves at a rate of 0.4 Hz for 25 seconds as summarized from Murray et al

(2019).[22] A predictable target moving back and forth at a frequency of 0.4Hz is expected to result in efficient smooth pursuit.

The Dynamic Vision Assessment also includes the Vertical Smooth Pursuit task. This was virtually the same as the Horizontal Smooth Pursuit task with the exception that the target traversed a vertical pattern. A predictable target moving up and down at a frequency of 0.4Hz is expected to result in efficient smooth pursuit.

The Dynamic Vision Assessment also includes the Horizontal Saccades task. Subjects were instructed to look back and forth between two (2) white dots on the left and right sides of the black screen "as quickly and accurately" as they could. The dots changed from white to green when the subject's eyes were directed at the target. The test lasted for ten (10) seconds. At the distance of 56cm the target is 0.2 degrees in diameter as summarized from Murray et al (2019)[22].

The Dynamic Vision Assessment also includes the Vertical Saccades task. This was essentially the same as the Horizontal Smooth Pursuit task with the exception that the targets were separated vertically.

The Dynamic Vision Assessment also includes the Fixation Stability task. Subjects were instructed as directed by RightEye, to stare or fixate one of three black targets as they appear subsequently on a white screen for seven (7) seconds each. The fixation targets were a letter "x" comprising one (1) degree of visual angle at 56 cm from the screen, four circles making up a small diamond with three (3) degrees of visual angle separating the circles vertically and horizontally, and a solid circle comprising one (1) degree of visual angle as summarized from Hunfalvay et al (2021)[23]. See Figure 1 below for images of stimuli provided. Target order did not change, and subjects acknowledged being ready before the next stimulus was presented.

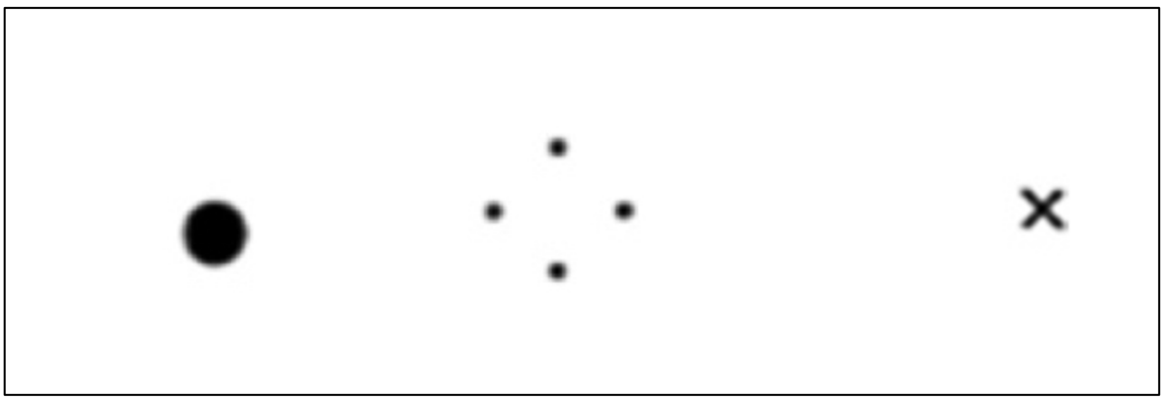

Figure 1. Fixation Stability task fixation targets as shown by Hunfalvay et al (2021)[23].

Eye Dominance Evaluation

Sensory Eye Dominance was evaluated using a binocular rivalry method of balancing dichoptic stimuli. This evaluation was analogous to the $SED_{Inhibition}$ protocol as described by Han et al (2018)[4]. Subjects were presented with two sets of gratings. One grating was oriented horizontally and one grating was oriented vertically. Outside of each set of gratings, four small circles provided binocular stimuli to fusion. Each eye saw its unique stimulus for 400 milliseconds and subjects were asked across repeated trials to choose which stimulus (horizontal or vertical) was most prominent. Once a subject identified which stimulus was more strongly perceived, the contrast of the stronger stimulus was decreased relative to the opposing stimulus. Over repeated trials the contrast in each eye was changed until the stimuli are perceived equally. The eye with the lower contrast stimulus once equality is established is the sensory dominant eye while the eye with the higher contrast stimulus is the non-sensory dominant eye.[4] The magnitude of the dominance can be measured by the magnitude of difference between the two eyes necessary to achieve equal representation of the visual stimuli. For the purposes of this study, data was examined in a binary fashion (ignoring magnitude) as most clinicians are unable to ascertain the magnitude of sensory eye dominance in office.

Motor Eye Dominance was evaluated via a sighting task was performed in which subjects held a disc with a small opening at arms length as they were asked to sight a target approximately two (2) meters away. This was consistent in principle to the Miles A-B-C test,[2] differing insignificantly in that the opening in this study was made of plastic rather than paper. Subjects' eyes were occluded one eye at a time, and they were asked which eye saw the target, giving a subjective measure of motor eye dominance. The motor dominant eye (MED) was taken to be the eye that was reported to continue seeing the target when the fellow eye was occluded. Test administrators then sighted through the opening to confirm objectively the line of sight connecting the target to the motor dominant eye. The non-motor dominant eye was the eye that was not sighting the target as determined by the above measures.

RightEye Determined Eye Dominance refers to the dominance determined by the RightEye system based on the results of the Fixation Stability task. This novel eye dominance determination made its debut in the RightEye System in 2022 and at this time, RightEye has provided no basis for this determination in published literature. A tentative link may be drawn to the works of Horgen and Langaas.[30] This study found that the standard deviation of eye position of the non-dominant eye was larger than that of the dominant eye. The motivations for this label, however, remain unclear. This "likely dominant eye" is determined by the comparing the Fixation Dispersion scores between the right and left eye. Fixation Dispersion is a measure of fixation accuracy obtained by averaging the distance between the target and the subjects gaze across the fixation stability task. The eye with the lower fixation dispersion score is determined by the RightEye to be the "likely dominant" eye (RED). The eye with the higher fixation dispersion score is determined as the RightEye non- "likely dominant" eye (NRED).

Eye Movement Metrics

Each time a task is completed within the Dynamic Vision Assessment, the RightEye Vision System generates a series of reports containing the metrics below. Metrics analyzed as part of this study were easily interpretable as presented publicly by RightEye and are described below:

Smooth Pursuit tasks were evaluated with one or more of the following:

- Efficiency (mm): The error in millimeters (mm) in the users' gaze from the ideal pathway averaged across all time points.
- Smooth Pursuit (%): eye movements that follow the target within a velocity range of the target and are reported as a percentage of the test time. Smooth Pursuit (%) refers to the percentage of time spent in smooth pursuit with an acceptable following distance (>1.2 degrees of visual angle) of the target and speed relative to the target speed (>0.25 degrees of visual angle "dispersion" or spread between consecutive data points sampled and speed <30 degrees per second). This velocity criteria is intended to help ensure that saccades are not included in the pursuit analyses. 100% means the eye was within these pre-specified ranges for the entire duration of the test.[31] A deviation from 100% indicates time spent outside of these parameters.

Saccade tasks were evaluated with:

- Saccadic Targeting (mm): Targeting accuracy refers to the distance the gaze is from the target, measured in millimeters (mm).[32]

Fixation task was evaluated with:

- Fixation Dispersion (mm): A measure of fixation accuracy obtained by averaging the distance between the target and the subject's gaze across the fixation stability task.

Analysis

For each of these metrics produced by the RightEye system, eye movement results were compared based on whether the dominant eye or the nondominant eye was viewing. This sorting process had to be done three times, to account for the fact that three different measures of dominance were used (SED, MED, and RED). The sorting process is represented in Figure 2 below. For example, when analyzing Sensory Eye Dominance (SED), if a subject was right eye dominant, the right eye viewing test condition was sorted to be the dominant eye viewing condition (a) while the left eye viewing test condition was sorted to be the non-dominant viewing condition (b). The binocular viewing test condition (c) consisted of both eyes unfiltered. The opposite sorting occurred if a subject was left eye dominant, the left eye viewing test condition was sorted to be the dominant eye viewing condition (1) and the right eye viewing test condition was sorted to be non-dominant eye viewing condition (2).

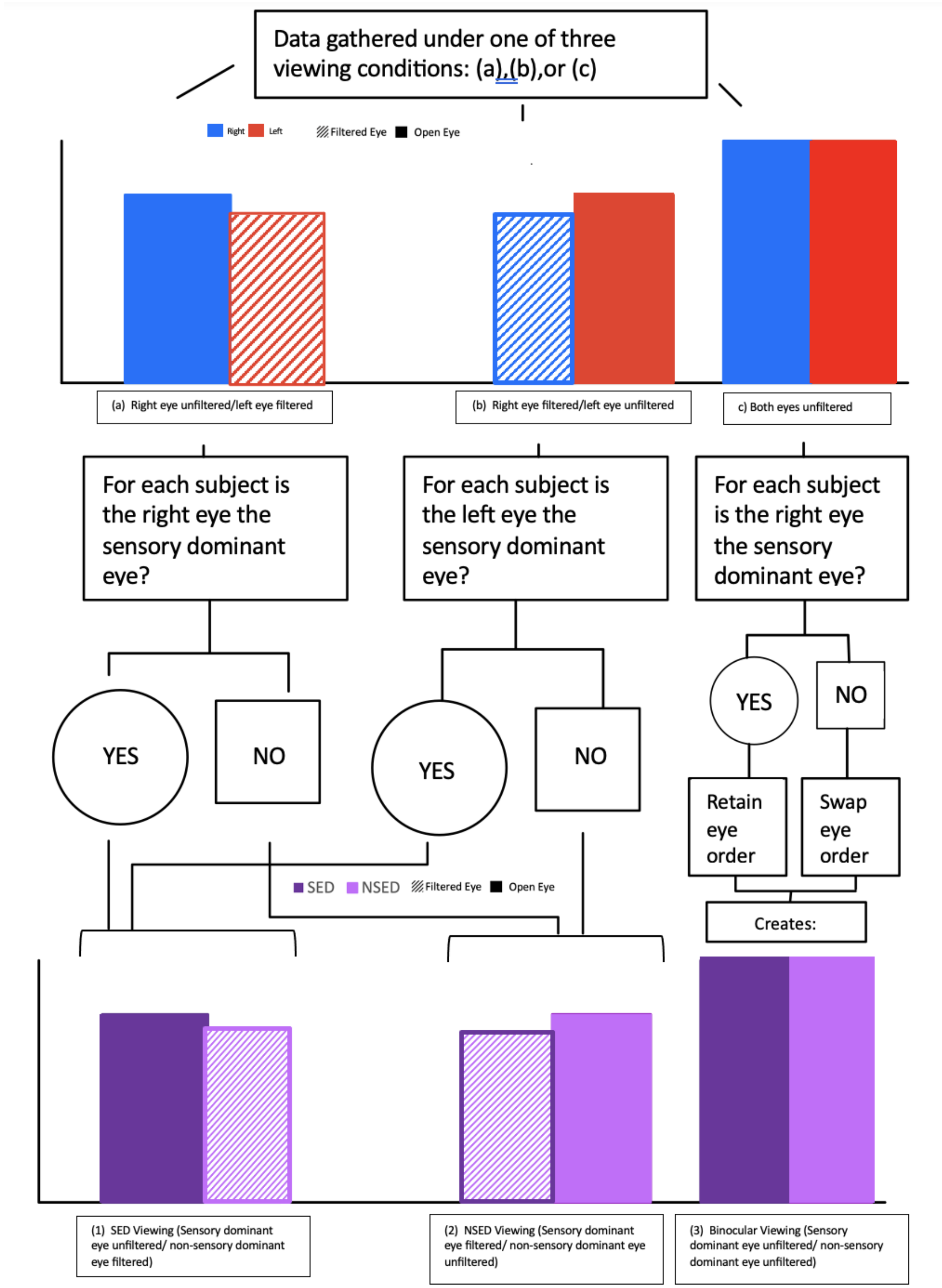

Figure 2. Example of sorting data by Sensory Eye Dominance from viewing test conditions (right eye viewing/left eye viewing/binocular) to sorted dominance viewing conditions.

Once sorting was completed, the following analyses were carried out. First, for each eye dominance measured (SED, MED and RED), a paired t-test was used to compare the direct response of the dominant eye when viewing the stimulus (the average performance of the dominant eye when it was the sole eye viewing the stimulus) and the direct response of the non-dominant eye (the average performance of the non-dominant eye when it was the sole eye viewing the stimulus). This would be used to evaluate if the dominant eye outperformed the non-dominant eye.

Second, for each eye dominance measured (SED, MED and RED), paired t-tests were used to compare the consensual response of the dominant eye when viewing the stimulus (the average performance of the dominant eye when it was the eye behind the filter and therefore not viewing the stimulus) and the consensual response of the non-dominant eye (the average performance of the non-dominant eye when it was the eye behind the filter and therefore not viewing the stimulus). It might be expected that the non-dominant eye would show worse performance when behind the filter compared to the case where the dominant eye was behind the filter.

Third, for each eye dominance measured (SED, MED and RED), paired t-tests were used to compare the dominant eye mean performance and the non-dominant eye mean performance when the dominant eye was open (that is, not behind the filter) and the non-dominant eye was behind the filter.

Fourth, for each dominance measure (SED, MED and RED), paired t-tests were used to compare the mean performance of the dominant eye and the mean performance of the non-dominant eye when the dominant eye was behind the filter and the non-dominant was open (that is when the non-dominant eye was not behind the filter).

Fifth, for each dominance measure (SED, MED and RED), paired t-tests were used to compare the mean performance of the dominant eye and the mean performance of the non-dominant eye under the binocular viewing condition.

For all comparisons described above, paired t-tests were used except in cases where the Shapiro-Wilk test of normality indicated non-normality. In these latter cases, the Wilcoxon Signed Rank Test was used in the statistical comparisons.

Additional analysis was performed via repeated measures ANOVA to examine the effect of the dominance measurement (SED, MED, RED) on performance. Bonferroni correction for multiple comparisons was applied. Dominance (coded in various ways as shown in Table 2) was treated as a between subjects' variable and dominance measurement was a within subjects' variable. Examples of SPSS outputs for the MED analysis of the Efficiency metric for the Circular Smooth Pursuit task can be found in Figure 3 below.

Multivariate Tests Pairwise Comparisons Circular Smooth Pursuit – Efficiency – MED[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[c]
ViewingCondition	Pillai's Trace	.395	21.895[b]	2.000	67.000	<.001	.395	43.789	1.000
	Wilks' Lambda	.605	21.895[b]	2.000	67.000	<.001	.395	43.789	1.000
	Hotelling's Trace	.654	21.895[b]	2.000	67.000	<.001	.395	43.789	1.000
	Roy's Largest Root	.654	21.895[b]	2.000	67.000	<.001	.395	43.789	1.000
ViewingCondition * dominant0nondominant1	Pillai's Trace	.381	20.582[b]	2.000	67.000	<.001	.381	41.164	1.000
	Wilks' Lambda	.619	20.582[b]	2.000	67.000	<.001	.381	41.164	1.000
	Hotelling's Trace	.614	20.582[b]	2.000	67.000	<.001	.381	41.164	1.000
	Roy's Largest Root	.614	20.582[b]	2.000	67.000	<.001	.381	41.164	1.000

a. Design: Intercept + dominant0nondominant1
Within Subjects Design: ViewingCondition

b. Exact statistic

c. Computed using alpha = .05

A

Pairwise Comparisons Circular Smooth Pursuit – Efficiency – MED

Measure: Efficiency

(I) ViewingCondition	(J) ViewingCondition	Mean Difference (I–J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	–.064	.468	1.000	–1.214	1.086
	3	1.945*	.365	<.001	1.050	2.840
2	1	.064	.468	1.000	–1.086	1.214
	3	2.009*	.396	<.001	1.038	2.981
3	1	–1.945*	.365	<.001	–2.840	–1.050
	2	–2.009*	.396	<.001	–2.981	–1.038

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

B Figure 3 Part A: Multivariate Tests Pairwise Comparisons Circular Smooth Pursuit - Efficiency - MED; Part B: Pairwise Comparisons Circular Smooth Pursuit - Efficiency – MED

Analysis was completed in parallel for each dominance SED, MED, RED.

Chapter 3. Results

The results for all the paired t-tests are summarized in Table 1 below, and the results for the repeated measures ANOVA analyses are shown in Table 2. Representative results are shown graphically in Figures 4 and 5.

Paired T-Test 2 Tailed P-Values						
Eye Movement - Metric	Dominance	Direct v Direct	Consensual vs Consensual	Dominant vs Non-Dominant: Sorted Dominant Eye Viewing	Dominant vs Non-Dominant: Sorted Non-Dominant Eye Viewing	Dominant vs Non-Dominant: Sorted Binocular Viewing
Circular SP - Efficiency (mm)	SED	0.245	0.771	<0.001	<0.001	0.049*
	MED	0.252*	0.856	<0.001	0.002*	0.389
	RED	0.990	0.068	<0.001	<0.001	0.787*
Circular SP - Smooth Pursuit %	SED	0.375	0 .987*	0.086	0.581*	0.871
	MED	0.492	0.187	0.860	0.029	0.269
	RED	0.757	0.229	0.856	0.068	0.110
Horizontal SP - Smooth Pursuit %	SED	0.935*	0.762*	0.002*	0.011*	0.032*
	MED	0.935*	0.207*	0.032*	<0.001*	0.793*
	RED	0.287*	0.676*	0.012*	0.002*	0.743*
Vertical SP - Smooth Pursuit %	SED	0.857*	0.566*	0.007*	0.014*	0.713*
	MED	0.342*	0.647*	0.009*	0.013*	0.752*
	RED	0.566*	0.600*	0.015*	0.008*	0.235*
Horizontal Saccades - Saccadic Targeting (mm)	SED	0.310	0.245*	0.003*	0.044*	0.036*
	MED	0.944	0.694*	0.040*	0.002*	0.287
	RED	0.716	0.682*	0.012*	0.006*	0.295*
Vertical Saccades - Saccadic Targeting (mm)	SED	0.078*	0.730*	<0.001*	<0.001*	0.098
	MED	0.133*	0.977*	<0.001*	<0.001*	0.055
	RED	0.372*	0.028*	<0.001*	<0.001*	0.413
Fixation Stability - Fixation Dispersion	SED	0.319	0.417*	<0.001*	<0.001	0.743*
	MED	0.857*	0.207*	<0.001*	<0.001*	0.909*
	RED	0.005	0.023*	<0.001*	0.005	<0.001
	* Denotes where one or more conditions did not satisfy Shapiro-Wilk test of normality and as such Wilcoxon Signed Rank Test was used to evaluate given relationship.					
	Denotes significance at 0.05 level					

Table 1. P-Values of 2-Tailed Paired T-Tests

Repeated Measures ANOVA P-Values	Column 1	Column 2	Column 3	Column 4	Column 5
Eye Movement - Metric	Dominance Measurement	Effect of Sorted Dominance Viewing Condition (dominant eye viewing, nondominant eye viewing, binocular)	Sorted Dominant Viewing vs Sorted Non-Dominant Viewing	Sorted Dominant Viewing vs Sorted Binocular Viewing	Sorted Non-Dominant Viewing vs Sorted Binocular Viewing
Circular SP - Efficiency (mm)	SED	<0.001	1.000	<0.001	<0.001
	MED	<0.001	1.000	<0.001	<0.001
	RED	<0.001	1.000	<0.001	0.003
Circular SP - Smooth Pursuit %	SED	0.002	1.000	0.004	0.001
	MED	<0.001	1.000	0.004	0.001
	RED	0.002	1.000	<0.001	0.003
Horizontal SP - Smooth Pursuit %	SED	<0.001	1.000	0.003	0.002
	MED	<0.001	1.000	0.005	0.001
	RED	0.001	1.000	<0.001	0.009
Vertical SP - Smooth Pursuit %	SED	0.006	1.000	0.008	0.038
	MED	0.006	1.000	0.081	0.002
	RED	0.005	1.000	0.014	0.024
Horizontal Saccades - Saccadic Targeting (mm)	SED	<0.001	1.000	<0.001	<0.001
	MED	<0.001	1.000	0.001	<0.001
	RED	<0.001	1.000	<0.001	<0.001
Vertical Saccades - Saccadic Targeting (mm)	SED	<0.001	1.000	<0.001	<0.001
	MED	<0.001	1.000	<0.001	<0.001
	RED	<0.001	1.000	<0.001	<0.001
Fixation Stability - Fixation Dispersion	SED	<0.001	1.000	<0.001	<0.001
	MED	<0.001	1.000	<0.001	<0.001
	RED	<0.001	1.000	<0.001	<0.001
	Denotes significance at 0.05 level				

Table 2. Repeated measures ANOVA P-Values

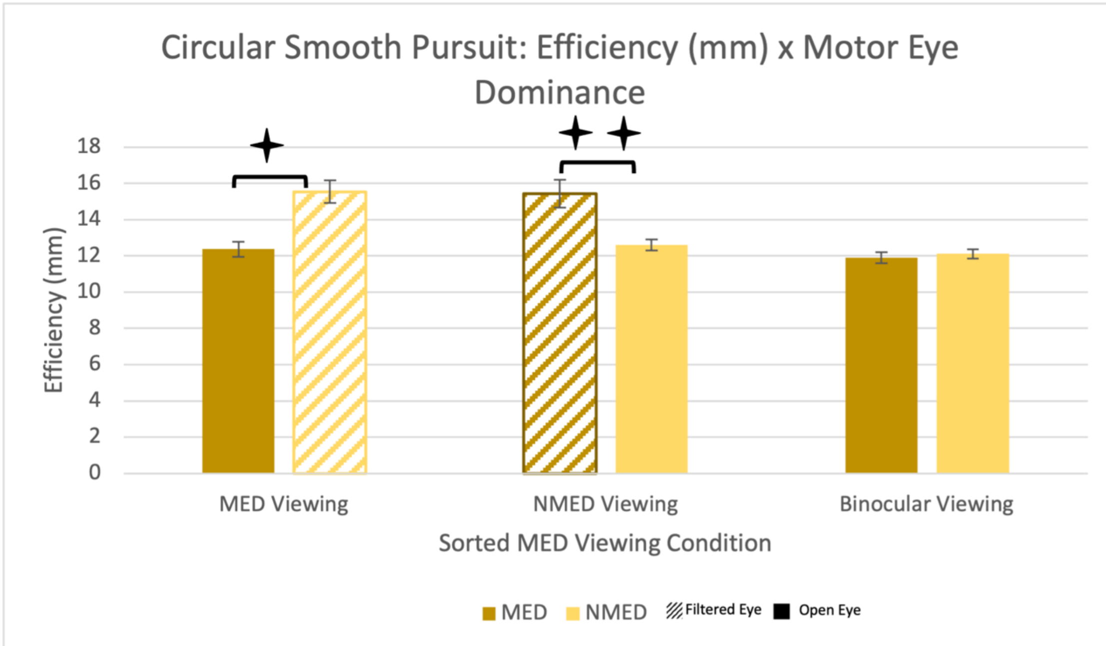

Figure 4. Sorted Motor Eye Dominant Efficiency data with significance denoted by stars and brackets.

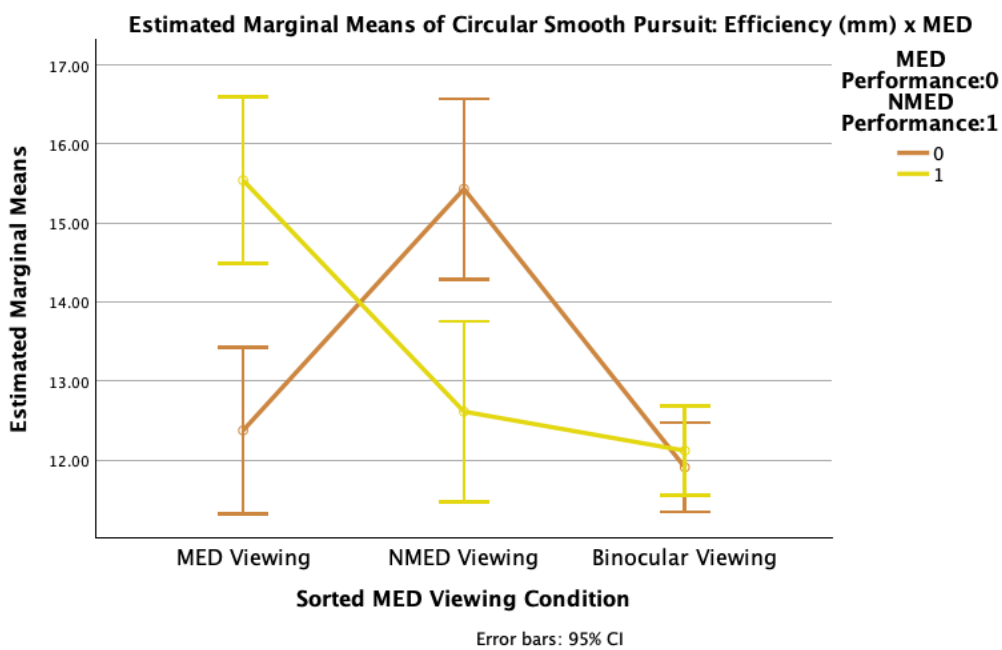

Figure 5. Estimated Marginal Means of Circular Smooth Pursuit: Efficiency. Viewing condition sorted by MED.

Circular Smooth Pursuit Task - Efficiency (mm)

During the Circular Smooth Pursuit task Efficiency was measured and recorded. Efficiency is the average distance within a trial from the subject's gaze to the target in millimeters. A lower value indicates better performance. The statistical analyses in Table 1 indicate a lack of significance when comparing direct response to direct response, and when comparing consensual response to consensual response. These data do demonstrate that the open eye consistently displayed significantly smaller and therefore better eye movement efficiency than the filtered eye. It did not matter if the dominant eye or the non-dominant eye was open (that is, the results were the same regardless of whether the dominant or non-dominant eye was unfiltered). When considering the differences within the binocular viewing condition only the SED analysis shows the dominant eye significantly outperforming the non-dominant eye.

The statistical analyses in Table 2 show a significant effect of sorted dominance viewing condition (dominant eye viewing, nondominant eye viewing, binocular viewing) on Circular Smooth Pursuit - Efficiency performance. The sorted binocular viewing condition was significantly different from both the sorted dominant eye viewing condition and the sorted non-dominant eye viewing condition. Performance with binocular viewing was significantly better for the binocular viewing condition compared to both the dominant eye viewing and nondominant eye viewing conditions, while performance was similar between the dominant and non-dominant eye viewing conditions. This suggests that overall, the significant difference between the three primary viewing conditions (dominant eye viewing, nondominant eye viewing, binocular viewing) as shown in Column 2 of Table 2 can be attributed to the better performance in the binocular viewing condition compared to the other viewing conditions. These differences and similarities can be seen visually in Figure 5, a representative plot of the similar data across analyses, by comparing the spread of data across the corresponding viewing conditions on the x-axis. The sorted binocular viewing condition was significantly different from both the sorted dominant eye viewing condition and the sorted non-dominant eye viewing condition in all comparisons.

Circular Smooth Pursuit Task - Smooth Pursuit (%)

During the Circular Smooth Pursuit task, the Smooth Pursuit (%) is recorded. This represents the amount of time within the test in which the subjects' ocular pursuit velocity was <30 degrees per second and gaze was located within 1.2 degrees of the moving target. The velocity criterion helped to ensure that the percentage of time spent making other eye movements such as catch-up saccades was excluded from the total. A larger Smooth Pursuit % value indicates better performance. The statistical analyses in Table 1 indicate a lack of significance across comparisons between sorted dominance viewing conditions. The dominant direct response was not significantly different from the non-dominant direct response performance. The dominant consensual response was not significantly different from the non-dominant consensual response performance. This was in large part also true when comparing sorted dominant performance to sorted non-dominant performance. The only exception was that the NMED eye significantly outperformed the MED eye when the NMED was viewing (MED under the filter).

The statistical analyses in Table 2 show a significant effect of the sorted dominance viewing condition on Circular Smooth Pursuit Smooth Pursuit % performance as seen in Column 2 (Effect of Sorted Dominance Viewing Condition). As before, the source of these differences was determined to be due to the sorted viewing condition of binocular viewing.

Horizontal Smooth Pursuits - Smooth Pursuit (%)

During the Horizontal Smooth Pursuit task, the Smooth Pursuit (%) is recorded. This represents the amount of time within the test in which the subjects' eyes were moving <30 degrees per second and were located within 1.2 degrees of the moving target. A larger value indicates better performance. The statistical analyses in Table 1 indicate a lack of significance when comparing direct response to direct response, and when comparing consensual response to consensual response when sorting data by dominance viewing conditions, amongst all dominances. These data do show however that comparing dominant performance to non-dominant performance, the open eye consistently displayed significantly larger (better) Smooth Pursuit % than the filtered eye. It did not matter if the dominant eye or the non-dominant eye was open. When considering the differences within the binocular viewing condition only the SED analysis shows the dominant eye significantly outperforming the non-dominant eye.

The statistical analyses in Table 2 show a significant effect of sorted dominance viewing condition (dominant eye viewing, non-dominant eye viewing, binocular viewing) on Horizontal Smooth Pursuit Smooth Pursuit % performance as seen in the Column 2 (Effect of Sorted Dominance Viewing Condition). As before, the source of this difference is most likely due to better performance in the binocular viewing condition.

Vertical Smooth Pursuits - Smooth Pursuit (%)

During the Vertical Smooth Pursuit task, Smooth Pursuit (%) is recorded. This represents the amount of time within the test in which the subjects' eyes were moving <30 degrees per second and were located within 1.2 degrees of the moving target. A larger value indicates better performance. The statistical analyses in Table 1 indicate a lack of significance when comparing direct response to direct response, and when comparing consensual response to consensual response. These data do show however that the open eye consistently displayed significantly larger (better) Smooth Pursuit % than the filtered eye. It did not matter if the dominant eye or the non-dominant eye was open. There were no significant differences between eyes within the sorted binocular viewing condition.

The statistical analyses in Table 2 show a significant effect of sorted dominance viewing condition on Vertical Smooth Pursuit Smooth Pursuit % performance as seen in Column 2 (Effect of Sorted Dominance Viewing Condition). Once again, this can likely be attributed to better performance in the binocular viewing condition.

Horizontal Saccades - Saccadic Targeting (mm)

During the Horizontal Saccades task, the Saccadic Targeting performance is recorded. This represents the average difference in position (mm) between where the subject's eye lands and the ideal target. A smaller value indicates better performance. The statistical analyses in Table 1 indicate a lack of significance when comparing direct response to direct response, and when comparing consensual response to consensual response. These data do show however that comparing dominant performance to non-dominant performance, the open eye consistently displayed significantly smaller (better) saccadic targeting (mm) values. It did not matter if the dominant eye or the non-dominant eye was open. When considering the differences within the binocular viewing condition only the SED analysis shows the dominant eye significantly outperforming the non-dominant eye.

The statistical analyses in Table 2 show a significant effect of sorted dominance (dominant eye viewing, nondominant eye viewing, binocular viewing) viewing condition on Horizontal Saccades – Saccadic Targeting performance. Once again, this can likely be attributed to better performance in the binocular viewing condition.

Vertical Saccades - Saccadic Targeting (mm)

During the vertical saccades task, the Saccadic Targeting performance is recorded. This represents the average difference in position in mm between where the subject's eye lands and the ideal target. A smaller value indicates better performance. The statistical analyses in Table 1 indicate a lack of significance when comparing direct response to direct response, and when comparing consensual response to consensual response. These data do show however that comparing dominant performance to non-dominant performance, the open eye consistently displayed significantly smaller (better) saccadic targeting (mm) values than the filtered eye. It did not matter if the sorted dominant eye or the sorted non-dominant eye was open. There were no significant differences between eyes when looking at comparisons involving the binocular viewing condition.

The statistical analyses in Table 2 shows a significant effect for Vertical Saccades – Saccadic Targeting performance in that the binocular viewing condition was significantly different from both the dominant eye centered viewing condition and the non-dominant eye centered viewing condition.

Fixation Stability - Fixation Dispersion

During the Fixation Stability task, the fixation dispersion performance of each eye is recorded. This represents the average difference in position in mm between where the subject's eye lands and the ideal target. A smaller value indicates better performance.

The statistical analyses in Table 1 indicate a lack of significance when comparing direct response to direct response, and when comparing consensual response to consensual response for the SED and MED measurement methods. These data do show however that comparing dominant performance to non-dominant performance, the open eye consistently displayed significantly smaller (better) fixation dispersion values than the filtered eye. It did not matter if the sorted dominant eye or the sorted non-dominant eye was open. When considering RED after sorting, the direct response of the RED eye outperformed the direct response of the NRED eye, completing the task with less fixation dispersion. When comparing the consensual responses, RED performed worse than the NRED when both were measured behind the filter. These data do show however that comparing sorted dominant eye performance to sorted non-dominant eye performance, the open eye consistently displayed significantly smaller (better) fixation values than the filtered eye across all sorted viewing conditions. It did not matter if the sorted dominant eye or the sorted non-dominant eye was open.

The statistical analysis in Table 2 show that the binocular viewing condition was significantly different from both the dominant viewing condition and the non-dominant viewing condition.

Chapter 4. Discussion

Summary of Findings

Despite the potentially shared neural origin of SED and eye movements these results fail to show that eye dominance confers an advantage in performing eye movements as assessed with the RightEye System. We hypothesized that one form of dominance examined, either SED, MED, or RED, would be linked, through a difference in structure (gray matter in visual cortex and white matter) to a performance advantage over the non-dominant eye. For each of the dominance measurement methods examined above, comparing the direct response of the sorted dominant eye vs sorted non-dominant eye did not yield significant results, nor did comparing consensual (filtered) responses under sorted dominance viewing conditions. Significant differences were seen between eyes when one eye was filtered. Importantly, it did not matter which eye (dominant or nondominant) was filtered. When the sorted non-dominant eye was filtered, the sorted dominant eye performed better. Importantly, the opposite was also true, when the sorted dominant eye was filtered, the sorted non-dominant eye performed better. Repeated measures ANOVA analysis shows that sorted dominance viewing condition significantly impacts the relative eye movement performances, with the sorted binocular conditions outperforming the monocular conditions.

These results suggest that when it comes to performance as evaluated using the RightEye System, dominance does not have an impact on performance. However binocular viewing does have an important advantage over monocular viewing. When sensory input is deprived from one eye, the open eye performs better on eye movement tasks. This is true regardless of the preference/dominance for one eye or the other in binocular conditions.

These findings are consistent with those of Raveendran et al[26] and Gonzales et al[33] both having found that binocular viewing conveyed stability in fixation stability as compared to an occluded eye condition. Gonzales et al[33] in particular, also found that the open eye outperforms the occluded eye, consistent with this study. This indicates that any advantage intrinsic to the dominant eye (and therefore driving preference to it) is not large enough to overcome the advantage of receiving binocular sensory input with no occlusion or filtering.

Furthermore, during the binocular condition the dominant eye did not outperform the nondominant eye, in contrary to the findings of Horgen and Langaas.[25] Our study however was performed in adults compared to children and this may account for difference in results as at a younger age. Asymmetric development of inhibitory pathways may temporarily result in performance gains of the dominant eye that may diminish through development with equalization of inhibition in normal adult populations.

It is worth discussing that there was a significant difference between monocular conditions for RightEye determined dominance for the Fixation Dispersion metric. This, however, is unsurprising as it is the metric RightEye uses to assign this dominance. This “likely” dominance does not show much other efficacy as neither SED nor MED showed this difference. This is unsurprising as the significance of RED in this case may not have been derived from some advantage given by eye dominance, but by the fact that the RightEye Fixation Dispersion metric was used to measure fixation accuracy and ascertain the dominant eye. Therefore, perhaps no difference in performance would be expected in other dominance measurements such as SED or MED compared to the performance differences found with the RED.

Limitations

Given the RightEye System’s proliferation into the world of eye movement assessment, the potential impact on clinical practice from a study of this design was large. However, embracing the ease of clinical assessment is not without consequences as the instrument itself may have led to an inability to detect differences in eye movement performance between dominant and non-dominant eyes. Specifically, the temporal resolution of the RightEye System is 90 Hz, meaning it would be able to confidently identify eye movements of duration up to 22 milliseconds (double the sample rate). Given the duration of microsaccades, it is possible that the RightEye system could miss some microsaccades. This might limit the validity of the smooth pursuit % and fixation dispersion measurements and RightEye’s own RED dominance determination.

In addition, the RightEye System relies solely on a single calibration before the Dynamic Vision Assessment. In each subsequent task there is a voluntary check to ensure that the subject is the correct distance away from the eye tracker. Correct positioning, however, is not required to begin the next task. Nor was positioning monitored in a way that subjects could receive feedback if they were moving out of position. Proper localization in space is important for accurate data collection throughout the assigned tasks.

A common practice in eye movement studies is to immobilize the patients head, either with a chin and forehead rest or more strictly with a bite bar eliminating head movement from confounding eye movements. Without this steadying of the head, it is possible for eye movements to be under or overestimated.

The metrics selected from the RightEye Systems report are those whose meaning and explanation are easily interpretable from publicly available, published descriptions. While clinically relevant to those who own a RightEye System, these selections are still subject to the calculations and interpretations of RightEye. The raw data is packaged into a neat handout following completion of the Dynamic Vision Assessment. This presents a concerning unknown regarding the data packaging and could mean that a given metric may not be what is expected by an operator.

One dominance that was not considered in this exam is the so-called sensory eye dominance as it is determined clinically with lenses for use in multi-focal contact lens fits. The contact lens protocol is different than that used to determine SED in this study.

Another limitation of this study is the use of IR filter. The filter's use allowed capture of data of the consensual eye when the direct eye was viewing the stimulus. This was necessary to accomplish the goals of this project. The RightEye System wouldn't allow for capture of position of one eye if the other pupil was occluded. This presents several concerns. First, the IR pass filter does allow for IR light to penetrate through it and thereby allows the RightEye System to see the eye. However, it works best when the filter is perpendicular to the source of IR radiation and other than registering detection of both eyes prior to beginning a given task, there was no guarantee to the quality of the data recorded of the covered eye.

Another concern about the use of the IR filter was how much sensory input the filtered eye received. While the filter did block most visible light, there were some tasks, particularly those with white backgrounds for which it was possible to make some of the display out through the filter. It is possible that completely denying the fellow eye of any stimulation would result in a more discernable difference between dominant and non-dominant eyes.

Finally, it is possible that differences in eye movement performance may be more pronounced in subjects with amblyopia or ocular disease. Our study did not include such subjects. Though not specifically excluded, this gap in our subject pool was at least partially due to ease of recruitment of young adults in and around a large university. Amblyopes or those with advanced ocular disease for whom dominance may be more pronounced, may manifest a larger and more easily detected difference in eye movement performance that would be clinically relevant and measurable.

Chapter 5. Conclusion

The RightEye System demonstrates no difference in eye movement performance when eyes are compared according to sensory eye dominance, motor eye dominance or RightEye determined "likely dominant" eye dominance. Eye movement performance is much more likely to be impacted by the availability of (binocular) sensory stimuli.

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