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**EYE MOVEMENT CONTROL: AN INDEX FOR ATHLETICISM**

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science at  
Virginia Commonwealth University

By

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## **ABBREVIATIONS/ ACRONYMS**

EM: Electromagnetic

LED: Light-emitting diode

GV: Gaze Vector

POG: Point of Gaze

POI: Point of Intersection (gaze with target plane)

RMS: Root mean square

SPI: Sports Performance Index

VOR: Vestibulo-ocular Reflex

VORc: Vestibular-ocular Reflex suppression/cancellation

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## ABSTRACT

### EYE MOVEMENT CONTROL: AN INDEX FOR ATHLETICISM

By Brittany L. O'Shea, M.S.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

Virginia Commonwealth University, 2017

Major Director: Peter E. Pidcoe, PT, DPT, Ph.D., Professor, Department of Physical Therapy

Athletic potential is one of the most complex human traits. An elite athlete is produced from a complex interaction of an innumerable number of traits exhibited by the athlete. However, it's not clear whether these traits are innate, allowing the athlete to excel, or, alternatively, are a consequence of practice. To be successful, athletes rely heavily on sensory information from the visual and vestibular systems. This study investigated the relationship eye movement control has with innate athleticism by comparing the saccadic and VOR responses of former, no longer practicing, elite athletes against their age and gender matched counterparts who were non-elite or non-athletes. Results showed subjects who participated in athletic activities longer (regardless of type or level achieved), showed both significantly better VOR suppression capabilities, as well as higher head velocities while suppressing their VOR. Although, these results are correlative in nature, they do not support the potential that VOR suppression is a learned trait of athletes. A longitudinal study would be required to assess this relationship fully.

## INTRODUCTION

Athletic potential is one of the most complex human qualities. An elite athlete is produced from an interaction of an innumerable number of traits exhibited by the athlete. However, it's not clear how an athlete comes to exhibit these traits. Although there has been considerable research in the area of roles played by both genetic factors and training in elite sporting performance, the age-old debate of nature vs nurture in sports science is still very much a research topic of interest. The effect of talent vs practice is unknown in the molding of a simply talented athlete into an elite athlete. Tucker and Collins (2012) concluded that individual performance thresholds are determined by an athlete's genetic makeup and that training is just the process by which genetic potential is released. In their study, they aimed to identify specific contributions made by deliberate practice and genetic factors in the development of elite athletes by looking at phenotype traits such as sex, height, skeletal muscle composition and VO<sub>2</sub> max (Tucker & Collins, 2012). Like others in this field, they determined which genetic characteristics tend to produce elite athletes. Research has been conducted as far as to look at specific genes and DNA components. However, little research in this field examines the sensorimotor traits of elite athletes.

Every sport has unique physical requirements that may drastically vary from sport to sport; however, there are key systems that all athletes, although some more than others, rely on, such as sensorimotor and cognitive characteristics, as they are important in physical motor control and efficiency of movements. These traits are not as characterized as some of the common factors analyzed in this field, nor do they stand out as critical factors of athleticism. However, cognitive and sensorimotor are critical systems of the human body; thus, could give insight into a person's attainable athletic potential, or athleticism.

## **Athleticism**

Athleticism is the term used to describe the qualities characteristic of athletes- i.e. strength, fitness, agility, coordination, etc. It is an umbrella term used to describe a person's potential for athletic success. A variety of factors have been proven to affect athletic performance. Starting at a biological level numerous pathways and biochemical systems function and optimally interact to enable athletes to perform at a high level (Tucker & Collins, 2012). However, each sport/athletic exercise may recruit different biological and physiological systems, calling for different mental and physical demands. Specific biological characteristics which are optimal can vary by sport. For example, endurance athletes require greater lung capacity and muscles resilient to fatigue whereas those characteristics would be detrimental for athletes requiring short, strong bursts of power and muscle force production. However, there are a few systems which are critical for any athletic skill, thus are important for all athletes- the sensorimotor system, and psychological tendencies. Such variables will be described in detail in later sections.

First it is necessary to explain the definitions of an elite athlete and a non-elite, or low-level, athlete. Although there is no clearly defined formula for distinguishing an elite athlete, traditionally an elite athlete is one that excels to the collegiate or professional level. Many variables have been used to define high level (elite) athletes such as anthropometric data and physiologic data, talent development and maturation, and physical performance (Lorenz, Reiman, Lehecka, & Naylor, 2013)). Furthermore, classification of elite athletes in the sporting world allow for varying degrees of elite athletes with sport specific definitions. For example, a high-level gymnast is considered to be one that competes at the top levels of the sport (max level 10). While collegiate gymnastics exists, it is considered to be a different category, as gymnasts at

levels 8-10 usually have the skill set to complete at the collegiate level; thus, high-level gymnasts are considered to be those at higher competitive gymnastic levels as well as collegiate gymnasts. Alternatively, compare gymnastics to other sports such as soccer, baseball and basketball where the high school or travel team level is recognized to be drastically below that of the collegiate or professional level of play.

Although the definitions of elite athletes may vary by sport, common questions still revolve around the makeup of an elite athlete- What performance characteristics are most predictive of athletic success? Are elite athletes of superior genetic makeup with an innate set of superior skills? Is training enough to make up for these genetic differences? At this point, no single characteristic has been defined as the main predictor of performance.

The nature vs nurture debate dates back to the 1800s. Sir Francis Galton philosophized the mental capabilities are limited by hereditary factors (Tucker & Collins, 2012). The Galtonian model proposes that practice and training leads to performance improvements, but caps at a ceiling, determined by genetic or innate factors, that exist for each person. Common acceptance in the sports science world is that elite performance is the result of both training and genetic factors (Tucker & Collins, 2012). However, whether athletes are born or made is still of considerable interest in exercise sciences as it has implications in talent identification and management, as well as general scientific knowledge of gaining insight into the complex workings of the human body.

### **Sensorimotor Control**

It is nearly impossible to perform well in athletics without sufficient sensorimotor control. Therefore, it is important to understand the inputs to the sensorimotor system before discussing their possible involvement in determining athletic potential. During motor control

activities, the proprioceptive, visual and vestibular systems provide vital inputs of sensory information (Riemann & Reppert, 2002; Bressel, Yonker, Kras, & Heath, 2007). While an athletic skill is being performed, the sensorimotor system relies on feedback from these input systems to be able to execute coordinated neuromuscular movements in response (Hedge, 2010). Figure 1 below gives a basic depiction of how the information from the proprioceptive, visual and vestibular systems is combined and interpreted by the central nervous system (CNS).

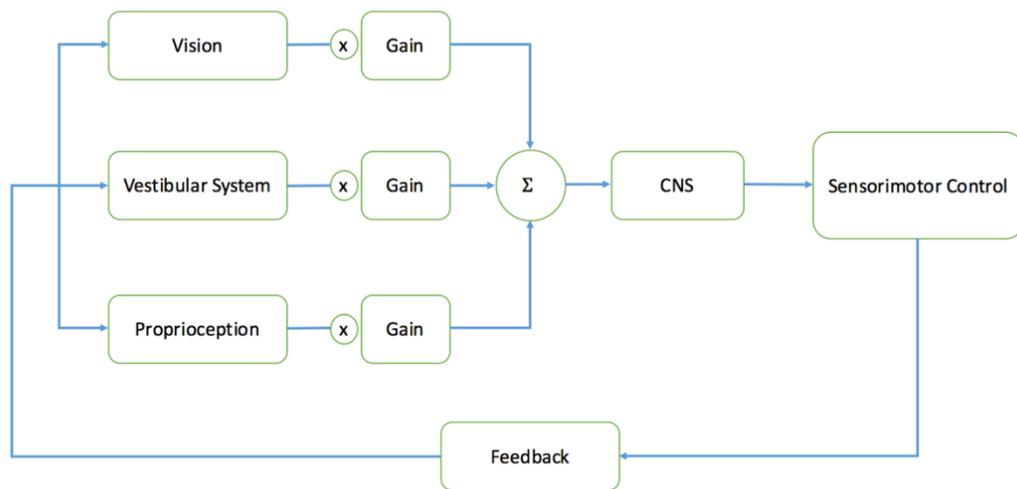


Figure 1. Sensorimotor Input Integration Overview

In athletic situations, the sensorimotor system is dynamic- constantly receiving feedback and adjusting its output as needed. Responses to these dynamic changes can be reflexive, while other responses require cognitive control (Hedge, 2010). Regardless, the sensorimotor system relies on rapid feedback from the visual, vestibular and proprioceptive systems to be able to execute rapid coordinated neuromuscular movements in response (Hrysomallis, 2011). In relation to athletics, different sports require different levels of sensorimotor processes to perform skills and protect the neuromuscular system from injury (Bressel, Yonker, Kras, & Heath, 2007). Skill requirements and environmental demands of different sports pose different challenges to these systems that can affect the sensorimotor control.

Classic theories of sensorimotor control suggest that loss or degradation of one system results in greater reliance and compensation on the remaining systems (Hedge, 2010; Stelmach & Homburg, 1993). In the case of Figure 1, a loss or degradation of a system is represented by a gain of less than 1. Such degradation of a system in athletics can be exemplified by considering a gymnast as they perform a flipping skill which also involves simultaneous twisting. Throughout the duration of the skill, the inputs of each system change from the beginning to completion. Proprioception, which is described in more detail in subsequent sections, relates to the body sensing joint position from contact with external surfaces (Hedge, 2010; Reimann & Reppert, 2002) (e.g. pressure changes felt while walking as the foot makes contact with the ground). As the gymnast leaves the ground at the start of the skill, the input for proprioception is lost from the external surface of the ground. Thus, for sensorimotor input, the gymnast must rely on visual and vestibular information to determine their body's position in space. With compromised proprioception in this case, if the visual input were lost as well (e.g. the gymnast closing their eyes), vestibular information on its own would not be sufficient to orient the gymnast for a successful landing (Dehl & Pidcoe, 2010). Thus, visual information is an extremely important input into sensory motor control and athletic skills. To understand the role and importance of each of these systems in sensorimotor control and athletics, they are described in detail below.

### Proprioception and Coordination

Proprioception is the ability to integrate sensory information from mechanoreceptors in the muscles, tendons and joints to determine body position and movements in space (Han, Waddington, Anson & Adams, 2015; Reimann & Reppert, 2002; Rose, 1997) or alternately the ability to sense joint position and movement of limb segments relative to one another (Muaidi,

Nicholson, & Refshauge, 2009). High levels of proprioceptive acuity may be more critical for skilled tasks than daily living activities (Muaidi, Nicholson, & Refshauge, 2009). Proprioception encompasses a static and dynamic sense of position- where the static sense allows conscious orientation of one body part, and the dynamic sense gives neuromuscular feedback about rate and direction of the movement (Frontera, 2007; Reimann & Reipart, 2002). Proprioception can also be broken down into conscious and unconscious proprioception. For athletics, conscious proprioception relates to goal-oriented motor control and, thus, coordination (Frontera, 2007).

Motor coordination can be defined as a cooperative interaction between the CNS and skeletal muscles (Frontera, 2007). This cooperative interaction builds off of the ability to sense position of a body part and guide it to a desired position utilizing provisions stimulated by feedback from sensory mechanoreceptors in the muscles and joints- i.e. the proprioceptive system (Reimann & Reipart, 2002). Additionally, the proprioceptive system anticipates change from previous experiences (e.g. rate and force needed to extend the arm a certain distance and direction) (Reimann & Reipart, 2002), which positively aids coordination.

Proprioception underlies coordinated movement control (Han, Waddington, Anson, & Adams, 2015). Both proprioception and coordination have repeatedly been suggested to underpin elite sports performance (Han, Waddington, Anson, & Adams, 2015). Although, proprioception, and coordination, can be improved upon with challenging practice, they can also be impaired by disease or discontinued practice (Rose, 1997). In his 2015 study, Han aimed to examine the relationship between an athletes' proprioceptive ability and their competition level or years of sport specific training achieved. One hundred elite athletes of different sports and competition levels were measured. His results showed that superior proprioceptive ability in athletes was found in athletes that achieved a higher competition level. Han does not attribute his findings to

years of athletic training but mentions that proprioception is an important determining attribute of athletic level reached that warrants further research. Along this line he states that while proprioceptive acuity is significantly associated with elite athletic performance, the amount of any improvement made to proprioceptive acuity associated with training may be constrained by biologically determined factors (Han, Waddington, Anson, & Adams, 2015); thus, linking acuity of the proprioceptive system to genetics. Additionally, in their review of related studies revolving around the biology and physiology of the proprioceptive system, Ashton-Miller et al (2001) argues that proprioception cannot be trained. Furthermore, since there are significant correlations between proprioceptive sensitivity and athletic competition level, tests encompassing proprioception or coordination may be useful in determining innate athletic potential (Han, Waddington, Anson, & Adams, 2015; Vandorpe et al., 2012).

### Visual System

The visual system is considered a dominant source of sensory information and is the most trusted when all sources of sensory information are available (Dalvin, Sands, & Schultz, 2001). The visual system is the part of the CNS which allows for the ability to process visual details by detecting and interpreting information from visual light. The visual system performs a number of functions including reception of light, monocular and binocular perception of images, identification and categorization of visual objects, assessing distances to and between objects, and guiding body movements in relation to objects seen. Not only are these functions important for carrying out normal, everyday tasks, but they are especially important in successful completion of complex tasks- such as those of athletics.

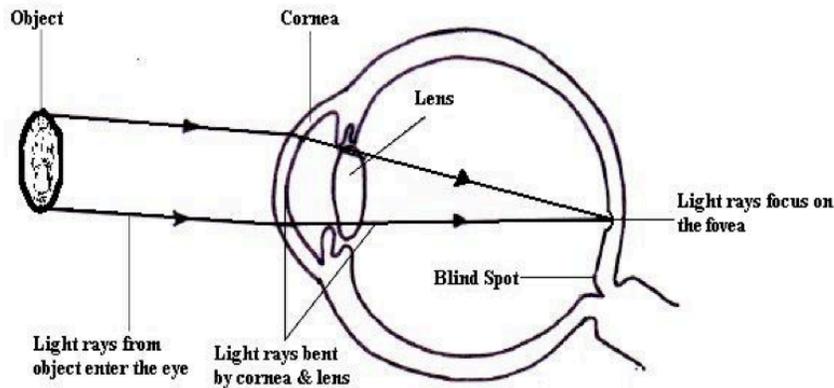


Figure 2. *The Visual System*- Path of light emitted from an object as it enters the eye. (Hedge, 2010)

Visual images are perceived by the brain as light entering the eye. As light enters the eye, it is refracted as it passes through the cornea, pupil and lens. The cornea and lens act together to focus the light and project the image onto the retina- the light sensitive membrane lining the back of the eye (figure 2). The retina consists of a large number of photoreceptor cells, called rods and cones, for seeing details such as color and brightness. As light hits these photoreceptor cells, nerve impulses are carried to the brain via the optic nerve. The neuron communication originating from the retina provides a significant amount of visual processing to the brain; however, only a small region of the retina represents the region of highest visual acuity. The fovea is a very small depression, or pit, in the retina covering only about 1/4000<sup>th</sup> of the retinal surface (Land, 2006) and representing a visual angle of about 1° (Paige, Telford, Seidman, & Barnes, 1998). Away from the foveal center, resolution falls drastically (Figure 3).

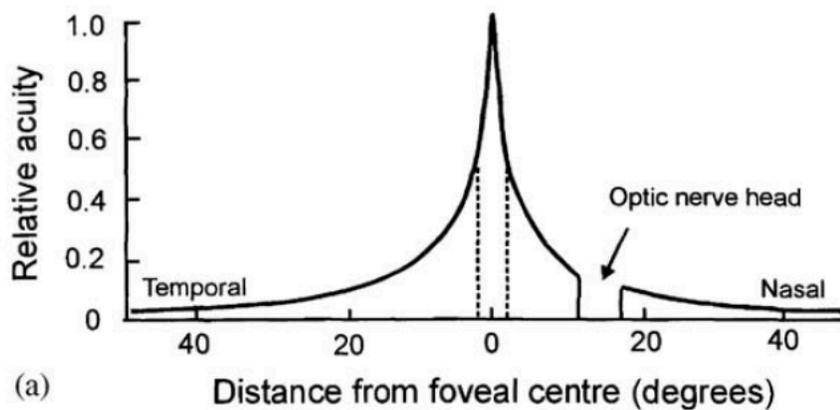
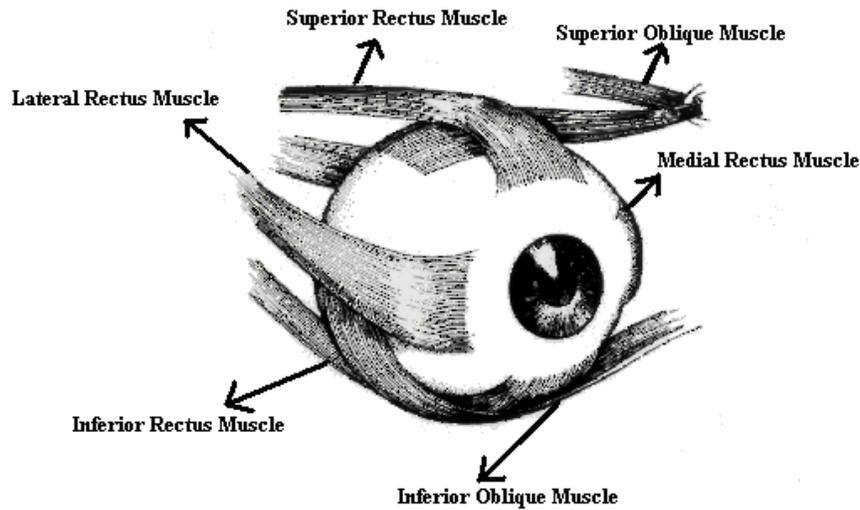


Figure 3. Relative Visual Acuity- (Land, 2006)

For details to be seen with high visual acuity, it is important that the target image is centered on the fovea. Due to its high concentration and spatial density of cones, the fovea is the region responsible for the highest visual acuity. It is located about 4-8 degrees temporal to the optical axis. Proximal to the fovea, there is a region in the retina of each eye where the optic nerve exits the retina forming the optic disc. This region is void of receptor cells; therefore, light projected on the area cannot be visually processed (Shown as 'blind spot' in Figure 2). When both eyes are open, the area of visual blindness is filled in by the visual field of the opposite eye and is typically unperceivable.

To understand the mechanisms of eye movements, it is first important to understand how the eyes are physically controlled. Six extraocular muscles are responsible for the control of eye movement. These muscles are exceptionally precise allowing the eye to perform complex tasks with finite control. The 6 extraocular muscles surround the eye and either singularly operate or work in synergy to produce eye movements (figure 4).



*Figure 4-Extraocular Muscles of the Right Eye- Also shows direction eye moves with activation of the muscle. (Hedge, 2010)*

The four rectus muscles control movement of the eye in the four cardinal directions. The Superior Rectus elevates the eye allowing the eye to look up. Its antagonist is the Inferior Rectus, allows for depression of the eye, causing the eye to look in a downward direction. On the medial side of the eye, the Medial Rectus adducts the eye, allowing movement of the eye towards the nose. The antagonist to the Medial Rectus is the Lateral Rectus. It abducts the eye, allowing for the eye to look away from the body's midline. The two oblique muscles of the eye are responsible for rotation as well as assisting the rectus muscles with their movements. The Superior Oblique rotates the eye medially and abducts it when facing forward. It is also responsible for movement of the top of the eye toward the nose. The Inferior Oblique rotates the eye laterally and adducts it and is responsible for movement away from the nose. Alternately, when the eye is adducted the Superior Oblique depresses the eye while the Inferior Oblique elevates it. Table 1 lists eye muscle combinations and associated eye movements.

<i>Axis of Rotation</i>	<i>Eye Motion</i>	<i>Contracting Muscles</i>	<i>Relaxing Muscles</i>
<i>Vertical</i>	Abduction	Lateral Rectus	Medial Rectus
	Adduction	Medial Rectus	Lateral Rectus
<i>Horizontal</i>	Supraduction (Elevation)	Superior Rectus Inferior Oblique	Inferior Rectus Superior Oblique
	Infraduction (Depression)	Inferior Rectus Superior Oblique	Superior Rectus Inferior Oblique
<i>Antero-posterior</i>	Incycloduction (Intorsion)	Superior Rectus	Inferior Rectus
		Superior Oblique	Inferior Oblique
	Excycloduction (Extortion)	Inferior Rectus Inferior Oblique	Superior Rectus Superior Oblique

*Table 1. Eye Movements and Associated Muscles*

When subjects are asked to look directly at a static, target, contraction of the extraocular muscles produce rapid eye movements to foveate the image and achieve clear vision. When subjects are asked to alternate their gaze between two different static targets, they produce a series of saccades with fixations in between. Saccades are the eye's rapid and accurate means of providing high acuity, foveal vision. They are movements with speeds reaching toward 700°/s for large saccadic movements (Land, 2006) and are responsible for rapid changes in fixation from one target to another, directing gaze toward objects of interest. They range in amplitude from small movements (e.g. made while reading) to large movements (e.g. gazing around the room). Saccades are very fast and accurate, enhancing rapid acquisition of visual information. They can be elicited voluntarily, as well as under reflexive control, whenever both eyes are open, even if the observer is intently fixated on a target.

Saccadic velocity profiles show two distributions of velocities- a low (< 100 °/s) and a high (>300 °/s); where the low and high represent fixational eye movements and larger, exploratory saccades respectively (Salvucci & Goldberg, 2000). When scanning a scene, fixations, or fixational eye movements, occur between larger saccadic movements to allow visual

processing (Rucci & Poletti, 2015). While the term ‘fixation’ is typically used to describe the periods visual processing in between large saccades, it is misleading as the eyes are never fully at rest (Rucci & Poletti, 2015; Rucci, 2016). The broad term “fixation” encompasses these fixational eye movements and is used to describe points where gaze is relatively stable, to allow visual processing, between high velocity saccades. The response of cone photoreception is relatively slow (about 20ms); therefore, fixations exist to provide adequate visual processing time. Although there are three types of fixational eye movements, ocular drift, tremor and micro-saccades, only micro-saccades will be discussed here as they are the largest and most easily characterized. During attempted visual fixations, tiny, micro-saccades work continually to keep vision foveated by reflexively moving the eye across a range of several dozen to several hundred photoreceptor widths, with a maximum of around 1° of visual arc in humans (Martinez-Conde, Macknik, Troncoso, & Hubel, 2009). Continual and unintentional slow drifts of the eyes during attempted fixations progressively shift the image to nearby photoreceptor cells causing slight blur. These micro-saccades work to refocus the targeted image on the retina (Collewyn & Tamminga 1984; Martinez-Conde, Macknik, Troncoso, & Hubel, 2009). For simplicity in this study, the term ‘saccade’ will be used to describe the large, exploratory saccades, and the term ‘fixation’ will be used to describe fixational eye movements where the subject is attempting to fixate their gaze.

Smooth pursuit movements are a second type of eye movement which are much slower than saccades and are designed to track moving targets. These movements are under voluntary control as the observer can choose whether or not to track the moving stimulus. Unlike saccadic movements, smooth pursuit movements do not have a fixed trajectory, but strive to conform to the velocity of the moving object (Hung & Ciuffreda, 2002). The presence of saccades helps to

quickly reduce target offset from the fovea that develops when the target velocity is greater than the pursuit velocity of the eye (Hung & Ciuffreda, 2002). The smooth pursuit system can follow target motion up to about 100 °/s. (Hung & Ciuffreda, 2002; Land, 2006; Myer, Lasker, & Robinson, 1985). Typical visual tracking is a mixture of smooth pursuit and saccadic movements (Hedge, 2010; Collewijn & Tamminga 1984; Shutz, Braun, & Gegenmutter, 2009). Combining these eye movements allow increased spatial resolution and decreased retina image motion causing blur (i.e. retinal smearing) (Shutz, Braun, & Gegenmutter, 2009). It has been shown that object recognition is reduced significantly if the image is not stable on the retina; thus, the need for combined smooth pursuit and saccadic movements.

Head movements can disrupt the ability of the eyes to track and fixate on targets. To account for how the eyes react to head movement it is imperative to understand the Vestibulo-ocular Reflex (VOR). During head movement, the goal of the VOR is to stabilize the eyes and assist in keeping the image of interest centered on the retina. It is a reflex response to minimize retinal smear. Semicircular canals of the vestibular system detect brief, transient changes in linear acceleration and angular velocity of the head, which signal rapid corrective eye movements in a direction which is ideally equal in amplitude and opposite direction to head movement. For example, if a person rotates their head to the left while staring at a target straight ahead, the eyes will move to the right, keeping the target centered on the fovea. To quantify this reflex, VOR gain is represented as eye velocity divided by head velocity. A value of -1 represents perfect compensation of eye movement relative to head movement. The negative sign for VOR gain mathematically represents opposite eye and head directions, confirming support of a stable retinal image.

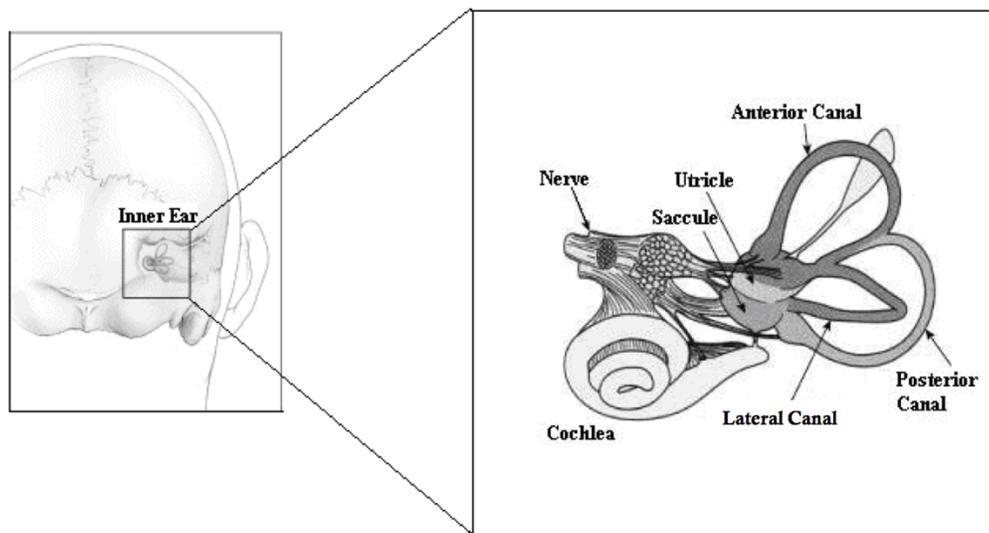
The VOR is driven by inputs from the vestibular system by enhanced by visual cues (Hedge, 2010; Hung & Ciuffreda, 2002). To present a stable target on the retina during head movement, the VOR utilizes some of the same pathways as the visually driven smooth pursuit system to produce smooth eye movements (Hashiba, 1996; Huebner et al., 1992). Furthermore, it does not simply represent a reflex arc of the ocular-motor system. Central vestibular pathways carry information to the vestibular cortex for spatial perception and the spinal cord for sensorimotor control, thus contributing to stabilization of gaze and posture and motor control (Dieterich & Brandt, 1995).

A number of previous studies have been conducted to analyze changes in VOR gain during head rotations (Crane & Demer, 1998; Viirre & Demer, 1996; Hedge, 2010). These studies presented subjects with a fixed visual target with subject rotations (both whole body and just head) in the transverse plane (yaw direction) and were able to measure angular head and eye velocities to calculate gain. Similarly, the suppression of the VOR can be looked at by providing a visual target that is linked to head motions (Crane & Demer, 1998; Hedge, 2010). VOR suppression is the ability of the CNS to suppress vestibular inputs during head motion, resulting in eye movements which are not fixating gaze on stable target. During pursuit of a moving target accompanied by active head movement, the VOR must be overridden; otherwise, the VOR would cause the eyes to be driven in the opposite direction of head movement. Research has shown that there is a strong correlation between the velocity limits of smooth pursuit movement and VOR suppression, leading to the hypothesis that the smooth pursuit system and VOR are superimposed in some affinity (Huebner et al., 1992; Chambers & Gresty, 1983). Theoretically, complete suppression would result in a VOR gain of zero, as eye-in-head relative angular velocity would be zero. In the context of athletics, the ability to suppress VOR may allow

superior athletic performance as exemplified by a gymnast being able to view their landing when performing a flipping skill with simultaneous twisting.

### Vestibular System

The input into the VOR is the vestibular system, and is also responsible for maintenance of balance and equilibrium. It is an important component of sensorimotor control and provides the leading contribution to sense balance and spatial orientation sending primary signals to the ocular and postural control muscles. The vestibular organs are known as the balance organs of the inner ear (Angleaki & Cullen, 2008). Three orthogonal semicircular canals sense rotational movement and two otolith organs, the utricle and saccule, sense linear acceleration.



*Figure 5. The labyrinth of the Inner Ear (Hedge, 2010)*

The semicircular canals sense motion from a shift in the fluid enclosed in them. As can be seen in Figure 5, they are approximately orthogonal to each other to account for 3-dimensional movements of the body. Movement of fluid within the horizontal canal, termed the Lateral Semicircular Canal, corresponds to rotation of the head around the vertical axis (rotation

around the neck). The Anterior and Posterior Semicircular Canals are vertical and detect rotations of the head in the sagittal plane (as in nodding the head forward and backward) and frontal plane (as in rotating the head towards either shoulder), respectively. The Anterior and Posterior canals are oriented about  $45^\circ$  between the frontal and sagittal planes. The canals are also arranged and linked to have counterparts on the other side of the head. This allow for a 'push-pull' mechanism with their counterpart- the stimulation of one canal leads to the inhibition of the corresponding canal on the opposite side of the head. For example, a head turn to the right stimulates activity in the right horizontal canal, while that of the left canal gets inhibited, and vice versa. This mechanism signals the CNS of movement as the head rotated and translates, and increased the sensitivity of the system by doubling the gain. For the CNS to get the full picture of movement, these combined, complimentary signals are necessary (Angleaki & Cullen, 2008).

Vestibular signals are highly convergent and multimodal (Angleaki & Cullen, 2008). For example, the visual/vestibular and proprioceptive/vestibular interaction occur throughout vestibular pathways and are vital to gaze and posture. Additionally, the vestibular system detects motion independently from the visual system, exemplified by VOR function even in complete darkness (Stelmach & Homburg, 1993). However, combining the visual and vestibular systems provide vital information to the sensorimotor system and are valuable for achieving high level athletic skills.

### **Psychological Contributions**

Analysis of athletic mental attitudes and personality traits is valuable in sports performance. Literature attests to the hereditary nature of specific psychological and cognitive characteristics that are relevant to elite sports performance (Baker & Horton, 2004). There are

many different definitions of personality and psychological tendencies. Shariati & Bakhtiari (2011) use the definition of a distinctive way of thinking, feeling, and acting that characterizes a person's reactions and responses to life situations and also mentions the existence of a psychological core or innate way of thinking. In the context of athletes, this would be their responses and reactions to athletic situations.

Evidence attests that 'psychological phenotypes' might provide additional, valuable elements to determine advantageous polygenic profiles of athletes (Lippi, Favaloro, & Guidi, 2008). Earlier studies have determined that genetic factors account for up to 62% variance in daily exercise behavior and up to 83% variance in sports participation or athletic tendencies (Lippi, Favaloro, & Guidi, 2008). Psychological phenotypes as a way to characterize elite athletes is often overlooked but important. An advantageous physical genotype must be supported by a strong mental background in order for an athlete's success.

Psychological studies have been performed to determine tendencies which facilitate the development of an elite athlete. Anshel (1997) reported that athletes are typically predisposed to higher amounts of risk taking and competitiveness than non-athletes. He also noted that elite athletes are distinguishable from non-elites on a number of behavioral tendencies, cognitive strategies and performance expectations. In a study looking at mental skills between elite basketball players and gymnasts vs their novice counterparts, Williams and Krane (2001) reported that successful athletes have higher levels of self-confidence, better concentration and are less likely to be distracted from their performance. They also reportedly have a more positive outlook than lower-level athletes. Furthermore, successful athletes have less anxiety and are able to channel what anxiety they do have to facilitate their performance. In this study, elite athletes were also found to have a great ability to rebound from their mistakes than their lesser

experienced counterparts. Gould et al. (2002) confirmed these findings with Olympic Gold Medalists.

Similarly, Jones et al. (2001) developed an 83-question survey which posed situational questions to further validate the findings of superior mental tendencies of elite athletes using situational questions. This survey evaluated 274 collegiate students (varsity athletes and non-athletes) at a Division I university on six interpretable factors: competitiveness, team orientation, mental toughness, emotional control, positive attitude and safety consciousness. A higher score from this survey correlated to an increased amount of psychological tendencies. Jones found that collegiate athletes produced a higher composite skill than non-athletes. They also scored higher in the categories of positive attitude and competitiveness.

### **Systems Integration**

Athletic performance requires both physical and mental effort. To be successful, athletes must be in tune with their body and environment; consequently, they rely heavily on sensory information from the visual and vestibular systems. There has been very little research around how innate sensorimotor acuity relates to or impacts a person's athleticism. The majority, if not all athletes, rely on the vestibular system and its associated signals working in conjunction with the visual and proprioceptive systems.

Previous experiments have shown that suppression of the VOR is important and successfully achieved in elite athletes (Burcham, 2010; Hedge, 2010; Land, 2006; Alpini, Botta, Mattei, & Tornese, 2009). A prior study conducted at VCU (Hedge, 2010) looked at the VOR response in adolescent gymnasts. As exemplified previously, gymnasts rely on the suppression of the VOR during skills which flip and simultaneously twist, to view their landing. For gymnasts,

activation of the VOR would result in a 'blind' landing as they need their gaze to follow their head to visualize landing zones. Further solidifying this, gymnasts report being able to view their landing during such skills, implying successful suppression of the VOR while performing flipping skills that also twist. The aim of Hedge's study was to investigate the relationship between gymnastics skill level and the gymnasts' ability to cancel or suppress their VOR. It analyzed the VOR performance of 10 female gymnasts (mean age  $15 \pm 2.2$ ) of elite (competitive) and non-elite (recreational) skill level. Each subject performed a series of visual tasks designed to evoke volitional saccades, a typical VOR response, and a VOR suppression response. Results of this study showed that saccadic peak velocities and latencies of gymnasts did not vary from the typical, normal values of these variables. VOR and VOR Suppression gains were calculated and compared with a positive correlation toward higher level gymnasts performing better in both the VOR and VOR Suppression experiments. Results of this study did not suggest that VOR differences develop as a result of practice and that they may simply allow some individuals to reach a higher level of performance (Hedge, 2010). The proposed study hopes to correlate these findings with measures of athleticism between elite athlete and low-level or non-athletic populations, termed Non-Elites from here on.

Similarly, VOR suppression has been shown to be valuable in other sports which do not encompass high rotational velocities like those in gymnastics, figure skating and diving. Suppression of the VOR has been successfully achieved in baseball players during a baseball pitch (Burcham, 2010). Likewise, ball sports which require athletes to keep their eyes on the ball as the head follows the ball also require suppression of VOR- the head and eyes would be moving in the same direction and at the same velocity to view the ball. In these sports such as baseball, tennis and table tennis, lacrosse, field hockey and even soccer, volleyball, and

basketball, the velocities exhibited are often too fast for players to use “normal ocular motor machinery” (Land, 2006).

## **Hypothesis**

The *purpose of the proposed experiment* is to investigate the relationship eye movement control has with innate athleticism by comparing the saccadic and VOR responses of former, no longer practicing, elite athletes against their age and gender matched counterparts who were non-elite or non-athletes. By testing former, elite athletes, who are no longer practicing, the potential for practice affecting the results is removed. *It is hypothesized that* former, elite athletes have superior saccadic performance metrics, VOR suppression capabilities, and spend less time foveating than their age and gender matched, non-elite counterparts.

Additionally, as illustrated earlier, innate athleticism can be measured in various ways. Psychological tendencies and a measure of the proprioceptive system, hand-eye coordination, will be used to measure innate athleticism of the subjects. While there is no single gene for hand-eye coordination, defined nervous system thresholds and differences have been shown to be inherited (Davids & Baker, 2007). The extent to which these thresholds and differences affect the CNS is unknown. By comparing a subject’s VOR’s responses and suppression capabilities to their level of innate athleticism, this study aims to provide more insight into categorizing these differences. Thus, it is *additionally hypothesized* that there is a correlation between elite athletes’ VOR suppression capabilities and their measured level of innate athleticism.

## METHODS

### Subjects

This study was approved by the IRB board at Virginia Commonwealth University prior to advertising, identifying subjects, or collecting data. Twelve subjects ages 23-28, mean age  $26.1 \pm 1.8$  years old, volunteered to participate in this study. Six of these subjects were identified as former, elite athletes- 3 high level competitive gymnasts (levels 8 and 9), and 3 varsity, collegiate athletes, with a mean athletic career spanning  $15.7 \pm 3.3$  years. The remaining six participants had varying athletic backgrounds ranging from no consistent childhood athletics to recreational athletics up to the age of 18, with a mean athletic duration of  $10 \pm 3.6$  years. All subjects consented to this study at the time of data collection and were notified that they were able to exit the study at any time without recourse. Table 2 shows participant data below.

PARTICIPANT*	GENDER	AGE	SPORT/SKILL LEVEL**	EYE DOMINANCE	HAND DOMINANCE	TWIST DIRECTION
<b>A_CM</b>	F	26	Gymnast- Lvl 9	right	right	right
<b>A_LR</b>	F	27	Gymnast- Lvl 8	right	right	left
<b>A_KB</b>	F	23	Gymnast- Lvl 9	right	right	left
<b>A_JP</b>	M	28	Baseball/Football	right	right	N/A
<b>A_ST</b>	M	27	Soccer	right	left	N/A
<b>A_TT</b>	F	25	Lacrosse	right	right	N/A
<b>N_NF</b>	F	26	Rec- Tennis	right	right	N/A
<b>N_AC</b>	F	28	Rec- Dance	right	right	N/A
<b>N_RS</b>	F	23	Rec- various	left	left	N/A
<b>N_SC</b>	M	28	Rec- various	right	right	N/A
<b>N_DL</b>	M	27	none	left	left	N/A
<b>N_WP</b>	F	25	Rec- Field Hockey	right	right	N/A

*Table 2. Participant Data*

\*prefix 'A' represents an elite athlete, prefix 'N' non- or low-level athletes.

\*\*'Rec' standing for recreational athletics, subjects participated in under age 18

Subjects were selected based on the criteria that former elite athletes were matched with age, and gender counterparts. Matched subjects had birthdates within 6 months of each other, even if their age number did not match. Twist direction, for former gymnasts only, and hand dominance were self-reported. Eye dominance was determined prior to data collection. To determine this, subjects were asked to stand facing a distant, stationary object on wall. They were told to make an outline of a triangle using the thumb and index finger of both hands, and with both eyes open, center the object in the triangle. After doing so, subjects were asked to close one eye. Eye-dominance was determined to be whichever eye closure resulted in the object to no longer be viewed within the triangle (i.e. if right eye was closed and object could no longer be viewed inside the triangle, right eye was determined to be dominant). The closure of both eyes separately was performed, to double check eye dominance was correctly determined.

Prior to data collection, subjects were explained the purpose of the study and given background information. Any concerns were addressed and questions answered. A written script was read to each subject to insure each subject was given the same instructions before the start of each experiment.

### **Psychological Performance Index**

The aim of this experiment was to determine a subject's athletic psychological tendencies. Natural athleticism is not just determined by a person's physical abilities; their mental drive, determination and thought processes in athletic situations contribute to athletic performance as well. In part, it is a person's psychological mindset that controls their athletic performance. A plethora of research in this field has suggested that the attitudes and beliefs an athlete holds can have an important effect on their performance as an athlete (Jones, Neuman,

Altmann, & Dreschler, 2001). This survey was used to determine a subject's "mental athleticism" in a way that was quantifiable.

An overview of the survey and instructions were given to each subject verbally at prior to subject reading instructions at the start of the survey. The survey consisted of 42 questions which aimed to evaluate the subject's psychological athletic tendencies based on six interpretable factors: competitiveness, team orientation, mental toughness, emotional control, positive attitude and safety consciousness. The combination of these factors was used to evaluate each subject's athletic level from a psychologic state (Jones, Neuman, Altmann, & Dreschler, 2001). Each question was posed as a statement to which there were 5 different responses for the subject to choose from: Almost Always, Often, Sometimes, Seldom, Almost Never. Each answer was given a point value ranging from 1-5. Lower points were given to answers which represented non-athletic tendencies, and higher points were given to answers which indicated an answer of a person with tendencies an athlete. Athletes were told to read instructions, answer questions at their own pace and as honestly as possible.

Points were totaled for each survey, with the total representing their score for the survey, and quantitatively compared against other subject's scores, allowing for a direct comparison of their psychological athletic tendencies. Jones et al. (2001) evaluated collegiate athletes using a similar survey testing the same six interpretable factors and found validity ( $p < .01$ ). in the survey on the overall composite attitude determining athlete type. The question types, format and interpretable factors of the survey used in this experiment were compared to that of Jones' survey and found to be congruent. Each survey was coded with the participant's code and stored with the rest of the data collection materials.

## **Hand-Eye Coordination**

Hand-eye coordination is a measure sensorimotor system efficiency (Saavendra, Joshi, Wollacott, & VanDonkelaar, 2009). The hands and eyes must coordinate together to perform a certain task. How well that task is performed depends on the strength of the visual connection from a person's eyes, to their brain, to their hand. Since coordination, especially hand-eye coordination, is a major aspect of athletics, it can be used as an indicator of athleticism (Dane, 2009). At birth, each person is born with a set of innate reflexes, with hand-eye coordination being one of these (Intelligence: its organization and development, Cunningham, 1972). Additionally, several studies have shown that elite athletes in various sports score higher in hand-eye coordination testing than those with lower or zero athletic skill (Kioumourtzoglou, Derri, Tzetzis, & Theodorakis, 1997; Erickson, 2007). While hand-eye coordination can be improved upon with practice, like any practiced skill, improvements are lost without consistent skill exercise (Rose, 1997). Thus, for this study, focusing on non-practicing, former elite athletes vs non- or low-level athletes, hand-eye coordination is an appropriate measure innate athleticism.

Hand-eye coordination was tested through a simple, timed exercise in which the subject tossed a tennis ball at a wall and caught it upon its rebound multiple times. Verbal instructions were given to subjects with the experimenter exemplifying and as they talked through them. Subjects were asked to stand 3ft back from a flat, smooth wall and told to hold a standard tennis ball in the palm of their chosen hand. Using an underhand motion, subjects tossed the ball against the wall, and attempted to catch the ball upon its rebound with their opposite hand. Then, keeping the ball in the same hand, subjects tossed the ball back at the wall, and attempted to catch it upon its rebound with their initial hand. Subjects were allowed to practice up to 3 rounds.

The number of successful catches was counted by the experimenter during a 30 second time period, and 3 trials were completed. In the event of any misses, subjects picked up the ball and were instructed to resume the activity. The number of successful catches and any notable observations were recorded on a data collection sheet. This sheet was coded using the subject's participant code and stored with the rest of the data collection materials.

## **Eye Tracking**

### Experimental Setup

Data were collected using a kinematic system to monitor head position, with 6 degrees-of-freedom (DOF), and a binocular eye tracking system to monitor eye position, with 2 DOF. Data collection from these two systems was integrated, providing a synchronous data set for analysis. Subjects were seated at the end of a 0.762m high workbench on a wooden stool. They were asked to wear a headpiece filled with a camera-based, infrared eye-tracker (EyeLink II™, SR Research Ltd. Mississauga, Ontario Canada.) The EyeLink II™ has a tracking range of  $\pm 30^\circ$  horizontal and  $\pm 20^\circ$  vertical and an accuracy of  $0.5^\circ$ . Data collection from this system was collected at 250Hz and provided eye-in-head data from the subject.

The integrated kinematic system collected data from 1 electromagnetic (EM) motion sensor (Motion Monitor™, Innovative Sports Training, Chicago, Illinois, USA) mounted on the headpiece and was used to collect head-in-space positional data. Data was collected at a 100Hz sampling rate with a linear resolution of 0.5mm and an angular resolution of  $0.1^\circ$ . Data from this system was up-sampled via linear interpolation to temporally integrate both systems to a 250Hz sampling rate.

A transmitter located behind the subject and in line with the origin in the negative y-direction provided orthogonally oriented EM fields to relay positional data to the collection system. The theory of operation behind this type of sensor is that it orients itself based on the transmitter's EM field strength. Field strength decreases as a square of the distance from the transmitter. For this particular setup, the transmitter used has a usable radius of 10ft, where the subject and all sensors were well within this limit. To minimize the possibility of eddy current distortion, the presence of metal was avoided in this range. Additionally, to further reduce any effect of metal, a metal mapping procedure was performed prior to any data collection in this study. It used known sensor locations to construct a distortion map of the collection space. The data from this mapping is then used to linearize any measurement error across the mapped space. All collected data were stored in a file coded with the participant's identification code, date the data was collected, and trial number.

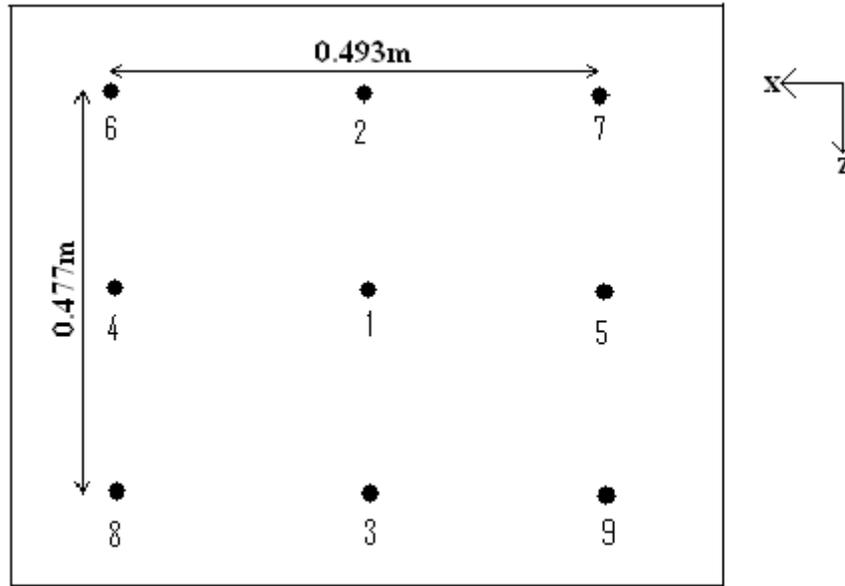
### Subject Setup

Subjects were seated on a wooden stool at the midline of the wooden bench as close to the edge (origin, along the positive X-axis) as possible. A world-based, right-hand coordinate system was defined on the workbench with the origin located to the right of the subject- Positive X-axis to the left of the origin, positive Z-axis toward the floor from the origin, subject facing the positive Y-direction. The headpiece with attached infrared cameras was fitted to the subject and anatomically lined up in the center, middle of their forehead (X and Z directions). The subject sat to face the LED display board at a distance of 1m away (as close to the end of the workbench as possible), and approximately eye level with the LED display board and in line with the center target of the board.

Subject landmarks were defined in a predefined manner using free-floating sensor attached to a stylus. The back of the head (occiput), C7 spinous process, and eye locations were all defined in space. The eye locations were digitized by gently placing the tip of the stylus at the center of the subject's closed eyelid, indicating the left and right pupil locations, as well as the bridge of the subject's nose to estimate the cyclopean eye location. Defining these landmarks provided an initial estimate of interpupillary distance, which was later improved upon dramatically during the calibration/validation process and will be discussed in the following section. Designating these locations allowed reconstruction of a rigid body digitized model of the subject for interpretation of data in the collection space.

### Calibration and Validation

Following subject setup with defined landmarks of the subject's head, neck and eyes located, the system needed to be calibrated. This procedure was done using a LED display board showing 9 LED targets symmetrically configured on a 0.493m wide by 0.477m high grid shown in Figure 6. At a distance of 1m, this provided a field of view of  $27^\circ \times 26^\circ$ . To help minimize any variations in eye gaze, LEDs were made as small as possible, while still distinct, occupying a visual angle of  $0.3^\circ$  at 1m distance.



**Figure 6. Calibration target display board-** Each dot represents an LED with the numbers representing the order of target presentation during calibration. (Hedge 2010)

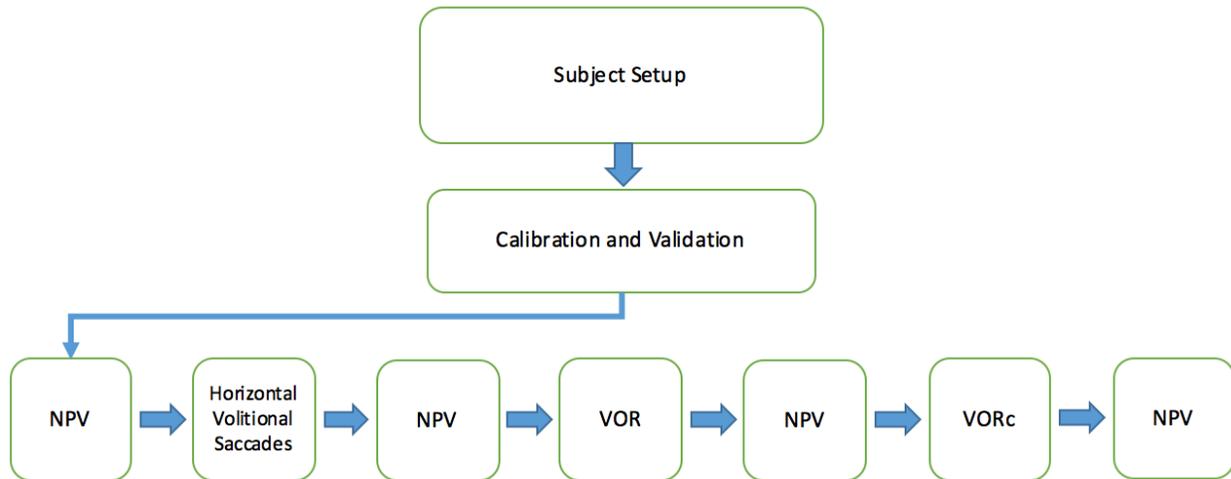
During a semi-automated calibration, each subject was instructed to keep eyes open wide, and minimize head movement to maximize the visually calibrated area; however, head movement did not negatively impact calibration in any other way. The process started with a predefined sequence of LEDs individually lit, kept on until a stable gaze was reached for at least 1000ms, and then extinguished allowing the sequence to advance. Left and right gaze were calculated independently using a combination of head-in-space and eye-in-head data.

Once calibration finished, the system needed to be validated. Subjects were once again instructed to keep eyes wide open and to minimize head movement while the same target LEDs were sequentially lit in a pattern different than calibration (LEDs shown in figure 6). Subjects were instructed to give a verbal cue when visually fixated, on the lit LED. The experimenter checked the visual feedback to validate the system was presenting a stable gaze, and the indicated such to the system. Left and right gaze data was once again calculated independently, and then compared to the gaze data from calibration. Singular targets were recollected up to 3

times if the difference (calibration - validation) was greater than  $0.5^\circ$ . At completion of the validation process, an error map was displayed for the experimenter showing error for each target. The calibration/validation process was repeated if the average error for all targets was greater than  $0.5^\circ$ .

To improve upon the interpupillary distance estimated previously during the subject setup, a vergence angle was calculated by having the subject stare at a stylus tip as it was moved toward and away from the subject along the positive Y-axis, at eye level. Assuming equal left and right eye fixation on the stylus, locations of the eyes were calculated using vergence angle data. After this process, RMS errors between known target locations and point-of-gaze (POG) were typically reduced due to improvement upon the interpupillary distance. If the error showed less than  $1^\circ$ , the calibration/validation was accepted. Ideally, these RMS errors were below  $0.57^\circ$ . A previous study done on this system found the system has an RMS error of  $0.45 \pm 0.12^\circ$  across 12 subjects (Diehl & Pidcoe, 2010). In this study, subjects were able to repeat located targets with a standard error mean of 1cm in the horizontal direction. At a target distance of 1m, this is a visual angle of  $0.57^\circ$ . Additionally, since the accuracy of the EyeLink II™ is  $0.5^\circ$ , an RMS error of less than  $1^\circ$  was accepted between target location and POG.

Once calibration and validation were accepted, 4 experiments were performed: Nine Point Validation (NPV), Horizontal Saccadic system characterization, VOR system assessment, and Volitional VOR suppression assessment (VORc). The experimental design is shown in Figure 7. Once instructions were given for each experiment, subjects were given the opportunity to perform a practice trial for that experiment.



**Figure 7. Experimental Design-** Headpiece remained fixed on all subjects throughout data collection. Any shift or movement of cameras or headpiece would've required re-calibration and validation before testing could resume.

Although listed as an experiment, the NPV was used as a control for integrity of the data collection. Some of the experiments required vigorous head rotations, which introduced the risk of headpiece shifting. NPV after each experiment allowed the system to be checked and compared through the data collection process to monitor data integrity. Even though NPV is a quality control, it is listed as an experiment for consistency.

### Required Calculations

Some common calculations are needed to evaluate the data from each experiment; therefore, they are presented before going deeper into the details of each experiment. In order to analyze target vs gaze errors, which are used throughout the eye tracking data analysis, it is necessary to find the gaze vector (GV)-target plane intercept locations. Eye gaze vergence, or Point-of-Gaze (POG), is the point of intersection of the vectors originating from each eye. The POG does not necessarily lie on plane with the targets. It could lie ahead or behind of the target plane; thus, it is necessary to determine the locations of the GV- plane intercept for each eye.

Data provided by both the eye tracker and EM sensor system gives the eye locations, gaze vectors, horizontal and vertical eye angles in X, Y, and Z coordinates to be used in this calculation. The plane of targets is in the Y-direction and is parallel to the X-axis. The following calculations will give the coordinates of the GV-target plane intercept in the XZ plane (X horizontal, Z vertical). Similar calculations are performed for both vertical and horizontal coordinates. Each equation is applied to both the right and left eyes.

- a) Gaze Angles ( $\alpha$  and  $\beta$ ): gives the measured gaze angles from the GVs (either horizontal or vertical) relative to measured GV depth (Y-direction).

$$\text{Vertical: } \alpha = \tan^{-1}\left(\frac{GV_z}{GV_y}\right) \dots\dots\dots \text{(Equation 1)}$$

$$\text{Horizontal: } \beta = \tan^{-1}\left(\frac{GV_x}{GV_y}\right) \dots\dots\dots \text{(Equation 2)}$$

- b) Plane depth (D): gives the plane distance from the eye

$$D = [1 + (-P_y)] \dots\dots\dots \text{(Equation 3)}$$

Where  $P_y$  is the Y-coordinate of the eye position. Even though the subject is sitting as close to the workbench as possible, although close, the location of their eye is not exactly 1m away from the target plane. This equation adds the distance of eye is located from the origin in the negative Y-direction to the distance of  $y = 1\text{m}$  where the target lies along the positive Y-axis from the origin.

- c) Point-of-Intersection (POI): Both the vertical (z) and vertical (x) coordinate

$$POI_z = [D * \tan(\alpha)] + P_z \dots\dots\dots \text{(Equation 4)}$$

Where  $P_z$  is the eye position in the vertical direction (i.e. the vertical offset).

$$POI_x = [D * \tan(\beta)] + P_x \dots\dots\dots \text{(Equation 5)}$$

Where  $P_x$  is the eye position in the horizontal direction (i.e. the horizontal offset).

d) Cyclopean Eye POI ( $POI_{CE}$ ):

Cyclopean eye (CE) is the average of the left and right eye positions (i.e. the location exactly between the two eyes). Assuming equal eye distance and contribution to gaze, a singular POI from the CE is found from the average of the left and right POI coordinates. This is to be done for both vertical and horizontal directions.

$$POI_{CE} = \frac{POI_L + POI_R}{2} \dots\dots\dots \text{(Equation 6)}$$

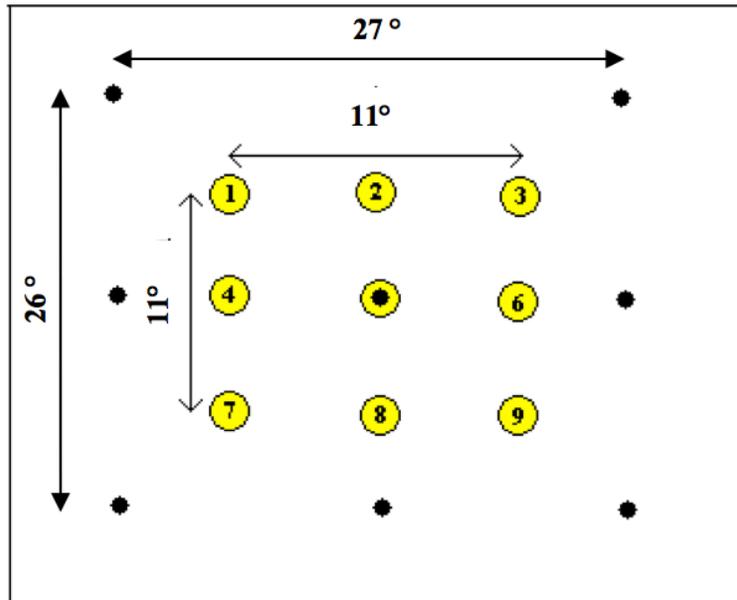
e) Intercept error:

Intercept error is the difference between the target location (x, y, z) coordinates and the POI. Since the POI has been calculated to be on plane with the targets, only the x and z coordinates are taken into account, giving a 2-D intercept error.

$$\text{Intercept Error} = \text{Point of interception} - \text{Target Position} \dots\dots \text{(Equation 7)}$$

### Nine Point Validation (NPV)

The aim of this control experiment is to allow evaluation and re-evaluation of the system calibration in a way that was easily repeated between experiments. This evaluation monitored the integrity and reliability of the data collected throughout the eye tracking data collection. Nine targets were positioned centrally in a grid arrangement on the target board with visual angles of  $11^\circ$  between them. These targets (yellow dots, Figure 8) were located within the calibrated space (black dots, Figure 8), subtend a visual field of  $1.1^\circ$ , and were numbered 1-9 starting at the top left (left-to-right, top-to-bottom).



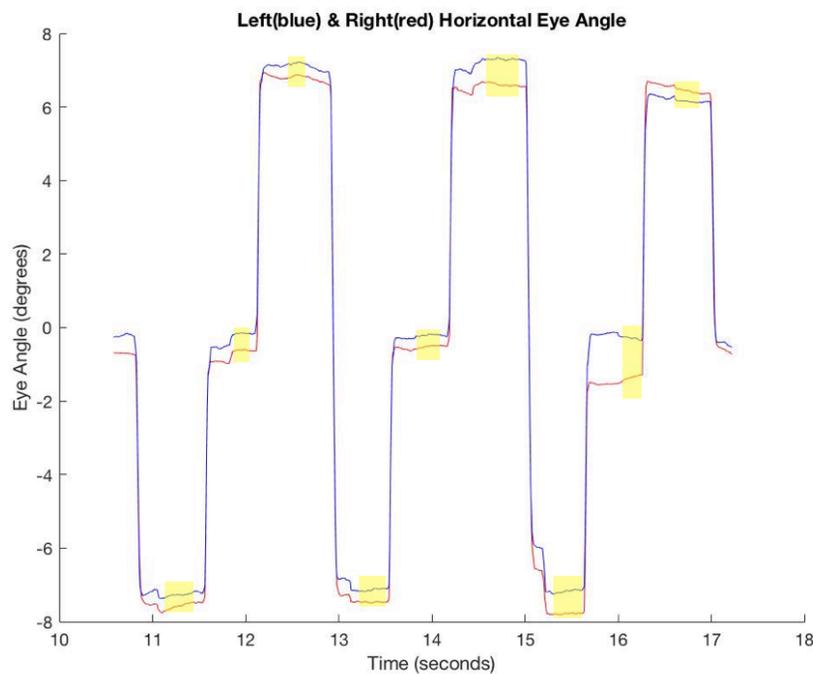
*Figure 8. Target Arrangement* – Target fixation locations and their corresponding numbers (Hedge, 2010).

Subjects were instructed to keep their eyes wide open and minimize head movement for the duration of the experiment. Starting at the center target (5), the subjects were asked to visually gaze at each target at a self-defined pace and call out the numbers as they moved through the targets. This was done in numerical order, starting and ending on the center target (5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 5). To account for subject mishaps during collection (i.e. blinks, head movement, target sequence error), this experiment was performed 3 times. Between each trial, subjects were given a change to relax and blink their eyes if needed.

POI fixations at each target were calculated and compared to each known target location, and the error (POI- target location) was used to assess the integrity of system calibration. Although qualitative assessment of the data was not available in real-time, objective evaluation of the NPV was done post-collection to evaluate the integrity of the collected data. This will be discussed in the subsequent sections.

a) Fixations/Eye Angle

While the POI was calculated for the entire data set, the only data of interest was the data assorted with a stable gaze. Stable gaze in this case is defined as a fixation on a target (i.e. not when gaze is moving from target-to-target). The temporal locations of these stable gaze periods are called fixation periods, and needed to be determined for each target location. Figure 9 below shows typical data for eye angle vs time. The fixation periods are highlighted, and represent a stable gaze.



**Figure 9. Stable Eye Fixations-** Zeroed Left and right horizontal eye angles during NPV (Eye position at 0 represents the center target, left direction is negative and right direction is positive). Fixation periods are highlighted.

Using spatial information provided from the eye tracker, fixations were found based on a velocity threshold. Salvucci and Goldberg (2000) termed this method

velocity-threshold Identification (I-VT) in their characterization of eye fixation identification methods. This velocity based method separates fixation and saccade points based on their point-to-point velocities. Saccadic velocity profiles show two distributions of velocities- a low (< 100 °/s) and a high (>300 °/s); where the low and high represent fixations and saccades respectively (Salvucci & Goldberg, 2000).

The eye angles for each eye, horizontal and vertical, were obtained from the raw data and used to calculate the average magnitude of left and right movements and the average planar intercept location (POI). Eye movement velocity was then calculated using the central difference method (Equation 8), and fixations were found based on the I-VT method.

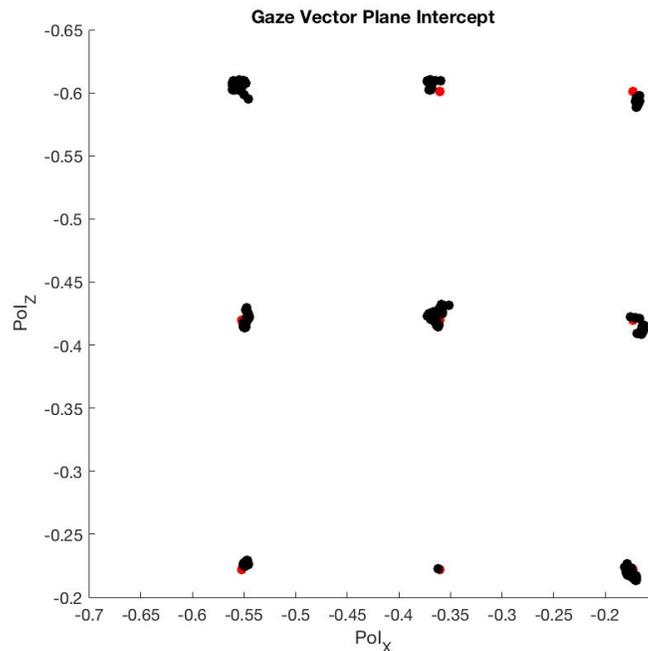
$$\frac{Eye\ Angle\ (i+1) - Eye\ Angle\ (i-1)}{2 * Sampling\ Rate} \dots\dots\dots Equation\ 8$$

Although fixations can be defined as below 100 °/s, to further constrain fixation periods on the target, a velocity threshold of 30°/s was used to define a fixation otherwise the movement was deemed a saccade for this experiment. Although, smooth pursuit eye movements also occur in this range, due to the nature of this experiment it was assumed that these low velocities were fixations. For stable eye-in-head head position, these fixations were grouped together to make a temporal “window” of stable eye temporal data to be compared to LED location.

b) Error

The “windows” of stable eye data were then plotted against the known target locations and compared. For the error calculation, each ‘window’ represented the middle 50% of stable eye data, as this was assumed to be the most accurate portion. A comparison plot of this data is shown in Figure 10. This plot allows for a qualitative view

of the error. For a quantitative analysis of the error, NPV was collected following each subsequent experiment, where each post NPV was the pre-NPV for the next experiment, and compared. If the absolute summed difference between pre- and post-NPV errors exceeded  $\pm 0.95^\circ$ , then data from that experiment was removed as its integrity was considered compromised. This error allowance is a compounded error of resolutions from the measurement devices, target and fovea and is described in detail later in the VOR target foveation section. All collected NPV data was found to be within this error tolerance; thus, no data was excluded from this study.



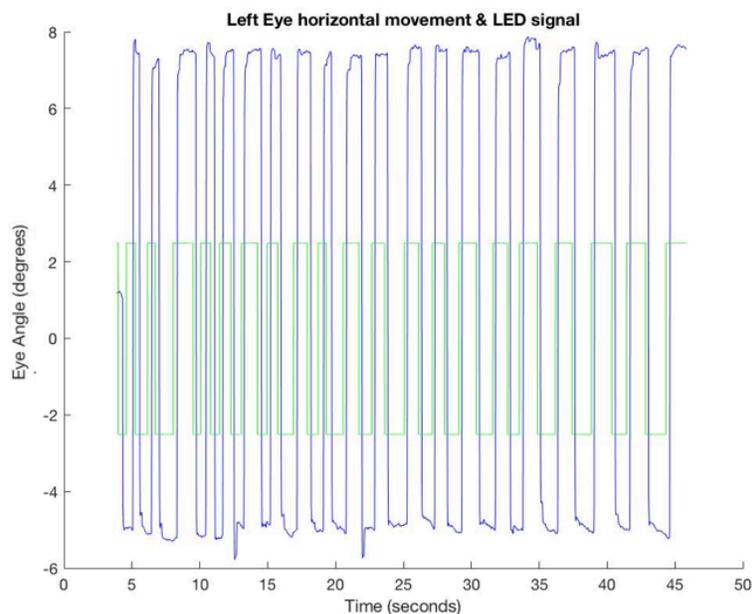
**Figure 10. NPV Error-** Target position indicated by red dots. POI during fixations shown in black. Axes are shown in relation to world coordinates and in meters to represent target and POI locations.

### Experiment 1: Horizontal Volitional Saccade Characterization

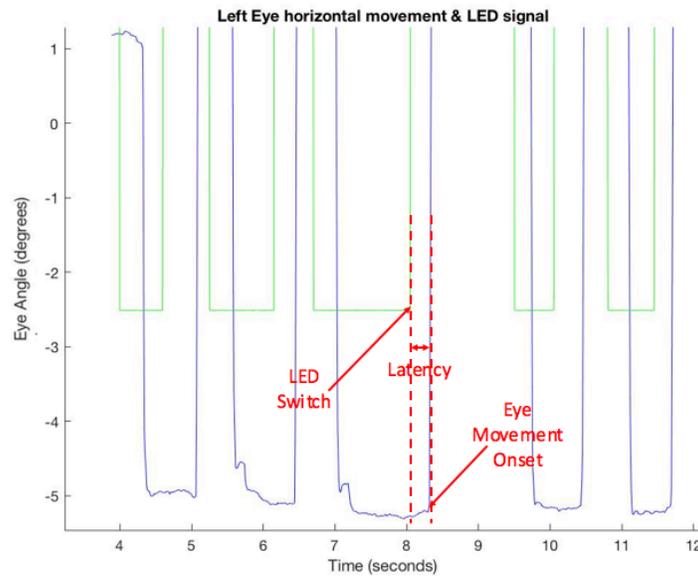
The aim of this experiment was to study the temporal variations of volitional saccades. A volitional saccade is a voluntary eye movement which occurs when a subject changes gaze

fixation from one target to another (Honda, 2002) (i.e. a rapid conjugate shift in gaze to a target). The targets in this experiment are two LEDs (locations 4 and 6, Figure 8 above) located along a horizontal line at subject eye level, 0.381m apart, spanning a visual angle of  $22^\circ$  between them. Each LED occupied a visual angle of  $0.3^\circ$  at 1m.

During this experiment, subjects were instructed to keep their eyes wide open and minimize head movement for the duration of the experiment and to begin by fixating their gaze at a centered LED between the two targets (location 5, Figure 8 above). The target LEDs were lit in an alternating pattern with random transition delays ranging from 550-1500ms, producing an unpredictable pattern. Subjects were instructed to stay visually fixated on the lit LED until it extinguished and they noticed the alternate LED ignite, and to continue to follow the pattern of the LEDs as accurately as possible without and predictions of LED switching. During a 50 second data collection window there were 20 LED changes. Two LED programs were chosen between at random, with different starting LEDs (right or left) and the series was repeated 4 times. A typical stimulus response is represented in Figure 11.



**Figure 11a. Horizontal Eye Angle and LED Signal-** Over-plot of LED signal (green) and horizontal eye angle (blue) response. LED signal +2.5 represents left LED, and -2.5 represents the right LED.



**Figure 11b. LED Response Exploded View-** Zoom-in of latencies between LED signal (green) onset and eye response (blue). Time between LED switch and the Eye Movement onset is defined as the saccadic latency in this situation.

During data analysis, saccades were separated by their direction (left or right) for comparison. Horizontal velocities, temporal latency, and settling time were calculated from both left and right eye data. The error between POI and target location relied on bilateral data as well. Detailed descriptions of the analysis and computation of each variable is described below.

a) Peak Velocity

Typical saccadic velocities range from 300°/s to over 600°/s (Irving et al, 2006; Griffiths, Marshall, & Richens, 1984) and are dependent on the amplitude of the saccadic movement. Peak velocity increases with the amplitude of movement reaching a maximum at around 30° (Griffiths, Marshall, & Richens, 1984). Recall there is a 22° target separation distance in this experiment, so higher velocities are expected. As mentioned previously, raw eye angle data was separated into left and right directions so

the velocities could be found for left and right movement following a target change.

Velocity was calculated using the central difference formula (Equation 8). Peak and mean velocities were calculated for each saccade as well as the standard deviation.

#### b) Latency

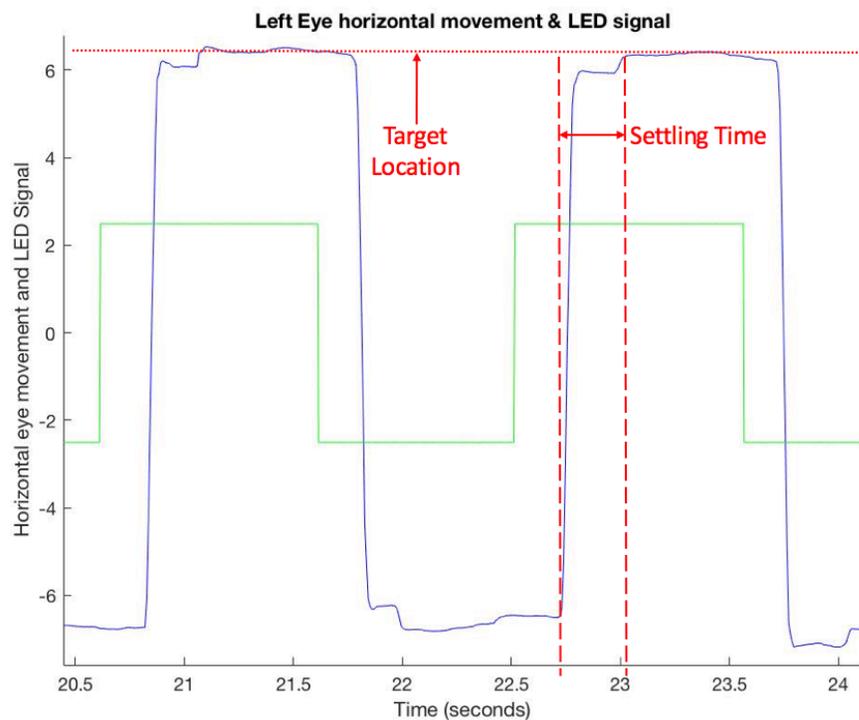
Saccadic latency is defined as the difference between the appearance of a target stimulus and the triggering of a saccade toward the target (Clark, 1999). In this study, latency is defined as the difference between the ignition of a LED and the onset of eye movement in an attempt to fixate on the newly lit LED. The temporal difference between these two events is noted as saccadic latency. A typical saccadic latency period for a horizontal saccade is around 180-200ms (Griffiths, Marshall, & Richens, 1984). It has been observed that saccadic latencies are reduced when the temporal gap between offset of the fixation stimulus and onset of the target stimulus was increased (Clark, 1999). In an effort to minimize saccadic latencies, stimulus target offset and new target onset happened simultaneously in our experiment.

Since the time period of data collection for each series was longer (42 seconds), subjects were instructed to try to minimize blinks. If a blink occurred, to avoid data skewing, it was manually removed from the data set and was replaced by linearly interpolated data.

Mean latencies and standard deviations were calculated for the subject overall as well as for each direction. A visual representation of latencies is exemplified in Figure 11b.

#### c) Settling time

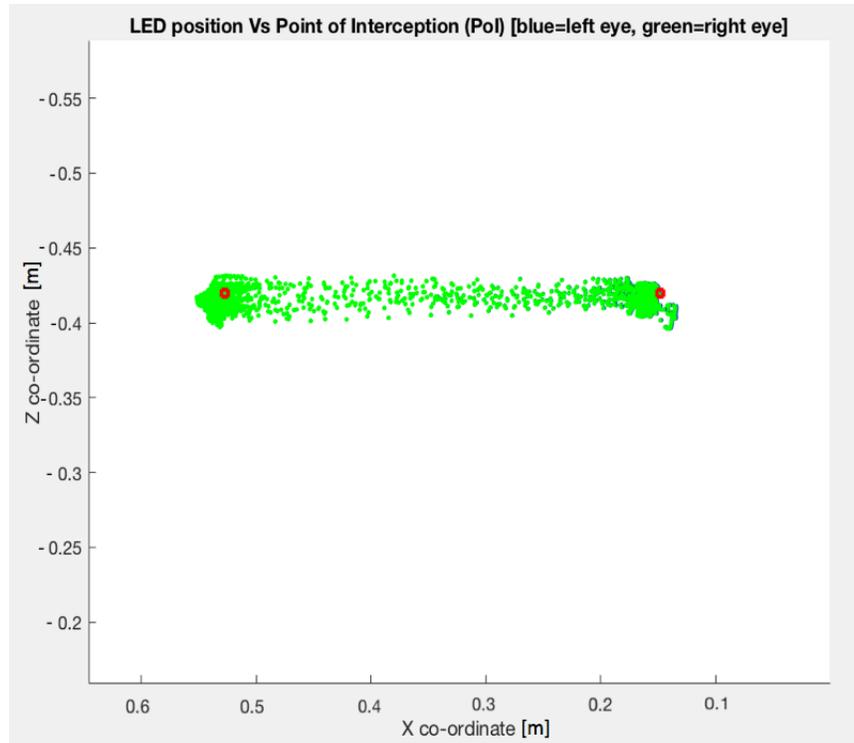
When a person makes a saccade to focus on a target, there is an initial acceleration in eye movement followed by a deceleration of the eye with a goal for it to stop with the target centered on the fovea (i.e. target foveation). It is normal for undershoot of the target, which then initiates secondary corrective saccades to further move eye fixation to reach the target. From the beginning of a saccade to the end of this corrective period (i.e. reducing error  $<1.9^\circ$ ), is defined as the settling time. Figure 12 shows the data that represents the settling time with a clearly defined overshoot and correction.



**Figure 12. Settling Time-** Exploded view of eye response showing settling time duration. Target location represented by the red horizontal line. Horizontal overshoot and subsequent correction is illustrated to represent the settling time.

d) Error

In general terms, error is defined as the difference between stimulus and response. For this experiment, the stimulus is the target location, and the response is the POI (Equation 7). Figure 13 shows a visual representation of the POI during the experiment in relation to the LED targets.



**Figure 13. POI vs LED target-** Typical gaze vector intersection on the target plane using World Axis Coordinates during the saccade experiment. Red dots represent LED target locations. Integrity of data from experiment easily checked as well as any error in gaze locations during experiments. Left and right eye data converges in this example- shown by right eye data (green) plotted over left eye (blue) data.

### Experiment 2: Vestibulo-ocular Reflex (VOR) Characterization

The aim of this experiment was to evaluate the subject's VOR response at a range of frequencies. Subjects were instructed to once more keep their eyes wide open throughout the

entire experiment. However, instead of keeping their head still, there were to keep their eye fixated on a centrally located target (location 5, figure 8) while rotating their head from side to side, or in a yaw direction, to a metronome beat. The target occupied a visual angle of  $0.3^\circ$  at a distance of 1m. The subject's head movements were paced by a metronome ranging from 72-196 bpm, incremented in steps of 20 bpm. The subjects were instructed to make sufficient head rotations (around  $\pm 15^\circ$ ); thus, spanning angular velocities of about 36-98°/s (Table 3). Verbal cues were given during the experiment for the subject to make sufficient head rotations at the higher frequencies to provide a full range of angular velocity data. Each trial consisted of 5 complete head rotations counted by the experimenter. The subject was instructed to start and end with their head in a neutral position, facing straight ahead.

<i>Metronome Pace (beats/min)</i>	<i>Frequency (Hz)</i>	<i>Expected head velocity (°/s) for <math>\pm 15^\circ</math> oscillation amplitude</i>
72	1.20	36.00
92	1.53	46.00
112	1.87	56.00
132	2.20	66.00
152	2.53	76.00
172	2.87	86.00
196	3.27	98.00

*Table 3. Metronome pace (bpm) and expected head velocities (°/s) at which VOR response was analyzed.*

To analyze the VOR response, transverse head and horizontal, angular eye data were extracted. To account for any start position offset, head and eye angular data were zeroed by subtracting the mean of the first 50 values. A typical VOR response can be seen by plotting angular head and eye data against each other. *Figure 14* shows this, and further exemplifies the inverse relationship of these two variables. *Figure 14a* illustrates typical data. *Figure 14b* is an angle/angle diagram of these data. Left and right head movements were separated for analysis

and verification with a positive for a left head movement and negative for a right head movement (fig 14c).

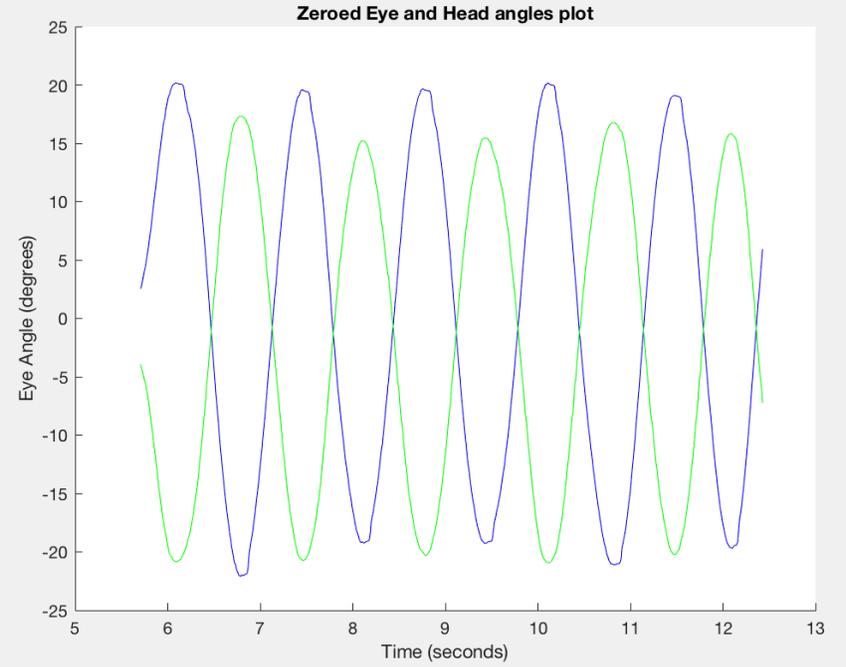
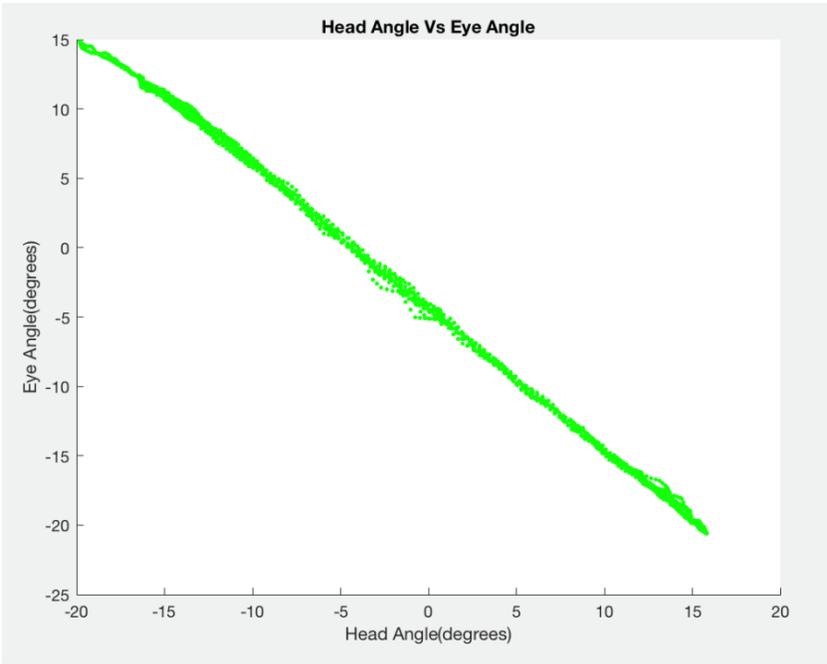
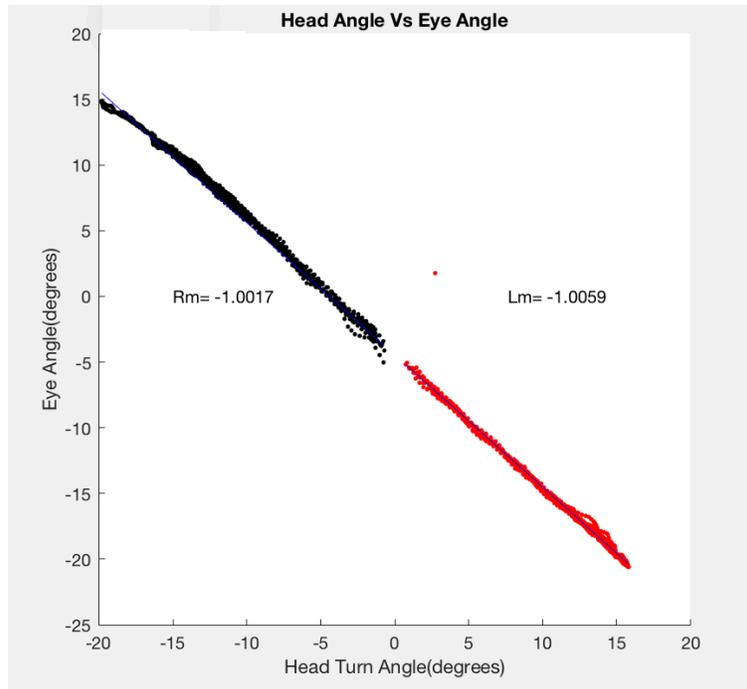


Figure 14a. Temporal Plot of Zeroed Eye and Head Angles- Typical Zeroed head (blue) and zeroed eye (green) angle results on a temporal axis. Note opposite and about equal amplitudes of the two signals showing an active VOR.



**Figure 15b. Zeroed eye and head angles-** Typical Zeroed head vs zeroed eye angle results. Shows ideal 15° amplitude of both head and eye angles during head oscillation.



**Figure 14c. Split direction Head and Eye angles-** Typical results during VOR experiment of right and left head and eye rotations split. Gains for each direction calculated and shown.

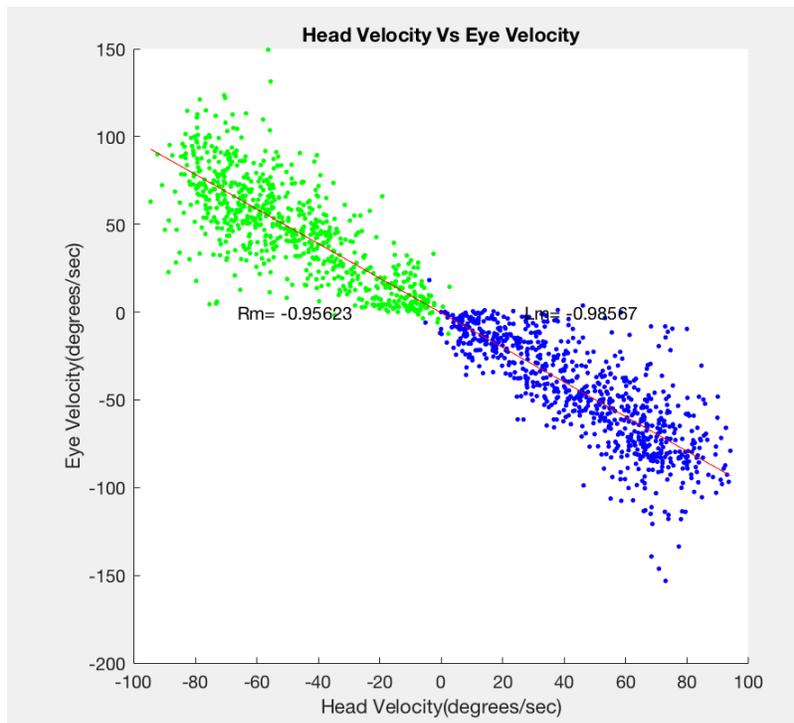
a) Angular Velocity

Angular velocities for the head and eyes were calculated using the previously described central difference method (Equation 8). Subjects in this study were considered healthy and normal (i.e. no motor control disorders, history of eye disease or surgery) zeroed eye angles were assumed congruent between eyes, and horizontal angle data was used from the left eye in this calculation (Viire, 2014).

b) VOR Gain

VOR gain is defined as the change in head angle relative to the change in eye angle during head movement, or, similarly, the ratio of head velocity to eye velocity.

Head and eye movements ideally are equal in amplitude and opposite in direction, yielding a gain of -1. In other words, a compensatory eye velocity and an equal head velocity but in the opposite direction; thus, allowing for stable retinal presentation of the target. Typical gain data is presented below (Figure 15) in the plot of angular head velocity vs angular eye velocity. Gain is represented as the slope of the linear regression line through the data. For each trial, a total gain was calculated as well as gains for left and right head movements. Distinction between left and right head movement was noted previously as positive angles representing a left head movement and negative angles representing a right head movement.

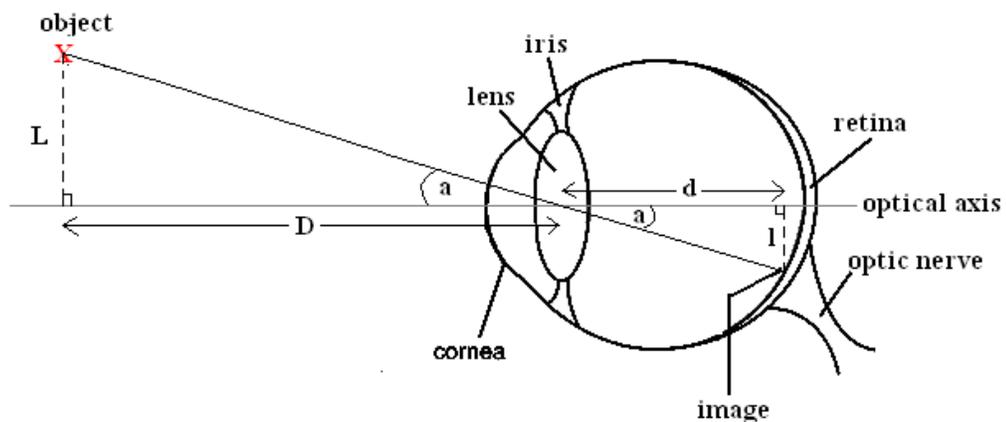


**Figure 16. Head vs Eye Velocity-** Typical Head vs Eye Velocity plot with linear regression for left and right directions shown.

Velocities were also separated for left and right head movements. A maximum, minimum and average velocity were found from this data.

c) Target Foveation

When the eyes track/fixate on an object, the image is seen using central vision (i.e. vision where the image is centered on the fovea). The fovea is the part of the eye in the retina responsible for acute central vision. Due to its high number of photoreceptors, visual acuity is the highest in the fovea; thus, while fixating, the eyes adjust to center the targeted image on the fovea. Compensatory eye movements caused by the VOR serve to stabilize binocular fixation on a target in space allowing for the eye to maintain a stable bifoveate image (Paige, Telford, Seidman, & Barnes, 1998). Although important for visual acuity, the fovea only occupies a visual field of 1°. The goal of the VOR is to promote central vision as the head moves, maximizing visual acuity.



$$\tan(a) = \frac{L}{D} = \frac{l}{d}$$

**Figure 17. Trigonometry of Object Location on Retina-** Relationship to find the location of an image on the retina. (Hedge, 2010)

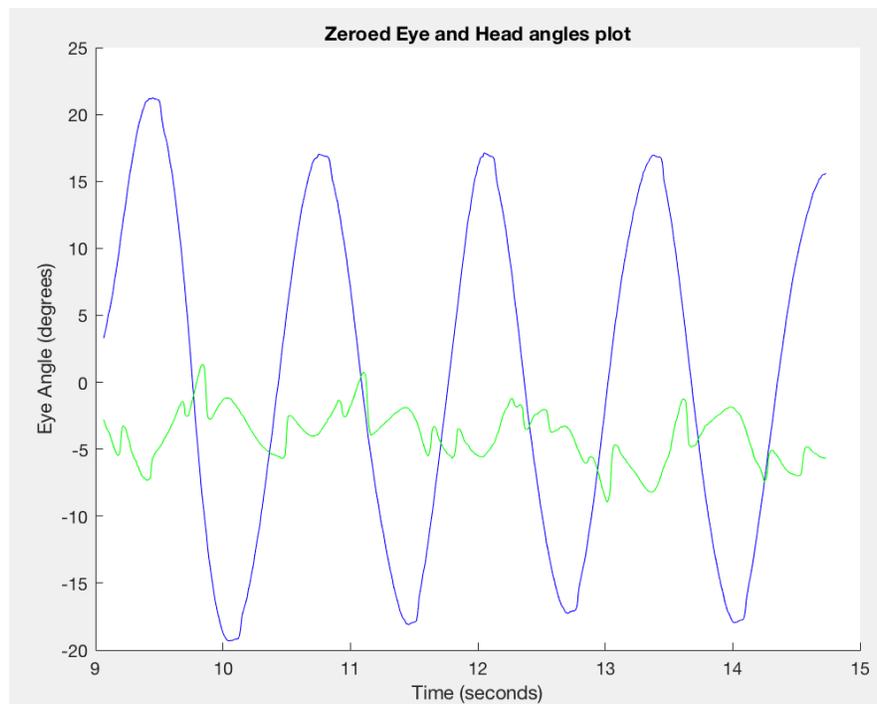
Since the eye-in-space location is known and the POI had been calculated, it is possible to determine when the target is centered on a subject's fovea (Figure 16). As the subject's head moves and the VOR is initiated, it is expected that target foveation will not be constant and retinal blurring or smearing of the image on the retina will occur. Therefore, target foveation can be expressed as a percentage of total data collection time, from the beginning of head movement until it ceases, where the error (Equation 7) is less than 3.8. This error is a compounded of the resolutions of the fovea ( $1^\circ$ ), the target ( $0.3^\circ$ ), EyeLink II™ ( $0.5^\circ$ ), and Motion Monitor ( $0.1^\circ$ ). The sum of these resolutions equals  $1.9^\circ$  ( $\pm 0.95^\circ$ ) and is used in the previous experiments as well. Due to extreme head movements during this experiment, the error allowance was doubled to  $3.8^\circ$ .

### Experiment 3: VOR Suppression (VORc)

The aim of this experiment was to determine a subject's ability to suppress their VOR. A black-trifold foam board (dimensions 0.914m x 1.22m) replaced the target display board at the same location and positioning. Light, but visible, marks were made on the board to represent a distance from the center at which the visual angle would be  $\pm 15^\circ$  for the subject at 1m away. A laser pointer was affixed to the headpiece and in line with the subject's cyclopean eye and turned on. With this setup, as the subject's head moved, the dot from the laser pointer also moved with the head. The dot from the laser pointer was smaller than the LED targets and occupied a visual field of about  $0.1^\circ$ . The sides of the trifold foam board were slightly angled in account for any overshoot of the laser during head movement. Ideally, this board would be curved to allow for constant target distance as the head rotates; however, for this experiment a board with slightly angled in sides was assumed to be congruent.

Once more, keeping their eyes open wide subjects were instructed to perform the same head movements as the previous experiment (yaw to a metronome beat). However, in this experiment subjects were to follow the red laser dot as accurately as possible as it moved with their head. For a head-fixed target, successful suppression of the VOR should result in head and eye angle difference of  $0^\circ$ . The eyes are fixed on the target, so as the head moves the eyes should move with it. Successful fixation on the target results in suppression of the VOR.

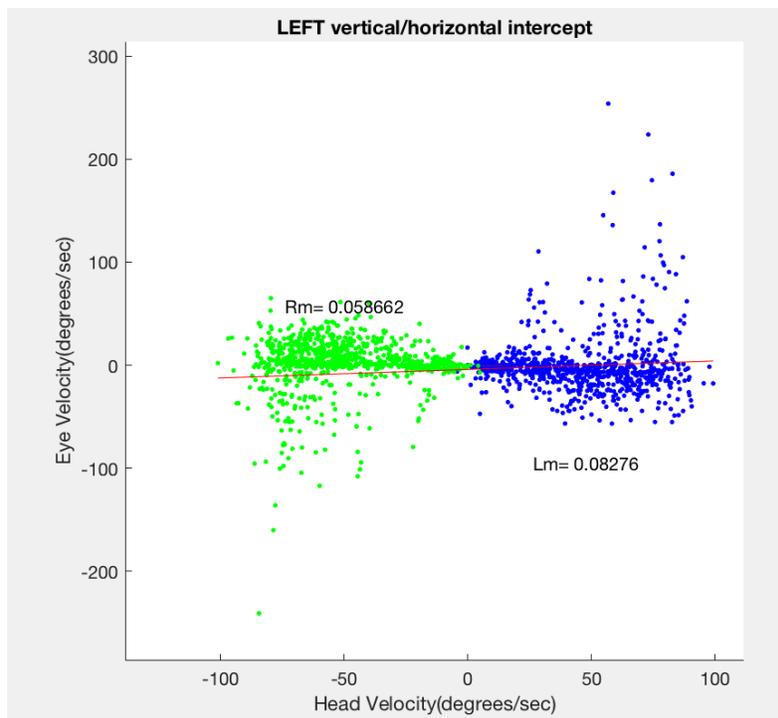
Just as in the experiment characterizing the VOR, transverse eye and head data was extracted and zeroed to account for any offset in start position. A typical example of the temporal data is shown in Figure 17 (zeroed eye (left and right) and zeroed head), Eye and head angles. Figure 17b illustrates near constant eye angle (eye-in-head) over a range of head angles ( $\pm 25^\circ$ ). Left and right head and eye movement data was separated for analysis once more. The variables analyzed and their calculations are described below.



**Figure 18. Zeroed eye and head angles-** Head angle (blue) vs eye angle (green). Note head rotational range about  $\pm 15^\circ$  as eye angle stays relatively constant. This illustrates successful VOR suppression.

a) VORc Gain

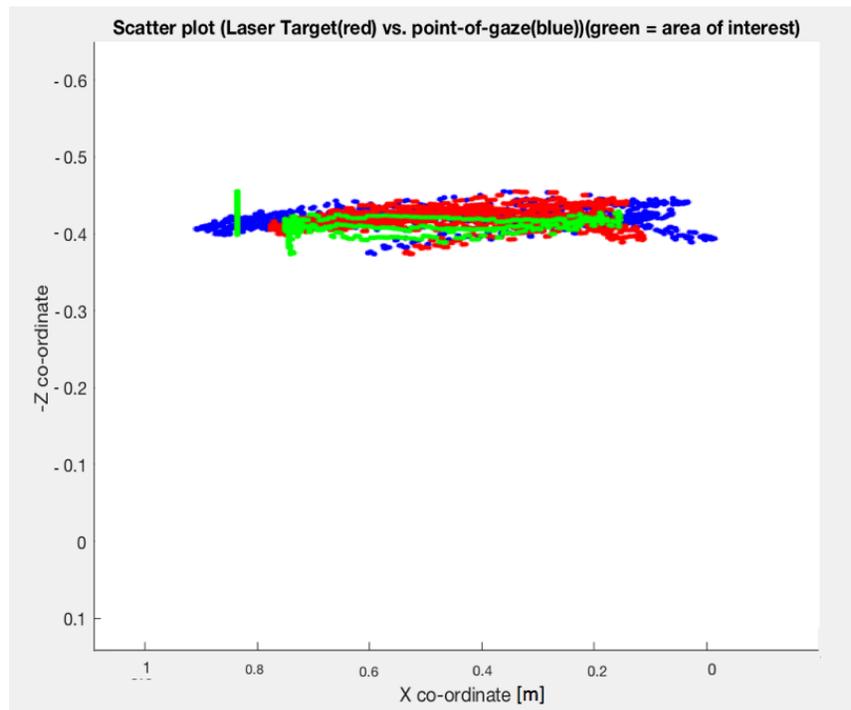
VORc gain was calculated in the same manner as VOR gain as a ratio between head and eye velocity. Theoretically, successful VOR suppression should yield and gain of 0 for a condition where the target is head-fixed (Paige, Telford, Seidman, & Barnes, 1998). An illustration of successful VOR suppression is shown in Figure 18. Left, right and singular total gains were calculated for each trial.



**Figure 19. VORc Gain-** Typical VOR suppression results and plot. Left and Right directions separated and between left and right and shown.

b) Target Foveation

Target foveation was calculated as a percentage of total data collection with the same method used in the VOR characterization experiment (percentage of data with an error  $< 3.8^\circ$ ). However, the target for this experiment was the dot produced from the laser. Its location on the black, tri-foam board was found using the location of the subject's cyclopean eye, POI and zeroed head angle.



**Figure 20. VORc Gaze and Target Path.-** Typical results during VORc experiment. Laser and POI paths in relation to the area of interest where they are expected. Blue represents POI, Red is the laser dot, and green is the  $\pm 15^\circ$  area of interest looked at.

Figure 19 shows the intersection of the target laser and gaze vector on the target plane (black, tri-fold board). Differences between the subject's gaze and the laser is easily seen from this figure and qualitatively assessed for error in the trial. Visually, target foveation is represented by the overlap of the POI and the laser during each experiment in this figure.

## RESULTS

To investigate the differences between Elite Athlete and Non-Elite VOR responses and suppression capabilities, subjects were separated into their respective groups, and additionally matched with their age and gender counterpart in the opposite group. Data was analyzed between the two groups as a whole, as well as between the matched pairs (Table 4). All data analyzed was considered to have a normal or near normal distribution through tests of normalcy and analyzing histogram plots of data; thus, parametric statistics were used in the analysis of these data.

<i>Pair</i>	<i>Elite Athlete</i>	<i>Non-Elite</i>	<i>Gender</i>	<i>Age</i>
1	A_CM	N_NF	F	26
2	A_KB	N_RS	F	23
3	A_LR	N_AC	F	27/28
4	A_TT	N_WP	F	25
5	A_ST	N_DL	M	27
6	A_JP	N_SC	M	28

*Table 4. Elite Athlete and Non-Elite Gender and Age Pairings*

### **Innate Athleticism Tests**

#### Sports Performance Index (SPI)

Scores from the Sports Performance Index survey were averaged for each group and are shown in the table below. In this survey, a higher SPI score correlates to a greater athletic psychological tendency. Results are shown in Table X. The mean score was found to be  $159 \pm 20.61$ . An independent sample t-test (SPSS) was performed comparing the Elite Athlete and Non-Elite groups, but no statistically significant differences were found ( $p > 0.05$ ) between the two groups. However, this could be due to the large standard deviations of each group, as the Elite Athletes averaged higher scores than the Non-Elites. This trend would support a correlation between SPI scores and athlete type.

<i>Sports Performance Index Score</i>			
	<b>N</b>	<b>AVG [points]</b>	<b>STDEV</b>
<i>Elite Athletes</i>	6	170.67	19.19
<i>Non-Elites</i>	6	147.33	-15.49

*Table 5. Averages Sports Performance Index Among Groups*

### Hand-Eye Coordination

Hand-eye Coordination scores for each subject were averaged to give one score representing coordination of the subject. Results are shown in Table X. The mean score was found to be  $29.97 \pm 7.47$ . An independent samples t-test (SPSS) was performed comparing the Elite Athlete and Non-Elite groups. No statistically significant differences were found ( $p > 0.05$ ) confirming a correlated relationship between the groups. However, this could be due to the large standard deviations of each group, as the Elite Athletes averaged higher scores than the Non-Elites. Such trend supports a correlation between hand eye coordination and athlete type.

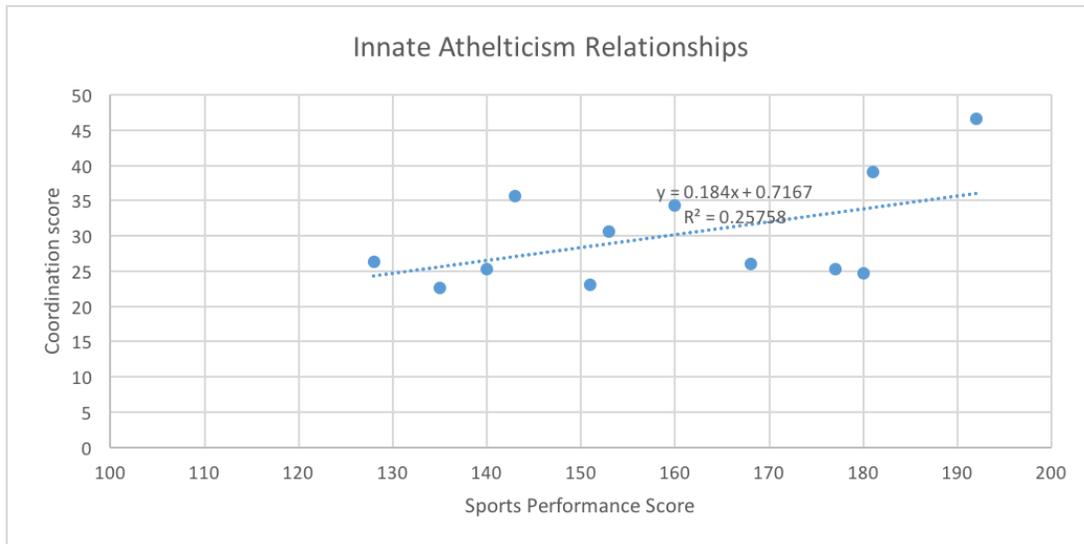
<i>Hand-Eye Coordination Scores</i>			
	<b>N</b>	<b>AVG [catches]</b>	<b>STDEV</b>
<i>Elite Athletes</i>	6	32.39	9.55
<i>Non-Elites</i>	6	27.56	4.20

*Table 6. Averaged Hand-Eye Coordination Scores among Groups*

### Innate Testing Variables Relationship

Previously presented in this paper is evidence which supports the theory that both psychological tendencies and coordination can be used as a measure of innate athleticism. *Figure 20* below shows the relationship of the two innate athleticism variables measured in this study. A bivariate correlation test (SPSS) was conducted using the raw, ungrouped data from each subject. The Pearson coefficient (R) for coordination and SPI was 0.508 which is statistically significant

( $p < 0.05$ ) based on all 12 observations. This slight positive correlation can also be seen in Figure 21 and its associated  $R^2$  value.



*Figure 21. Relationship between Coordination and Athletic Psychological Tendency*

### **Nine Point Validation (NPV)**

This data was used as a quality control measure for analyzing error throughout data collection as some experiments required vigorous head movements which could affect the calibration of the equipment. NPV's were collected before and after each experiment and the error between the targets and difference from previous error values was calculated for each NPV. Error tolerance has been discussed previously with a value of  $\pm 0.95^\circ$ . All subject's NPV error fell within this range for the duration of each data collection; therefore, no data sets were excluded from this study.

### **Experiment 1: Horizontal Volitional Saccade Characterization**

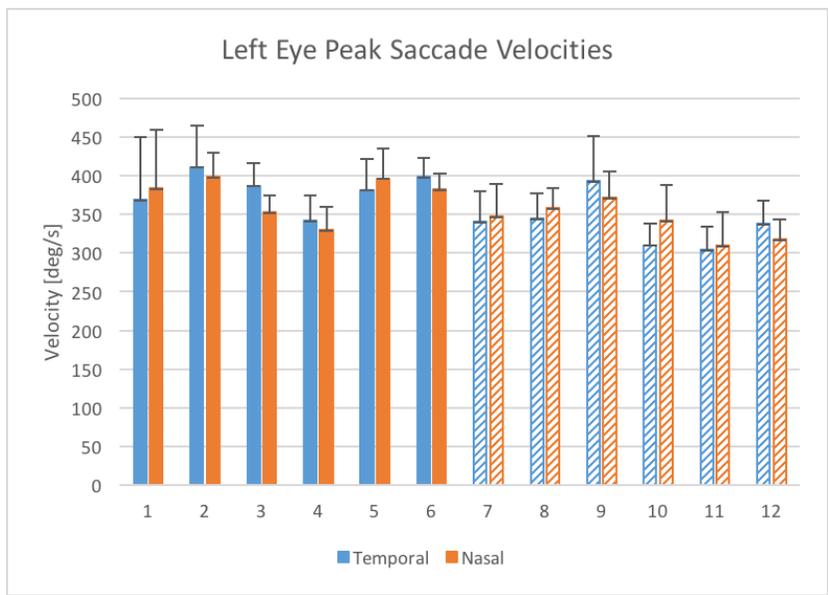
The separated eye movement directions were further categorized into temporal and nasal directions for each eye and values for each variable were compared against each other.

Peak Saccade Velocity

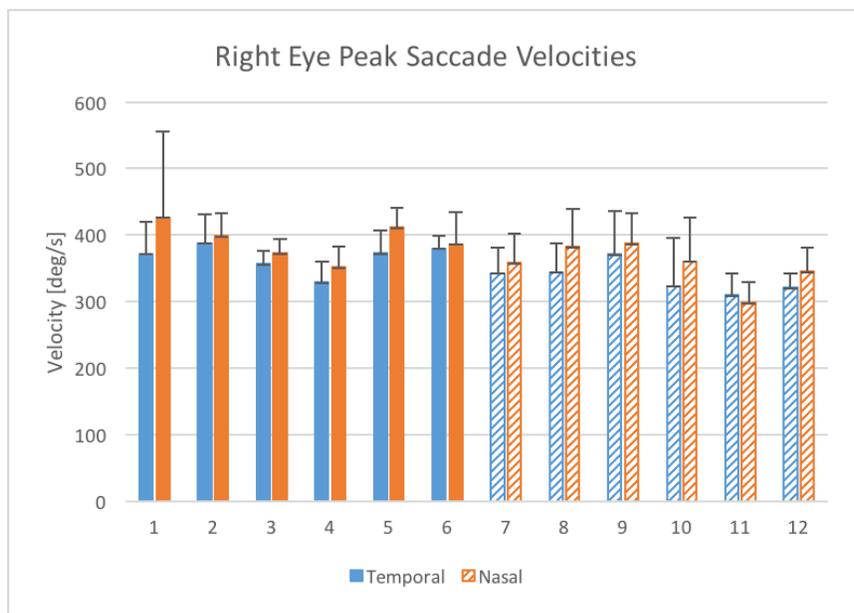
An independent sample t-test (SPSS) was used to compare the temporal and nasal saccadic velocities for each eye between Elite Athletes and Non-Elites. It was found that the Elite Athletes had higher right temporal saccadic velocities ( $366.70^{\circ}/s \pm 20.98$ ) than the Non-Elites ( $335.60^{\circ}/s \pm 22.09$ ),  $p = 0.031$ . Subsequently, to determine whether elite sport type had an effect on right temporal velocities, the elite athletes were split between gymnasts and non-gymnasts and an ANOVA was performed with the 3 groups. However, no statistically significant differences ( $p > 0.05$ ) were found. The results are shown in *Table 7* and *Figures 21a and 21b*.

<i>SACCADE PEAK VELOCITIES [<math>^{\circ}/s</math>]</i>								
	Left eye				Right Eye			
	Temporal		Nasal		Temporal		Nasal	
	AVG	STDEV	AVG	STDEV	AVG	STDEV	AVG	STDEV
<i>Elite Athletes</i>	381.42	24.17	374.07	26.85	366.70	20.98	391.42	27.18
<i>Non-Elites</i>	338.56	31.38	340.91	23.50	335.60	22.09	355.40	31.91

*Table 7. Averaged Peak Saccade Velocities*



**Figure 22a. Averaged Left Eye Peak Saccade Velocities-** Results separated by subject. Subjects 1-6 are (solid) elite athletes and 7-12 (striped) are non-elites.



**Figure 21b. Averaged Right Eye Peak Saccade Velocities-** Results separated by subject. Subjects 1-6 are (solid) elite athletes and 7-12 (striped) are non-elites.

## Latency

An independent sample t-test (SPSS) was used to compare the temporal and nasal latencies for each eye between Elite Athletes and Non-Elites. It was found that the Elite Athletes had statistically significant higher right eye nasal latencies ( $0.238s \pm 0.036$ ) than the Non-Elites ( $0.189s \pm 0.027$ ),  $p = 0.023$ . Subsequently, to determine whether elite sport type had an effect on right nasal latencies, the Elite Athletes were split between gymnasts and non-gymnast Elite Athletes and an ANOVA was performed with the 3 groups. It was found that the non-gymnast Elite Athletes had a larger right eye nasal latency ( $.262s \pm 0.031$ ) than the gymnasts ( $.214s \pm 0.022$ ),  $p = 0.013$ . The results are shown in *Table 8a* and *8b*, and *Figures 22a* and *22b*.

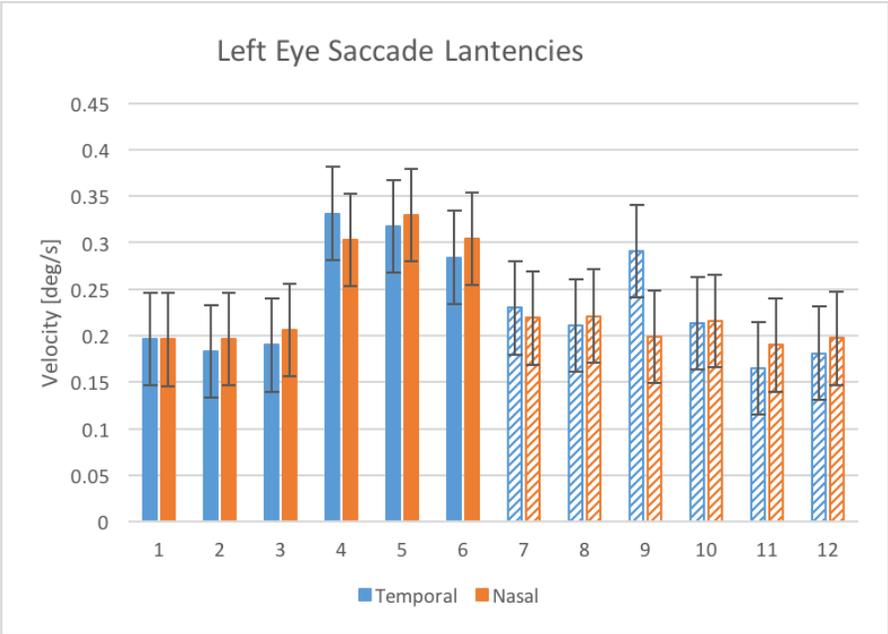
<b>SACCADE LATENCIES [s]</b>								
	<b>Left eye</b>				<b>Right Eye</b>			
	<b>Temporal</b>		<b>Nasal</b>		<b>Temporal</b>		<b>Nasal</b>	
	<b>AVG</b>	<b>STDEV</b>	<b>AVG</b>	<b>STDEV</b>	<b>AVG</b>	<b>STDEV</b>	<b>AVG</b>	<b>STDEV</b>
<i>Elite Athletes</i>	0.250	0.068	0.256	0.063	0.236	0.040	0.238	0.036
<i>Non-Elites</i>	0.215	0.044	0.207	0.013	0.209	0.015	0.189	0.027

*Table 8a. Averaged Saccade Latencies*

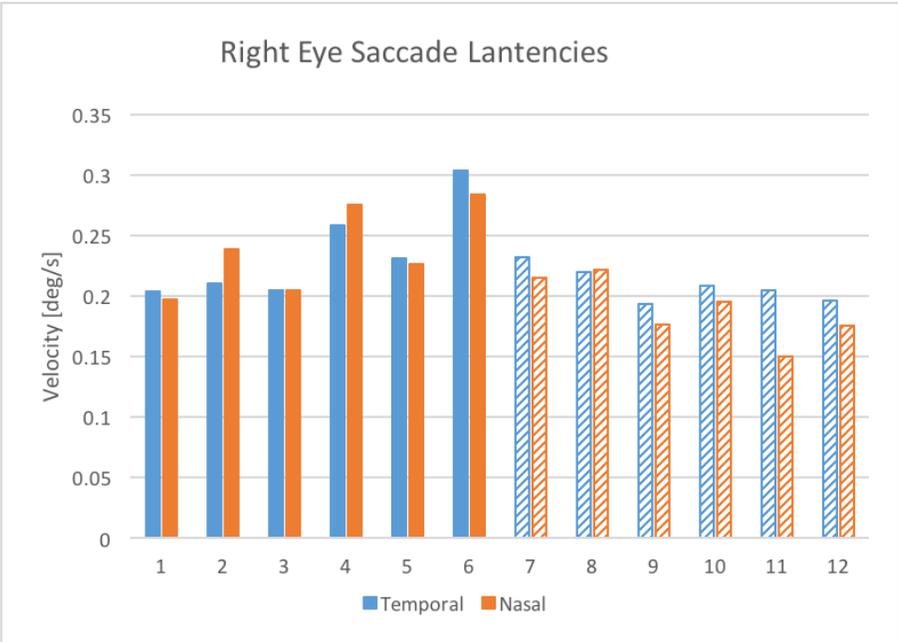
<b>Right Eye Nasal Latencies [s]</b>		
<b>Athlete Type</b>	<b>AVG</b>	<b>STDEV</b>
<i>Gymnast</i>	0.197	0.035
<i>Gymnast</i>	0.239	0.131
<i>Gymnast</i>	0.205	0.041
<i>Non-Gymnast</i>	0.275	0.237
<i>Non-Gymnast</i>	0.227	0.027
<i>Non-Gymnast</i>	0.284	0.136
<i>Non-Elite</i>	0.215	0.046
<i>Non-Elite</i>	0.221	0.045
<i>Non-Elite</i>	0.177	0.123
<i>Non-Elite</i>	0.196	0.063
<i>Non-Elite</i>	0.150	0.039

<i>Non-Elite</i>	0.175	0.068
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**Table 8b. Averaged Right Eye Nasal Saccade Latencies-** Elite Athlete Types divided between gymnasts and non-gymnasts



**Figure 23a. Averaged Left Eye Latencies-** Subjects 1-3 are gymnasts, 4-6 Elite non-gymnasts, and 7-12 (striped) non-elites.



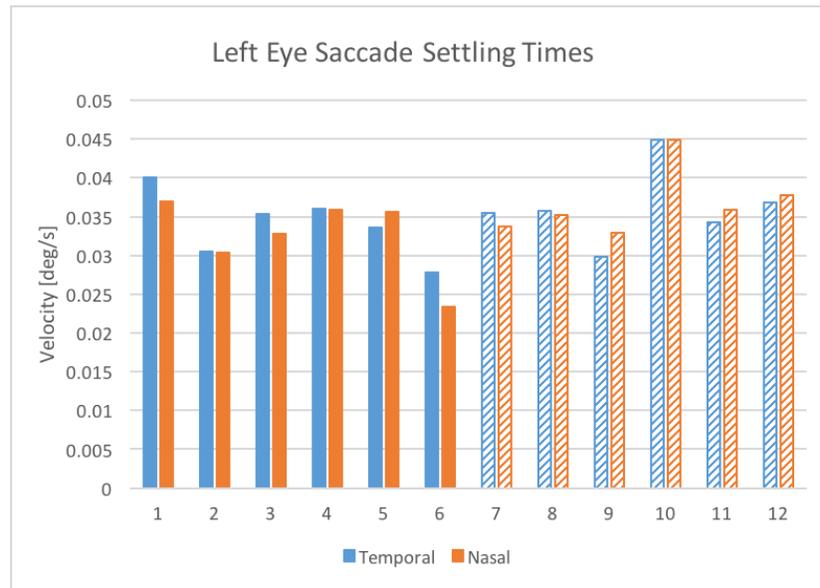
**Figure 24b. Averaged Right Eye Latencies-** Subjects 1-3 are gymnasts, 4-6 Elite non-gymnasts, and 7-12 (striped) non-elites.

## Settling Time

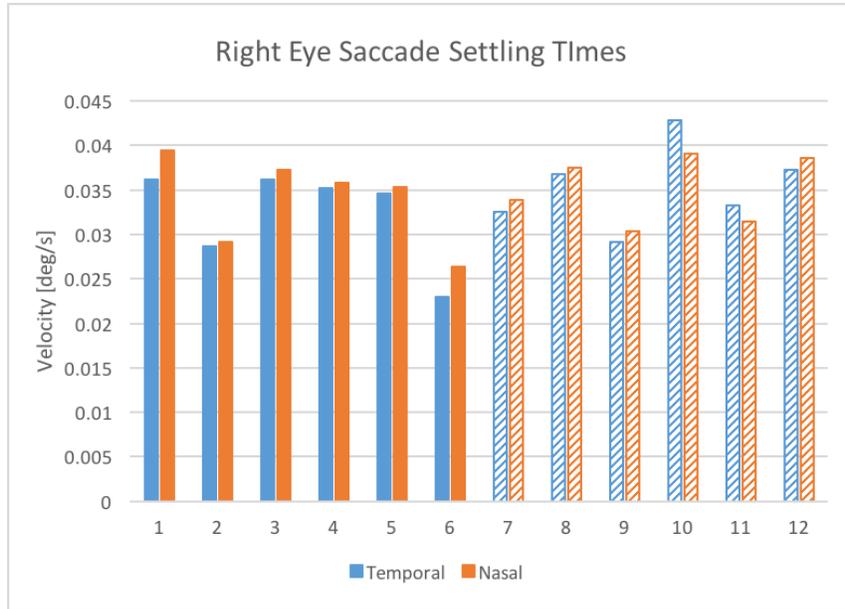
An independent sample t-test (SPSS) was used to compare the temporal and nasal settling times for each eye between Elite Athletes and Non-Elites. No statistically significant differences were found between the groups ( $p > 0.05$ ). This implies both a nasal/temporal and eye performance symmetry between the groups. Results for settling times are shown in *Table 9* and *Figures 24a* and *24b*.

<i>SACCADE SETTLING TIMES [s]</i>								
	Left eye				Right Eye			
	Temporal		Nasal		Temporal		Nasal	
	AVG	STDEV	AVG	STDEV	AVG	STDEV	AVG	STDEV
<i>Elite Athletes</i>	0.034	0.004	0.033	0.005	0.032	0.005	0.034	0.005
<i>Non-Elites</i>	0.034	0.002	0.037	0.004	0.035	0.005	0.035	0.004

*Table 9. Average Saccade Settling Times*



*Figure 25a. Averaged Left Eye Settling Times*- Results separated by subject. Subjects 1-6 (solid) are elite athletes and 7-12 (striped) are non-elites.



**Figure 26b. Averaged Right Eye Settling Times-** Results separated by subject. Subjects 1-6 (solid) are elite athletes and 7-12 (striped) are non-elites.

### Saccade Foveation

An independent sample t-test (SPSS) was used to compare the foveations between the Elite Athletes and Non-Elites. No statistically significant differences were found between the groups ( $p > 0.05$ ). Table 10 shows these findings.

<i>Saccade Foveation</i>		
	<b>AVG</b>	<b>STDEV</b>
<i>Elite Athletes</i>	75.975	20.0378
<i>Non-Elites</i>	88.318	13.280

**Table 10. Saccade Foveation Averages**

### Pairings

A one-way ANOVA was performed between the 6 pairs of matched subjects with peak saccade velocity, latency and settling time data. No statistically significant differences were found between the pairs when analyzing the specified saccade data.

### Experiment 2: Vestibulo-ocular Reflex (VOR) Characterization

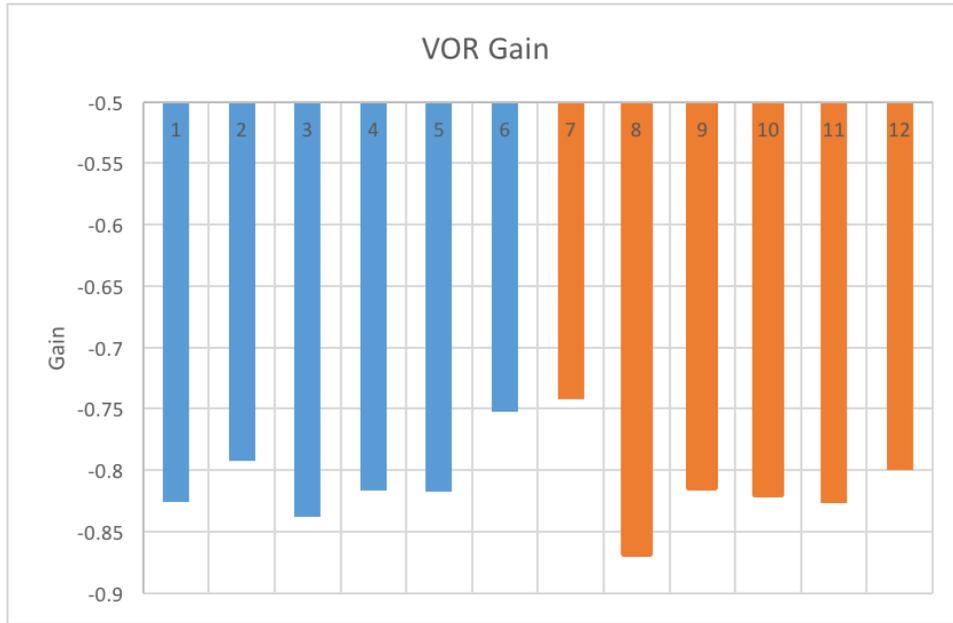
VOR gains were calculated for each subject as they rotated their heads about the superior/inferior axis (from side to side) while the subjects visually fixated on a stationary, lit LED target. As mentioned previously, the results were additionally separated into left and right head rotation directions. Gains were calculated for each direction as well as a total composite gain (Table 11). The expected value for the gain for this experiment was -1, representing equal and opposite head and eye directional movements. All subjects demonstrated a gain close to this, exhibiting a normal, expected VOR response.

#### VOR Gain

An independent sample t-test (SPSS) was performed between the gains of Elite Athlete and Non-Elite groups. No statistically significant differences were found ( $p > 0.05$ ) between groups. Results are shown in *Table 11* and *Figure 26*.

<i>VOR GAIN</i>						
	<b>Total</b>		<b>Left</b>		<b>Right</b>	
	<b>Average</b>	<b>Stdev</b>	<b>Average</b>	<b>Stdev</b>	<b>Average</b>	<b>Stdev</b>
<i>Elite Athletes</i>	-0.807	0.031	-0.808	0.037	-0.811	0.032
<i>Non-Elites</i>	-0.812	0.041	-0.817	0.049	-0.808	0.045

*Table 11. VOR Gains-* Separated into Total gains as well as Left and Right head directions.



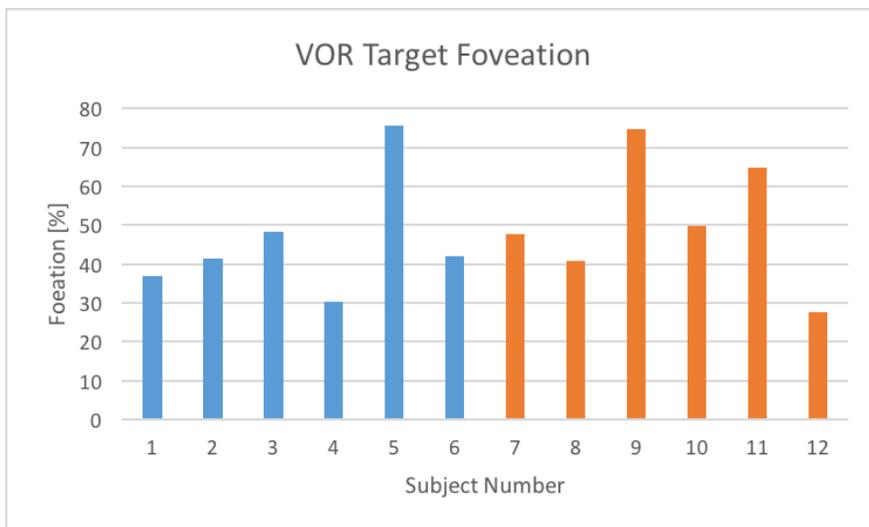
**Figure 27. Total VOR Gains-** Elite Athlete gains are subjects 1-6 (blue) and Non-Elites are subjects 7-12 (red).

### Target Foveation

As explained previously, foveation during this experiment was found as a percentage of the total data collection when the subject’s visual field is focused on their fovea. An independent sample t-test (SPSS) was performed on target foveation between Elite Athlete and Non-Elite groups. No statistically significant differences were found ( $P>0.05$ ) from this analysis. The results are shown below in *Table 12* and *Figure 27*.

<b>VOR FOVEATION [%]</b>		
	<b>AVG</b>	<b>STDEV</b>
<i>Elite Athletes</i>	45.72	15.82
<i>Non-Elites</i>	50.86	5.28

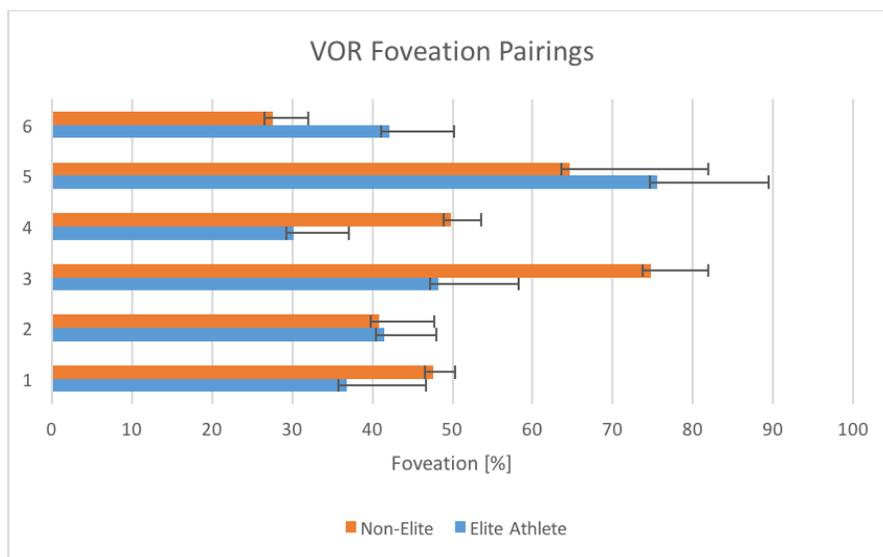
**Table 12. Averaged Foveation During VOR Experiments**



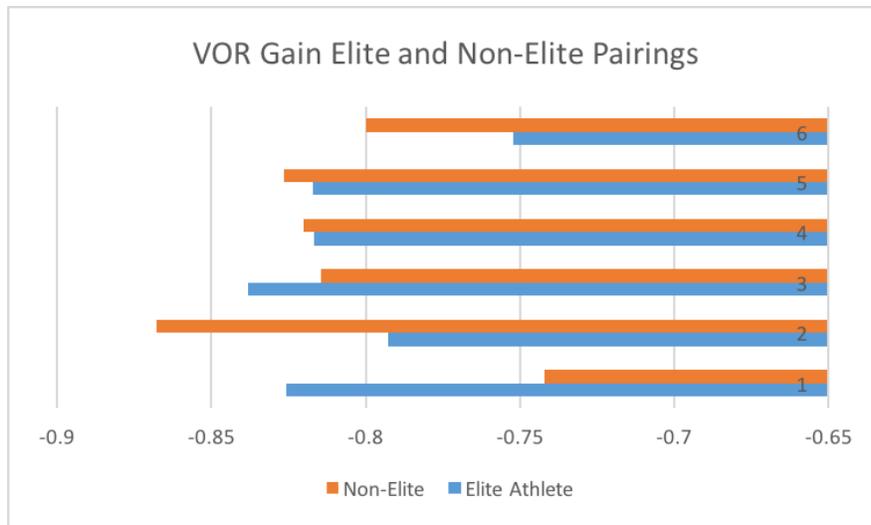
**Figure 28. Target Foveation during VOR Experiments-** Elite Athletes are shown as subject 1-6 (blue) and Non-Elites as subjects 1-7 (red).

### Pairings

A one-way ANOVA was performed between the 6 pairs of matched subjects with VOR gain and VOR foveation. No statistically significant differences were found between the pairs when analyzing the specified VOR data.



**Figure 29. VOR Foveation Pairings-** Elite Athlete and Non-Elite pairings plotted to compare VOR foveation.



**Figure 30. VOR Gain Parings-** Elite Athlete and Non-Elite pairings plotted to compare VOR gain.

#### **Experiment 4: Vestibulo-ocular Reflex Suppression/Cancellation (VORc)**

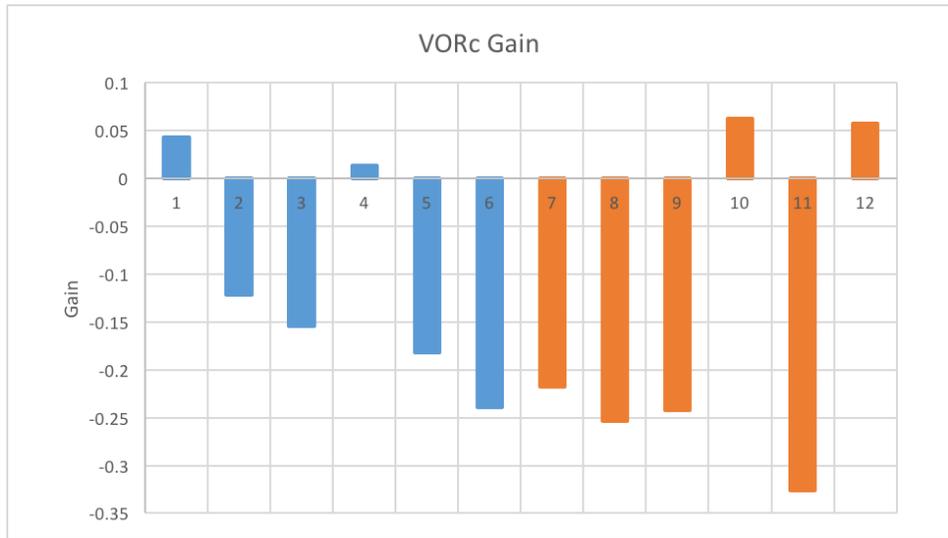
VORc gains were calculated for each subject as they rotated their head around the superior/inferior axis (side-to-side) while they visually fixated on a target produced by a laser attached to their head (i.e. target and head movement linked in direction and amplitude). An overall, total gain was calculated along with a left and right gain from the separated data into left and right directions mentioned previously. In this experiment, the ideal VORc gain would be near zero, representing perfect fixation on the target as the head rotates. A VORc gain of zero represents complete suppression of the VOR system. While all subjects exhibited gains close to zero, some subjects were better at suppressing their VOR than others.

#### VORc Gain

An independent sample t-test was performed on VORc gains between Elite Athlete and Non-Elite groups. No statistically significant differences were found ( $p > 0.05$ ) between these groups for VORc gain. *Table 13* and *Figure 30* show these results.

	<b>VORc GAIN</b>					
	<b>Total</b>		<b>Left</b>		<b>Right</b>	
	<b>Average</b>	<b>Stdev</b>	<b>Average</b>	<b>Stdev</b>	<b>Average</b>	<b>Stdev</b>
<i>Elite Athletes</i>	-0.107	0.112	-0.104	0.109	-0.120	0.130
<i>Non-Elites</i>	-0.153	0.169	-0.168	0.208	-0.143	0.169

**Table 13. Averaged VORc Gains.** – Left, Right and Total gains shown for both groups.



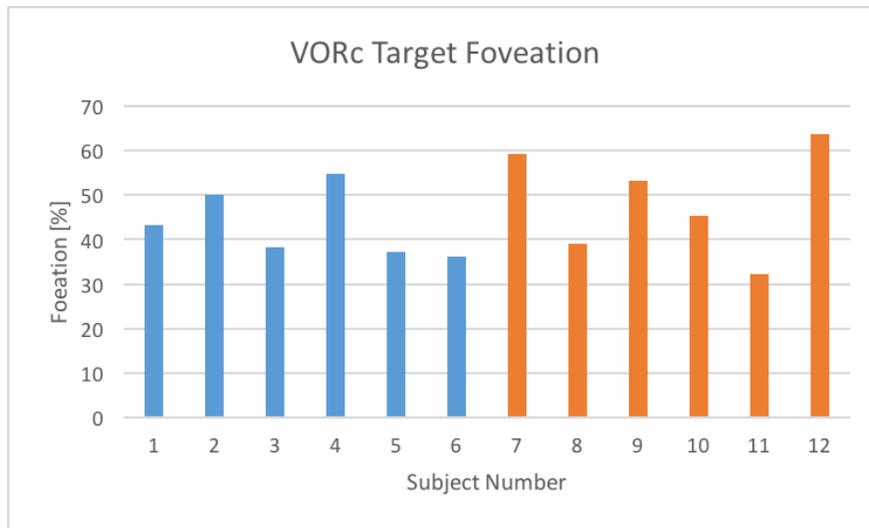
**Figure 31. Target Foveation during VORc Experiments-** Elite Athletes are shown as subject 1-6 (blue) and Non-Elites as subjects 1-7 (red).

VORc Foveation

As explained previously, foveation during this experiment was found as a percentage of the total data collection when the target focused on the subject’s fovea. An independent sample t-test (SPSS) was performed on target foveation between elite athlete and non-elite groups. No statistically significant differences were found ( $P>0.05$ ) from this analysis.

	<b>VORc FOVEATION</b>	
	<b>AVG</b>	<b>STDEV</b>
<i>Elite Athletes</i>	43.31	7.67
<i>Non-Elites</i>	48.83	12.11

**Table 14. Averaged Foveation During VORc Experiments**



**Figure 32. Target Foveation during VOR Experiments-** Elite Athletes are shown as subject 1-6 (blue) and Non-Elites as subjects 1-7 (red).

### Pairings

A one-way ANOVA was performed between the 6 pairs of matched subjects using VORc gain and VORc foveation. No statistically significant differences were found between the pairs when analyzing the specified VORc data. The results from this ANOVA imply neither the ages tested (23-28 years old) nor gender have a statistically significant effect on the VORc gain or VORc foveation in this case.

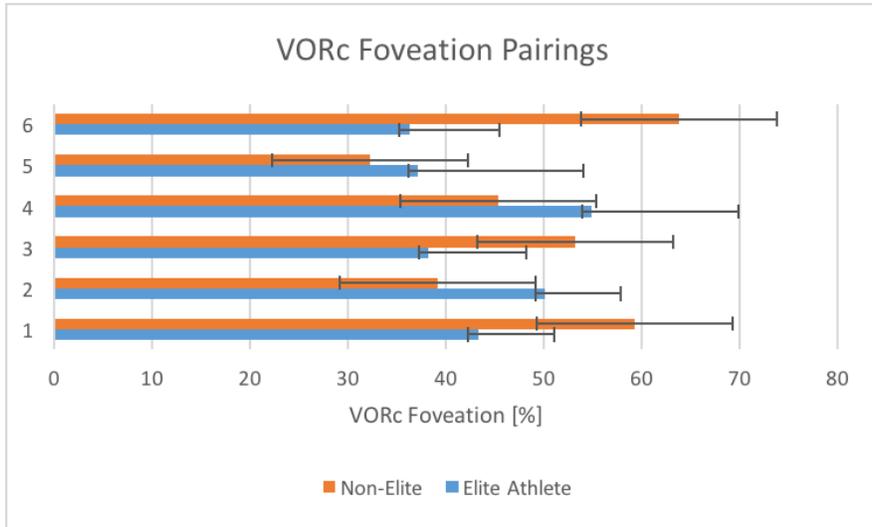


Figure 33. *VORc Foveation Pairings*- Elite Athlete and Non-Elite pairings plotted to compare VORc foveation.

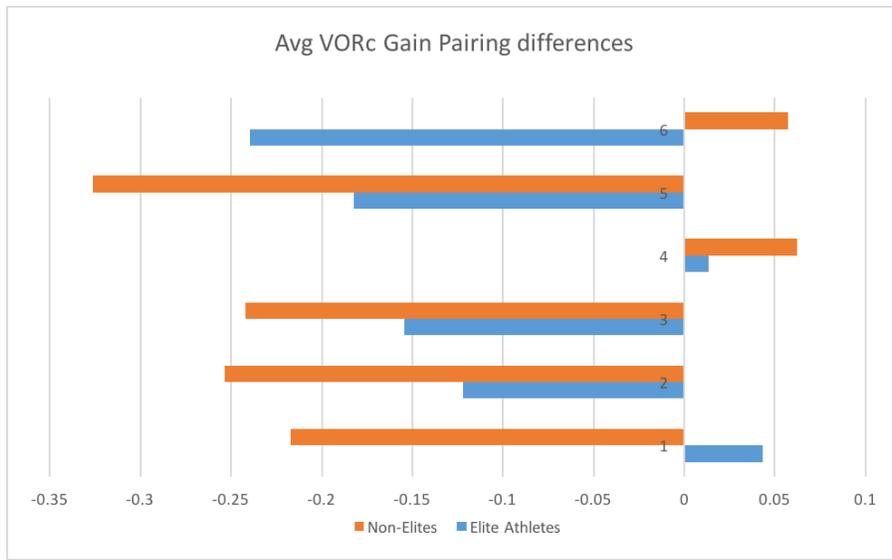


Figure 34. *VORc Gain Pairings*- Elite Athlete and Non-Elite pairings plotted to compare VORc gain.

## VOR and VORc Characterization

Recall that the pace for head movement was set by a metronome using a range of 72-196 bpm. Based on the present metronome pace range and a head range of motion of  $\pm 15^\circ$ , head

angular velocities were expected to range from 35 to 98°/s with constant head velocities assumed. However, since with each head excursion time must be spent accelerating and decelerating, constant head velocity cannot be assumed. Thus, the average head velocity for overall head velocity and each direction was used to represent velocity for the trial. Clinical studies have shown that eye velocities under vestibular control can reach a maximum velocity of 315°/s (Recker, 1980). The angular head velocities reported from the current study are well below this limit with a maximum (head angular velocities ranged from 26-145°/s over all subjects) and are therefore within the bandwidth of VOR response. Additionally, it was observed that the majority of data for any given subject was in the mid-range of velocities. This is due to the fact that subjects tended to decrease their head rotational range of motion as the metronome pacing frequencies increased. The range of head velocities for each subject is shown in *Table 14*.

### **VOR and VORc Head Velocities**

Recall that the pace for head movement was set by a metronome using a range of 72-196 bpm. Based on the present metronome pace range and a head range of motion of  $\pm 15^\circ$ , head angular velocities were expected to range from 35 to 98°/s with constant head velocities assumed. However, since with each head excursion time must be spent accelerating and decelerating, constant head velocity cannot be assumed. Thus, the average head velocity for overall head velocity and each direction was used to represent velocity for the trial. Clinical studies have shown that eye velocities under vestibular control can reach a maximum velocity of 315°/s (33). The angular head velocities reported from the current study are well below this limit with a maximum (head angular velocities ranged from 26-148°/s over all subjects) and are therefore within the bandwidth of VOR response. Additionally, it was observed that the majority

of data for any given subject was in the mid-range of velocities. This is due to the fact that subjects tended to decrease their head rotational range of motion as the metronome pacing frequencies increased. The range of head velocities for each subject is shown in *Table 15*.

<i>Subject</i>	<i>VOR</i>		<i>VORc</i>	
	<b>Velocity Range</b> (°/s)	<b>Max Velocity</b> (°/s)	<b>Velocity Range</b> (°/s)	<b>Max Velocity</b> (°/s)
<i>A_CM</i>	38.01	74.47	77.38	121.4
<i>A_KB</i>	63.82	107.21	39.4	83.85
<i>A_LR</i>	27.78	67.4	49.66	87.33
<i>A_TT</i>	57.66	104.22	45.18	88.18
<i>A_ST</i>	31.29	76.45	69.78	107.89
<i>A_JP</i>	86.67	147.87	52.5	109.85
<i>N_NF</i>	33.28	93.98	49.16	88.84
<i>N_RS</i>	68.49	132.74	60.96	98.26
<i>N_AC</i>	77.36	127.47	42.11	80.67
<i>N_WP</i>	75.21	142.91	57.54	103.63
<i>N_DL</i>	46.98	89.16	45.68	36.88
<i>N_SC</i>	104.35	148.43	80.38	118.34

*Table 15. Head Velocity Ranges for each Subject*

### **Further Findings**

Since a post-hoc analysis of the paired-subject experimental data yielded no statistically significant differences between the Elite Athlete and Non-Elite groups in VOR responses and suppression performance metrics, further comparisons were tested to look at other groupings and categories representing athleticism.

### Combining Athletic Indicators

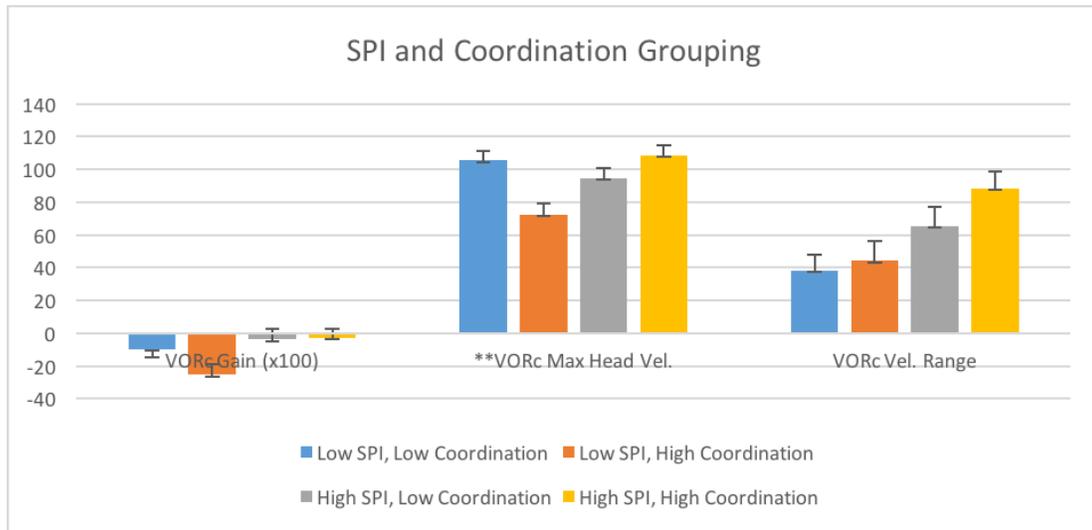
The main grouping of this study, Elite Athletes vs Non-Elite, was based on a subject's reaching a standardized athletic level. Those who met or exceed this level were categorized as

Elite Athletes and those who did not were grouped as Non-Elites. However, this study also tested for a level of innate athleticism in two other groupings- Psychological Athletic Tendency (SPI score) and Coordination (Hand-Eye Coordination). Recall that the mean SPI score was 159. To categorize subjects into 2 athletic tendency groups, those who scored greater than or equal to 159 were classified as having a greater tendency towards innate athleticism, and those with a score of less than 159 were classified as having less of an innate athletic tendency. Additionally, recall that the mean score for hand-eye coordination was found to be  $29.97 \pm 7.47$ . To categorize subjects into groups based on coordination level, those who scored greater than or equal to 29.97 were grouped as having a higher coordination level, and those scoring less than 29.97 were categorized as having a lower coordination level. To test the relationships between these factors and a subject's VOR suppression capabilities a 3x3 MANOVA (SPSS) was performed using these 3 categories defined previously (Elite Athletes and Non-Elites, SPI and Coordination score groupings) to look at VORc gain, VORc Max Head Velocity and VORc Head Velocity Range. There was not a statistically significant difference found ( $p > 0.05$ ) between all in 3 categories in their athlete groupings of these variables. However, statistically significant differences were found ( $p < 0.05$ ) twice with the pairing of only 2 of the 3 grouping categories.

a) Coordination and SPI categories

For this combination of athletic groupings, the MANOVA yielded a statistically significant difference ( $p < 0.05$ ), meaning that when athletes were grouped according to both coordination level (Low or High) and athletic psychological tendency (Low or High SPI score), a significant difference in the VORc variables tested was observed. The results of the

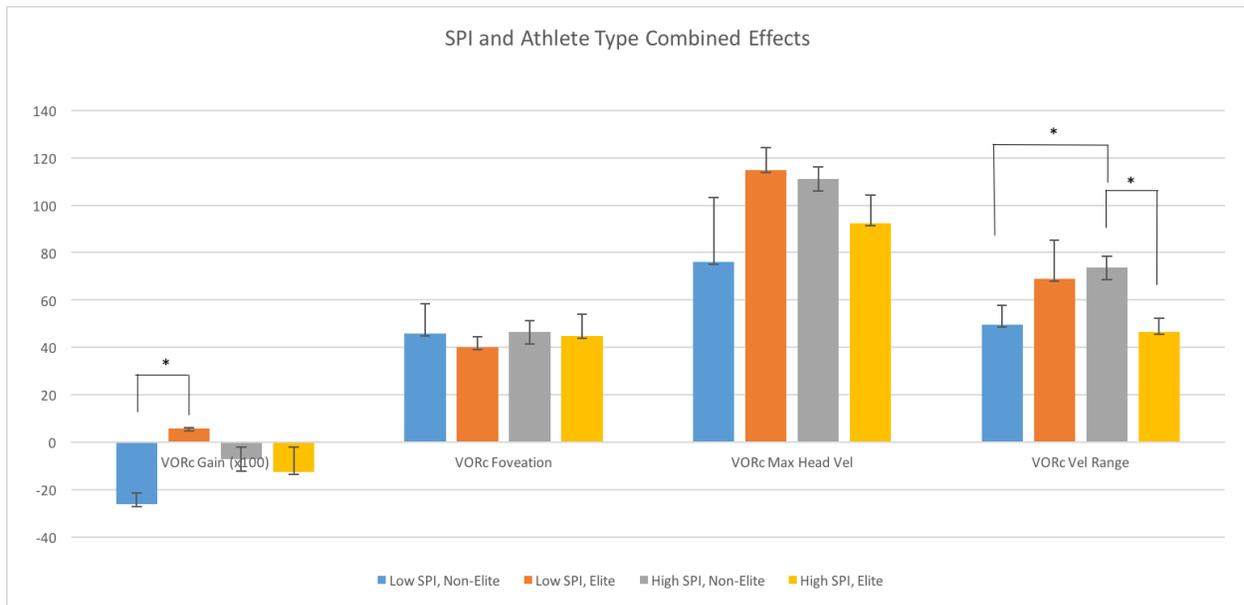
testing between subjects effect showed a statistically significant difference ( $p < 0.05$ ) for the Max Head Velocity variable achieved during the VORc testing (Experiment 4).



**Figure 35. Coordination and SPI effect on VORc Variables-** \*\*Significant differences between VORc Max Head Vel. Groups  $p < 0.05$

b) Athlete Type and SPI categories

For this combination of athletic groupings, the MANOVA yielded a statistically significant difference ( $p < 0.05$ ), meaning that when athletes were separated according to Elite Athlete and Non-Elite groups, and additionally athletic psychological tendency (Low or High SPI score), a significant difference in the VORc variables that were tested was observed. Further analysis was completed using an ANOVA where a post-hoc Tukey test (SPSS) revealed a statistically significant difference ( $p < 0.05$ ) between VORc Gain of subjects that were categorized as Low SPI, Non-Elites and Low SPI, Elite Athletes, as well as a statistically significant difference ( $p < 0.05$ ) between the Head Velocity Range accomplished by subjects classified as High SPI, Non-Elites during the VORc experiment (Experiment 3).



**Figure 36. SPI and Athlete Type effect on VORc Variables-** \*\*statistically significant difference,  $p < 0.05$  Significant differences only found in variables of VORc gain and VORc Velocity Range

### Duration of Athletic Career

The methodology behind this study was to characterize athletes based on the level of athletic success they achieved in their careers; however, another way to characterize athletes is based on the duration of their athletic careers, or years of active play. The mean amount of time subjects were involved in athletic activities, independent of skill level, was found to be  $12.8 \pm 4.6$  years. When athletes were grouped based active athletic years (greater than or equal to 12.8 years, or less than 12.8 years) it was found that significant statistical differences existed between the two groups in VORc gain and Maximum Head Velocity obtained (greater amplitude of head rotation at higher rotation speed) during VORc testing using ANOVA (SPSS). The results of this testing are illustrated in *Figure 36* and *Table 16* below.

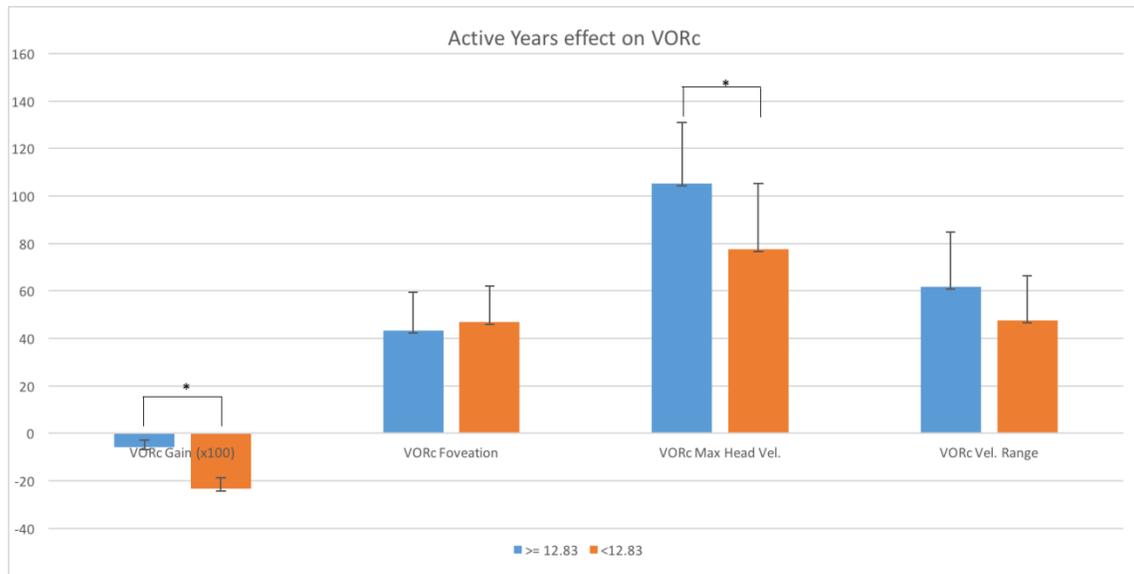


Figure 37. Active Athletic Years Grouping

\* (p<0.05)

<i>LONGER ATHLETIC CAREER</i>				<i>SHORTER ATHLETIC CAREER</i>			
<i>Subject</i>	<i>Duration</i>	<i>VORc Gain</i>	<i>VORc Max Head Vel.</i>	<i>Subject</i>	<i>Duration</i>	<i>VORc Gain</i>	<i>VORc Max Head Vel.</i>
<i>A_CM</i>	20	0.043	121.4	<i>A_KB</i>	11	-0.122	83.85
<i>A_LR</i>	13	-0.154	87.33	<i>N_NF</i>	4	-0.217	88.84
<i>A_TT</i>	16	0.013	88.18	<i>N_RS</i>	8	-0.253	98.26
<i>A_ST</i>	16	-0.182	107.89	<i>N_AC</i>	10	-0.242	80.67
<i>A_JP</i>	18	-0.240	109.85	<i>N_DL</i>	11	-0.326	36.88
<i>N_WP</i>	14	0.062	103.63				
<i>N_SC</i>	13	0.057	118.34				
<i>Average</i>	15.71 ± 2.63	-0.056 ± 0.13	105.23 ± 13.39		8.8 ± 2.95	-0.232 ± 0.07	77.7 ± 23.77

Table 16. VORc Gain and Max Head Velocity Groupings by Athletic Career Duration

### Foveation

Previous studies have shown that higher level athletes foveate less than those with less athletic success (Piras, 2010). While no statistically significant differences have been found, the foveation data throughout this study between Elite-Athletes and Non-Elite Athletes follows this

trend. This can be seen in the foveation data *Tables 11 and 13* as well as *Figures 28, 32, 35, and 36* above where the subjects characterized as Elite have smaller foveation values (less foveated during data collection) than the Non-Elites.

## DISCUSSION

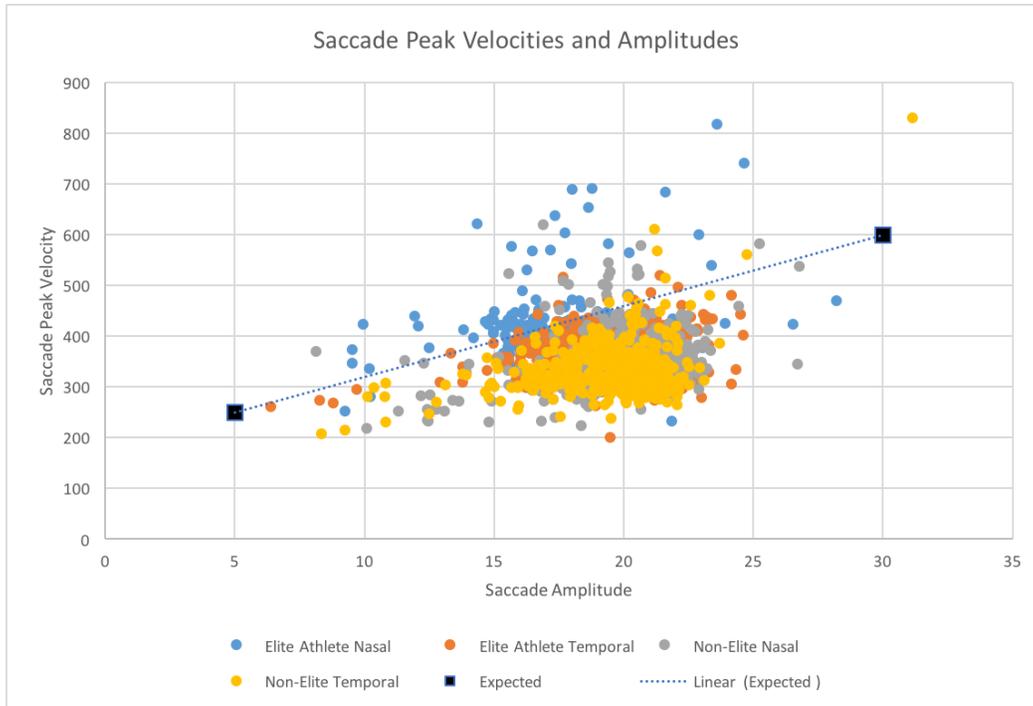
### **Horizontal Volitional Saccades**

While many studies have identified superior saccade dynamics of higher level athletes (Piras, 2010, Jafarzadehpur, 2007, Burcham 2010, Paeglis, 2008) the results of this study do not provide significant support for these findings for peak saccadic velocity, latency or settling times.

### Peak Velocities

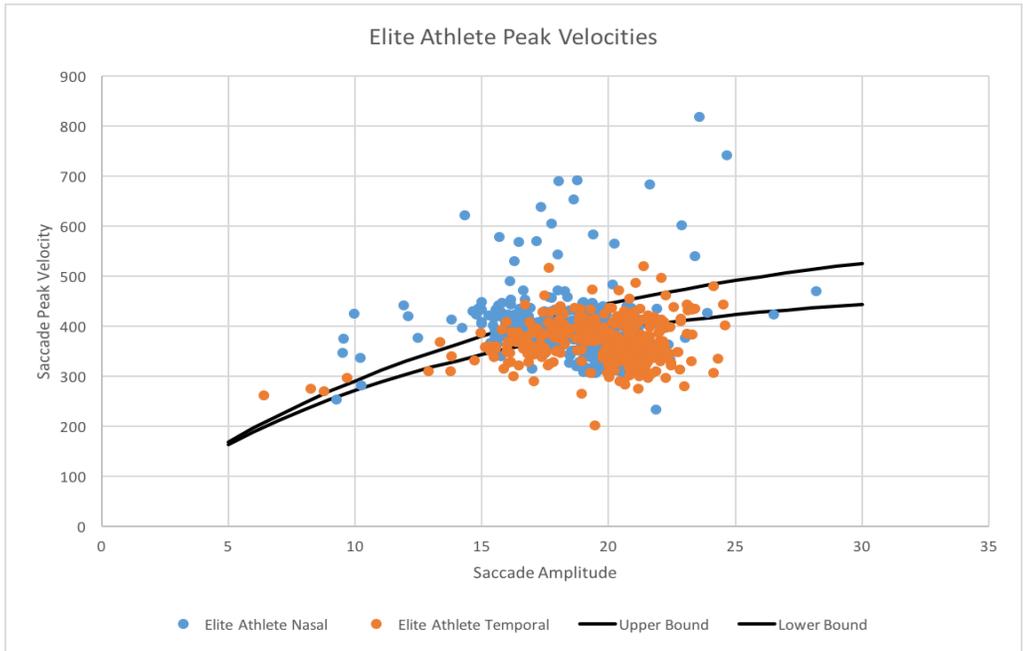
Studies aiming to quantify saccade amplitude, duration and velocity on normal human subjects have shown a linear relationship between duration and amplitude showing peak velocities increase with saccade amplitude, reaching a maximum around 30°/s (Baloh, Sills, Kumley, & Honrubia, 1975; Freedman 2008; Irving et al., 2006). Results from testing volitional horizontal saccades in our study support this claim. Figure 38 below shows right eye data for the saccade amplitudes, observed during Experiment 1, plotted against their associated peak velocities for each saccade. Recall that this data was collected while subjects transitioned between two LED targets having a 22° target separation distance. While it was observed that there was some variance in the amplitudes of saccades during the experiment, the majority of the data is seen as clustered around the 18-22° amplitude range with peak saccade velocities ranging from about 300-450°/s. However, these velocities are slightly less than what would be expected

from reported values tested in normal populations at these amplitudes (labeled Expected in *Figure 37*) (Irving et al., 2006; Baloh, Sills, Kumley, & Honrubia, 1975). This may be explained as artifact of data collection or it can be considered that participants of this study, in the age range of 23-28, differ slightly than the standards for a normal population.

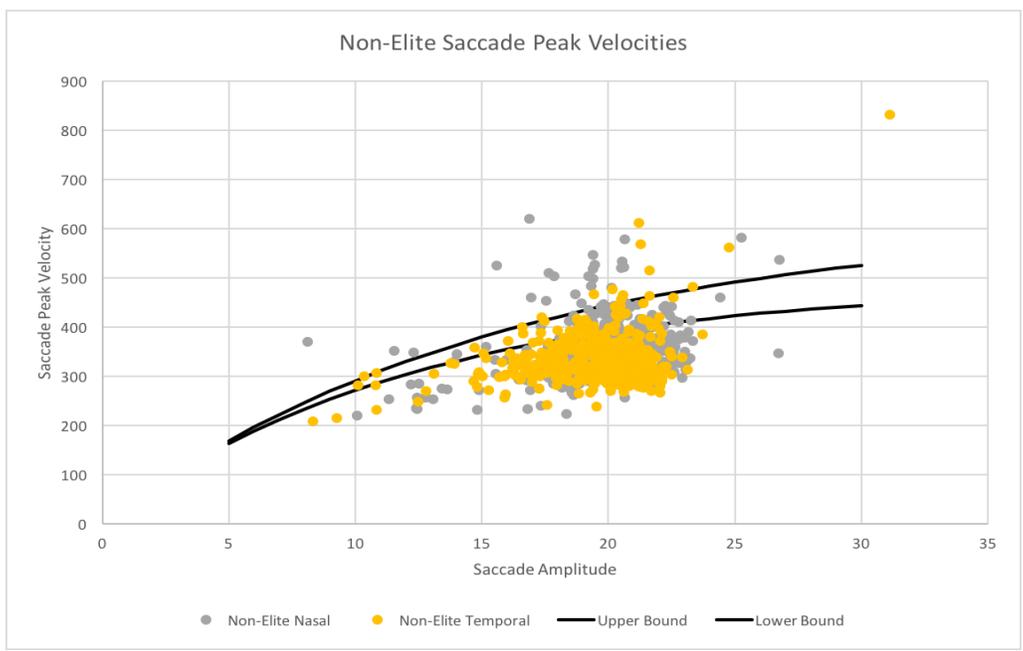


**Figure 38. Peak Saccade Velocities vs Expected Values-** Expected Values reported by Irving et al. (2006) and Baloh et al. (1975)

While assessing eye movement velocities, Baloh et al. (1975) also plotted Peak Saccade Velocities against amplitude. He fit his velocity data by bounds with the exponential equation  $\text{Time} = K(1 - e^{-(\text{Amplitude}/L)})$  where K and L were constants with ranges  $551 \pm 65^\circ$  and  $14 \pm 1.7^\circ$  respectively. *Figure 38a* and *38b* show plotted data from the Elite Athletes and Non-Elites respectively. While both groups show data slightly out of this range, the Non-Elite group has more of a general shift to lower velocities than both the Elite Athletes and expected values.



**Figure 39a. Athlete Peak Velocities and Normal Ranges-** Peak velocity vs amplitude plot comparison for right eye Elite Athlete data. The lines represent the upper and lower boundaries for data obtained by Baloh et al. (1975).



**Figure 39b. Non-Elite Peak Velocities and Normal Ranges-** Peak velocity vs amplitude plot comparison for right eye Elite Athlete data. The lines represent the upper and lower boundaries for data obtained by Baloh et al. (1975).

In this experiment, it was also noted that the Elite Athletes produced higher left eye temporal velocities than the Non-Elites. However, it should be noted that all Elite Athlete subjects were determined to be right eye dominant, while only 4 of the 6 Non-Elites were right eye dominant. Previous work has shown mixed results as to whether athletes have higher peak saccadic velocities (Babu, 2004; Paeglis et al., 2008). Furthermore, a significant difference was only found in the right eye temporal velocities between the two groups. This could simply be artifact or due to the differences in eye dominance between the groups.

### Latency

Significant differences in latencies of the right eye were shown between the groups in this study. Figures 23a and 23b show these differences and specify that the non-gymnast Elite Athletes had higher right eye nasal latencies than both Elite Athlete gymnasts and the Non-Elite group. Typical saccadic latencies have been reports as between 180-200msec (Griffiths, Marshall, & Richens, 1984; Irving et al., 2006). Results from the non-gymnast Elite Athletes are shown to be above this, while the other two groups are within this range for right eye nasal data, as shown in Table 8a. Additionally, a significant difference in the latencies was observed only in the right eye nasal values, thus, it is not appropriate to draw conclusions from this data as these results may simply be artifact of the experiment.

### **VOR and VORc Characterization**

No significant differences were shown when comparisons were made between Elite Athletes and Non-Elites VOR gain, VOR foveation, VORc gain and VORc foveation. While past studies have shown there to be a correlation between VOR performance variables and athletic

level in the same sport (Hedge, 2010), no correlations were found from this study with the grouping method used of Elite Athletes vs Non-Elites.

Hedge (2010) also found correlations between VORc L/R gains with gymnast’s preferred twist direction, where VOR suppression capabilities were greater in the direction the gymnast twisted when performing skills. In six of the ten gymnasts tested in his study, Hedge found their preferred direction of twist matched a VORc gain asymmetry that was biased in their preferred direction of twist. The gymnasts where the VORc gain asymmetry did not match their twist, were lower level gymnasts who had not mastered such skills where twisting is utilized. The results from this study agree with Hedge’s finding for two out of the three gymnasts tested. All gymnasts were at a skill level where they would be proficient at performing skills which required twisting. For the one gymnast who did not match these findings, it could be due to artifact as her standard deviations are much larger than the other two gymnasts. This data is seen in *Table 17* below.

SUBJECT	LEFT VORC GAIN		RIGHT VORC GAIN		TWIST DIRECTION	LEVEL
	Average	Stdev	Average	Stdev		
A_CM	0.0435	0.078	0.006	0.099	Right	9
A_KB	-0.099	0.081	-0.145	0.095	Left	9
A_LR	-.211	.188	-.144	.233	Left	8

*Table 17. Left and Right VORc Gains and Twist Directions for Gymnasts*

Twist direction is a constant topic of controversy in developing gymnasts in the gymnastics community. These data not only supports evidence that VOR suppression is used in gymnasts who perform simultaneous flipping and twisting skills, but also that gymnasts who take advantage of their VORc asymmetry are likely to be more successful in learning these skills and attaining a higher gymnastics level.

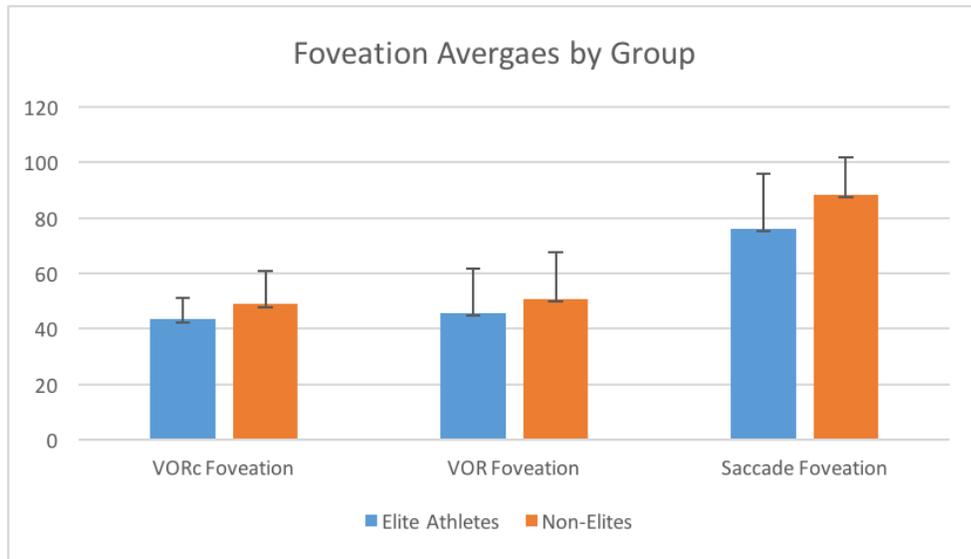
## **Elite Athlete and Non-Elite Pairings**

The purpose of this study was to investigate the relationship the VOR has with innate athleticism by comparing the VOR responses of former, no longer practicing, elite athletes (i.e. grouped as Elite Athletes) against their age and gender matched counterparts who were characterized as Non-Elites. The determining factor for Elite Athlete subject characterization was based on athletes reaching a level of varsity collegiate play (for non-gymnasts) or gymnasts who reached competitive levels 8-10. However, the results show this may not have been an appropriate method of categorizing athletes since no significant differences between the groups in any experiment exists to support this hypothesis.

## Target Foveation

The percentage of time a person's visual image is focused on the retina, provide an index for the amount of information that person is taking in from their central vision. However, studies have shown that elite athletes spend less time foveated on a central target (Williams & Chow, 1998; Williams & Elliott, 1997). Meaning, they tend to center their vision (central/ foveate vision) on a central region of interest which allows them best to use their peripheral vision to take in other details of their visual field (Williams & Chow, 1998; Williams & Elliott, 1997). Additionally, research has shown that athletes tend to perform less fixations, but for longer durations (Piras, 2010; Paeglis et al, 2008; Williams & Chow, 1998). This allows the athletes to take in more visual information for each fixation, which in turn allows them to anticipate and account for multiple environmental factors at once. Although the results of this study do not show a statistically significant correlation between Elite-Athletes and decreased foveation

percentages, there is a trend throughout the data that supports this theory. Figure 41 shows this trend.



**Figure 40. Foveation Trend-** Foveations averages for each Experiment. Elites Athletes' foveation is shown as being less for each experiment supporting the claim that Athletes tend to foveate less than their novice counterparts.

Although the initially defined groupings of athleticism may have been uncorrelated with VOR suppression performance characteristics, when grouped alternately, evidence was extracted to support the hypothesis that VOR suppression and athleticism are related.

### Coordination and Psychological Athletic Tendencies

Coordination and psychological athletic tendencies were two of the variables used in testing innate athleticism. While results from this study did not produce a direct correlation between the two variables, when combined they showed a significant difference between the maximum head velocities produced between groups. Williams and Krane, ( 2001), Anshel (1997), Gould et al. (2002) and Jones et al. (2002) all report that athletes are typically predisposed to higher amounts of self-motivation, and competitiveness than non-athletes.

Additionally, during data collection, it was observed that athletes were more competitive, racing against the clock and aiming to improve upon their hand-eye scores with each trial. As mentioned previously, since each trial of data collection was paced by a metronome (Experiment 3), head velocity was dependent on the rotational range of motion of each subject's head (i.e. larger head rotations produced higher head velocities). A theory behind these results could be that subjects who showed more athletic psychological tendencies (i.e. competitiveness, and self-motivation), were also highly coordinated in their hand-eye coordination (able to increase their hand-eye catches and minimize misses to yield a high hand-eye score), and their head-eye coordination (able to achieve a larger head rotation range while suppressing their VOR).

#### Psychological Athletic Tendencies

Evidence has shown that some people are more psychologically aligned with being an athlete than others (Baker & Horton, 2004; Anshel, 1997; Williams & Krane, 2001; Gould et al, 2002). Since a person's psychological tendencies, i.e. their personality and approach to situations, has been deemed genetic, its relation to determining innate athleticism is supported (Lippi, Favaloro, & Guidi, 2008). When combined with the groupings of Elite Athletes and Non-Elites, VORc performance measures showed significant differences between the groups. Specifically, VORc gain differences between groupings who scored a low SPI, and the head velocity range produced during VORc showed a significant difference between groups with a Low SPI. For the range of head velocities produced during VORc, differences existed between the grouping of High SPI score, Non-Elites and groupings at opposite ends of the spectrum (Low SPi score, Non-Elites and High SPI score, Elite Athletes). Here subject's athletic psychological tendencies aligned with their level of achievement in their sport to correlate to the range of head

velocities they were able to produce. Recall that while the metronome aimed to pace head movement in the experiments, subjects tended to decrease their rotational range of motion as the metronome pace increase, thus decreasing the velocities they were able to produce. The results extracted here show that SPI has a significant effect on the range of head velocities produced during VORc for Non-Elites, those with higher SPI produced a significantly larger range of head velocities. Additionally, for those subjects who had a higher SPI (both Elite Athletes and Non-Elites), the Elite Athletes actually produced a lower range of angular head velocities during VORc.

While the causation behind these results is unknown and unable to be determined, some correlation does exist, and theories for these results can be extrapolated. Jones (2002) reports that many researchers have classified top performing athletes as high levels of confidence, self-belief and self-esteem. Therefore, these factors combined with an athlete's listening skills could explain these results by athletes projecting they understand the task and can successfully complete it before listening to all of the instructions (i.e. not fully listening to directions because they think they understand). Additionally, Williams and Krane (2001) reported that athletes tend to have better concentration and are less likely to be distracted from their performance. An alternate theory behind these results could be due to athletes being focused on pacing their head exactly to the metronome pace, they were not able to achieve as wide of a rotational head range as the athletes were more precise in their head movements. It is also important to note that while many theories behind these results can be derived, the results cannot be traced back to one specific causation factor. Additionally, the variability in the effects of SPI on VOR suppression performance metrics does not present strong evidence that innate athleticism measured by psychological tendencies has an effect on VOR suppression.

### Duration of Athletic Career

Instead of using athletic success (i.e. highest athletic level achieved), it may have been more relevant to group athletes based on the duration of their athletic careers. Subjects who participated in athletic activities longer (regardless of type), showed both significantly better VOR suppression capabilities, as well as higher head velocities while suppressing their VOR.

Grouping athletes like this does not take into account athlete skill level nor specific sport types. When surveyed, most of the athletes listed multiple sport types in their athletic history. Thus, while VOR suppression is more important in certain types of sports (Burcham, 2010; Hedge, 2010; Land 2006; Alpini, Botta, & Mattei, 2009), these results show evidence that in general those involved in athletic activities for longer had superior VOR suppression performance factors. This evidence supports the theory that VOR suppression may be a learned, rather than innate, trait of athletes.

### Conclusions

The purpose of this research was to investigate the relationship of eye movement control has with innate athleticism. While the groupings used in experimentation (Elite Athletes vs Non-Elites) did not support the hypothesis that the grouping of Elite Athletes had superior VOR suppression capabilities, other factors of athleticism (i.e. coordination, psychological tendencies, and duration of athletic career) do play a part in one's VOR suppression performance. However, it is not possible to directly relate innate athleticism to a superior ability to suppress one's VOR.

The limitations of this study include a small sample size, lack of extreme subject type varying between the Elite Athletes and Non-Elites, and grouping factors chosen to contrast the

data. Table 18 shows the observed means and standard deviations for VORc gain for different groupings looked at, and the number of subjects needed have a high power for the experiment.

	<i>N</i>	<i>Mean</i>	<i>Std. Deviation</i>	<i>Number Subjects needed for Power = 0.8</i>
<i>Elite Athlete</i>	6	-0.107	0.112	
<i>Non-Elite</i>	6	-0.153	0.169	295
<i>High SPI</i>	6	-0.06382	0.125615	31
<i>Low SPI</i>	6	-0.1963	0.126772	
<i>High Coord</i>	5	-0.207015	0.145241	51
<i>Low Coord</i>	7	-0.11244	0.089796	
<i>Longer duration</i>	7	-0.05713	0.129601	13
<i>Shorter Duration</i>	5	-0.23216	0.07379	

**Table 18. Subjects needed for Strong Power of VORc differences-** For each grouping of subjects, power analysis done to determine the number of subjects needed for a power of 0.8 when comparing VORc variables between groups.

Since duration emerged as a key factor of VOR suppression abilities, future work could be done in this area to further investigate how duration of athletic career has an effect on eye movement control and VOR suppression. Additionally, to relate innate athleticism to VOR suppression performance, a longitudinal study could be conducted in which subjects are tested at an early age and then subsequently throughout their lifetime to determine differences in their abilities.

## REFERENCES

Alpini, D., Botta, M., Mattei, V., & Tornese, D. (2009). Figure ice skating induces vestibulo-ocular adaptation specific to required athletic skills. *Sports Science Health*, 5, 129-134. doi:10.1007/s11332-009-0088-4

Angelaki, D., & Cullen, K. (Annual Review of Neuroscience). Vestibular system: The many facets of a multimodal sense. 2008, 31, 125-150. doi:10.1146/annurev.neuro.31.060407.125555

Anshel, M.H. (1997). *Sport psychology from theory to practice* (3<sup>rd</sup> edn). (Scottsdale, AZ, Gorsuch, Scarisbrick).

Ashton-Miller, J. A., Wojtys, E. M., Huston, L. J., & Fry-Welch, D. (2001). Can proprioception really be improved by exercises? *Knee Surgery, Sports Traumatology, Arthroscopy*, 9(3), 128-136. doi:10.1007/s001670100208

Babu, R. (2004). A Study of Saccade Dynamics and Adaptation in Athletes and Non Athletes. UWSpace.

Baker, J., & Horton, S. (2004). A review of primary and secondary influences on sport expertise. *High Ability Studies*, 15(2), 11-18. doi:10.1080/1359813042000314781

Baloh RW, Sills AW, Kumley WE, Honrubia V. (1975). Quantitative measurement of saccade amplitude, duration and velocity.

Barnes, G. R., & Paige, G. D. (2004). Anticipatory VOR suppression induced by visual and nonvisual stimuli in humans. *Journal of Neurophysiology*, 92, 1501-1511. doi:10.1152/jn.00611.2003.

- Bessel, E., Yonker, J. C., Kras, J., & Heath, E. M. (2007). Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes. *Journal of Athletic Training, 42*(1), 42-46.
- Burcham, M. A. (2010). *Suppression of the rotational vestibulo-ocular reflex during a baseball pitch* (Master of Science).
- Campbell, F. W., & Green, D. G. (1965). Optical and retinal factors affecting visual resolution. *Journal of Physiology, 181*(1), 576-593.
- Chambers, B. R., & a, M. A. (1983). The relationship between disordered pursuit and vestibulo-ocular reflex suppression. *Journal of Neurology, Neurosurgery, and Psychiatry, 46*, 61-66.
- Clark, J.J. (1999). Spatial attention and latencies of saccadic eye movements. *Vision Research, 39*(3), 562-602. *Doi:10.1016/s0042-689(98)00190-4*
- Collewijn, H., & Tamminga, E. (1984). Human smooth and saccadic eye movements during voluntary pursuit of different target motions on different backgrounds . *Journal of Physiology, 351*, 217-250.
- Crane, B., & Demer, J. (1998). Human horizontal vestibulo-ocular reflex initiation: Effects of acceleration, target distance, and unilateral differentiation. *Journal of Neurophysiology, 80*(3), 1151-1166.
- Cunningham, M. (1972). *Intelligence: its organization and development*. New York: Academic Press.

- Dalvin, C. D., Sands, W. A., & Schultz, B. (2001). The role of vision in control of orientation in a back tuck somersault. *Motor Control*, (5), 337-346.
- Dane, S. (2009). Athletes have faster eye-hand visual reaction times and higher scores on visuospatial intelligence than nonathletes. *Turkish Journal of Medical Sciences*, 39(6), 871-874. doi:10.3906/sag-0809-44
- Das, V., Dell'osso, L., & Leigh, J. (1999). Enhancement of the vestibulo-ocular reflex by prior eye movements. *Journal of Neurophysiology*, 81, 2884-2892.
- Davids, K., & Baker, J. (2007). Genes, environment and sport performance: Why the nature-nurture dualism is no longer relevant. *Sports Medicine*, 37(11)
- Diehl, M. D., & Pidcoe, P. E. (2010). The influence of gaze stabilization and fixation on stepping reactions in younger and older adults. *Journal of Geriatric Physical Therapy*, 33(1), 19-25.
- Dietrich, M., & Brandt, T. (1995). Vestibulo-ocular reflex. *Current Opinion in Neurology*, 8, 83-88.
- Erickson, G.B. (2007). *Sports Vision: Vision care for the enhancement of sports performance*. Oxford: Butterworth-Heinemann.
- Freedman, E. G. (2008). Coordination of the eyes and head during visual orienting. *Experimental Brain Research*, 190(4), 369-387. doi:10.1007/s00221-008-1504-8
- Frontera, W. R. (Ed.). (2007). *Clinical sports medicine: Medical management and rehabilitation* (illustrated ed.) Elsevier Health Sciences.

- Gianna-Poulin, C. C., & Peterka, R. J. (2008). Use of a visual guide to improve the quality of VOR responses evoked by high-velocity rotational stimuli. *Journal of Vestibular Research*, 18(1), 15-24.
- Gould, D., Dieffenbach, K., & Moffett, A. (2002) Psychology characteristics and their development in Olympic champions, *Journal of Applied Sport Physiology*, 14, 172-204.
- Griffiths, A. N., Marshall, R. W., & Richens, A. (1984). Saccadic eye movement analysis as a measure of drug effects on human psychomotor performance. *British Journal of Clinical Pharmacology*, 18, 73-82.
- Han, J., Waddington, G., Anson, J., & Adams, R. (2015). Level of competitive success achieved by elite athletes and multi-joint proprioceptive ability. *Journal of Science and Medicine in Sport*, 18, 77-81.
- Hasegawa, T., Yamashita, M., Suzuki, T., Hisa, Y., & Wada, Y. (2009). Active linear head motion improves dynamic visual acuity in pursuing a high-speed moving object. *Experimental Brain Research*, 194, 505-516. doi:10.1007/s00221-009-1716-6
- Hashiba, M., Matsuoka, T., Baba S, & Watanabe, S. (1996) Non-visually induced smooth pursuit eye movements using sinusoidal target motion.
- Hedge, H. (2010). Eye movements in elite athletes - an index for performance. *Virginia Commonwealth University*. (Master of Science).
- Honda, H. (2002). Idiosyncratic left–right asymmetries of saccadic latencies: Examination in a gap paradigm. *Vision Research*, 42, 1437-1445.

- Hrysomallis, C. (2011). Balance ability and athletic performance. *Sports Medicine*, 41(2), 221-232. doi:10.2165/11538560-000000000-00000
- Huebner, W., Leigh, R. J., Seidman, S. H., Thomas, C., Billian, C., DiScenna, A., & Dell'osso, L. (1992). Experimental tests of a superposition hypothesis to explain the relationship between the vestibuloocular reflex and smooth pursuit during horizontal combined eye-head tracking in humans. *Journal of Neurophysiology*, 68(5), 1775-1792.
- Hung, C.K., & Ciuffreda, K.C. (Eds). (2002). *Models of the Visual System*. Springer.
- Irving, E., Steinbach, M., Lillakes, L., Babu, R., & Hutchings, N. (2006). Horizontal saccade dynamics across the human life span. *Investigative Ophthalmology & Visual Science*, 47(6), 2478-2484.
- Jafarzadehpur, E., Aazami, N., & Bolouri, B. (2007). Comparison of saccadic eye movements and facility of ocular accommodation in female volleyball players and non-players. *Scandinavian Journal of Medicine and Science in Sports*, 17(2), 186-190.
- Jones, G., Hanton, S., & Connuaghton, D. (2002). What is this thing called mental toughness? An investigation of elite sport performers. *Journal of Applied Sports Psychology*, 14, 205-218. doi:10.1080/10413200290103509
- Jones, J.W., Neuman, G., Altmann, R., Dreschler, B. (2001). Development of the Sports Performance Inventory: A psychological measure of athletic potential. *Journal of Business and Psychology*, 15(3),491-503.

- Kioumourtzoglou, E., Derri, V., Tzetzis, G., & Theodorakis, Y. (1998). Cognitive, perceptual, and motor abilities in skilled basketball performance. *Perceptual and Motor Skills*, 86(3), 771-786. doi:10.2466/pms.1998.86.3.771
- Keshner, E. A., & Cohen, H. (1989). Current concepts of the vestibular system reviewed: 1. the role of the vestibulospinal system in postural control. *American Journal of Occupational Therapy*, 43(5), 320-330.
- Land, M. (2006). Eye movements and the control of actions in everyday life. *Progress in Retinal and Eye Research*, 25, 296-324.
- Lippi, G., Favaloro, E., & Guidi, G. C. (2008).  
The genetic basis of human athletic performance. why are psychological components so often overlooked? *Journal of Physiology*, 586(12), 3017. doi:10.1113/jphysiol.2008.155887
- Lorenz, D. S., Reiman, M. P., Lehecka, B. J., & Naylor, A. (2013). What performance characteristics determine elite versus nonelite athletes in the same sport? *Sports Health*, 5(6), 542-547. doi:10.1177/1941738113479763
- Muaidi, Q. I., Nicholson, L. L., & Refshauge, K. M. (2009). Do elite athletes exhibit enhanced proprioceptive acuity, range and strength of knee rotation compared with non-athletes? *Scandinavian Journal of Medicine and Science in Sports*, 19, 103-112. doi:10.1111/j.1600-0838.2008.00783.x

- Martinez-Conde, S., Macknik, S., Troncoso, X., & Hubel, D. (2009). Microsaccades: A neurophysiological analysis. *Trends in Neuroscience*, 32(9), 463-475.  
doi:10.1016/j.tins.2009.05.006
- Misslisch, H., & Tweed, D. (2000). Torsional dynamics and cross-coupling in the human vestibulo-ocular reflex during active head rotation. *Journal of Vestibular Research*, 10, 119-125.
- MRI findings in the lumbar spines of asymptomatic, adolescent, elite tennis players. (2007). *British Journal of Sports Medicine*, 41, 836-841. doi:10.1136/bjism.2007.037747
- Munoz, D. P., Broughton, J. R., Goldring, J. E., & Armstrong, I. T. (1998). Age-related performance of human subjects on saccadic eye movement tasks. *Experimental Brain Research*, 121(121), 391-400.
- Myer, G. H., Lasker, A. G., & Robinson, D. A. (1985). The upper limit of human smooth pursuit velocity. *Vision Research*, 25(4), 561-563.
- Paeglis, R., Spunde, A., Kalvish, A., Vilkausha, L., & Lacis, I. (2008). Eye kinematics of athletes in non-familiar sports situations. *14th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics*, 20 149-149.
- Paige, G. D., Telford, L., Seidman, S. H., & Barnes, G. R. (1998). Human vestibuloocular reflex and its interactions with vision and fixation distance during linear and angular head movement. *Journal of Neurophysiology*, 80(5), 2391-2404.

- Piras, A., Lobiectiy, R., & Squatrito, S. (2010). A study of saccadic eye movement dynamics in volleyball: Comparison between athletes and non-athletes. *Journal of Sports Medicine and Physical Fitness*, 50(1), 99-108.
- Ramat, S., Straumann, D., & Zee, D. (2005). Interaural translational VOR: Suppression, enhancement, and cognitive control. *Journal of Neurophysiology*, 94, 2391-2402.  
doi:10.1152/jn.01328.2004
- Reker, U. (1980). Extent of reaction capacity of the vestibulo-ocular reflex. *Archives of oto-rhino-laryngology*, 228(35).
- Reimann, B. L., & Repart, S. M. (2002). The sensorimotor system, part II: The role of proprioception in motor control and functional joint stability. *Journal of Athletic Training*, 37(1), 80-84.
- Riemann, B., & Lephart, S. M. (2002). The sensorimotor system, part I: The role of proprioception in motor control and functional joint stability. *Journal of Athletic Training*, 32(1), 80-84.
- Robinson, D. A. (1976). Adaptive gain control of vestibule-ocular reflex by the cerebellum. *Journal of Neurophysiology*, 39(5), 954-969.
- Rose, D. J. (1997). In Spivey S. (Ed.), *A multilevel approach to the study of motor control and learning* (1st ed.). Need ham Heights, MA: Allyn & Bacon.
- Rucci, M., & Poletti (2015). Control and Functions of Fixational Eye Movements. *Annual Review of Vision Science*, 1, 499-518. doi:10.1146/annurev-vision-082114-035742

- Rucci, M. (2016). Fixational eye movements and perception. *Vision Research, 118*, 1-4.  
doi:10.1016/j.visres.2015.12.001
- Saavedra, S., Joshi, A., Wollacott, M., & VanDonkelaar, P. (2009). Eye hand coordination in children with cerebral palsy. *Experimental Brain Research, 192*(2), 155-165.  
doi:10.1007/s00221-008-1549-8
- Salvucci, D., & Goldberg, J. (2000). Identifying fixations and saccades in eye-tracking protocols. *Eye Tracking Research and Applications Symposium, New York, 1*, 71-78.
- Schutz, A., Braun, D., & Gegenmutter, K. (2009). Object recognition during foveating eye movements. *Vision Research, 49*, 2241-2253. doi:10.1016/j.visres.2009.05.022
- Sensorimotor impairment in the elderly* (1993). In Stelmach G. E., Homburg V. (Eds.), Springer Netherlands.
- Shariati, M., & Bakhtiari, S. (2011). Comparison of personality characteristics athlete and non-athlete students. *Social and Behavioral Sciences, 20*, 2312-2315.  
doi:10.1016/j.sbspro.2011.10.450
- Sideman, S. H., Leigh, R. J., Tomsak, R., Grant, M. P., & Dell'osso, L. (1995). Dynamic properties of the human vestibulo-ocular reflex during head rotations in roll. *Vision Research, 35*(5), 679-689.
- Snodderly, D. M. (2016). A physiological perspective on fixational eye movements. *Vision Research, 118*, 31-47.

- Solomon, D., & Straumann, D. (2003). Torsional and horizontal vestibular ocular reflex adaptation: three-dimensional eye movement analysis. *Experimental Brain Research*, 152, 150-155. doi:10.1007/s00221-003-1460-2
- Straka, H., & Dieringer, N. (2004). Basic organization principles of the VOR: Lessons from frogs. *Progress in Neurobiology*, 73, 259-309.
- Tanguy, S. G., Quark, G. M., Gauthier, A., & Densie, P. (2008). Are otolithic inputs interpreted better in figure skaters? *Neuroreport*, 19(5), 565-568.
- Tucker, R., Collins, M. (2012). What makes champions? A review of the relative contribution of genes and training to sporting success. *British Journal of Sports Medicine*, (46), 555-561. doi:0.1136/bjsports-2011-090548
- Vandorpe, B., Vandendriessche, J., Vaeyens, R., Pion, J., Mathys, S., Lefèvre, J., . . . Lenoir, M. (2002). Relationship between sports participation and the level of motor coordination in childhood: A longitudinal approach. *Journal of Science and Medicine in Sport*, 15(3), 220-225. doi:10.1016/j.jsams.2011.09.006
- Viire, E. (2014).  
Dynamic assessment of binocular eye movement coordination: Norms and functional implications. *Medical Hypothesis, Discovery, & Innovation Ophthalmology Journal*, 3(1), 31-37.

- Viire, E., & Demer, J. (1996). The human vertical vestibulo-ocular reflex during combined linear and angular acceleration with near-target fixation. *Experimental Brain Research*, 112, 313-324.
- Williams, J. P., Chow, J. Y., & Williams, M. (1998). *Visual Perception and Action in Sport*(1st ed.). Taylor & Francis.
- Williams, A.M., Davids, K, (1997). ‘Assessing cue usage in performance contexts: a comparison between eye movement and verbal report methods’, *Behavioral Research Methods, Instruments, and Computers* 29:364–75.
- Williams, A.M. and Elliott, D. (1997). ‘Visual search strategy in karate kumite: A function of experience and anxiety’, in R.Lidor and M.Bar-Eli (eds) *Innovations in Sport Psychology: Linking Theory and Practice*, Netanya, Israel: ISSP.
- Williams, J.M. and Krane, V. (2001) Psychological Characteristics of Peak Performance. In: Williams, J.M., Ed., *Applied Sport Psychology: Personal Growth to Peak Performance*, May Field Publishing Company, Mountain View, 137-144
- Wilson, C., Simpson, S. E., VanEmmerik, R. E., & Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics*, 7(1), 2-9.
- Wilson, C., Simpson, S. E., VanEmmerik, R. E., & Hamill, J. (2008). Coordination variability and skill

**APPENDIX A**

**MATLAB Code for NPV**

```

%-----
-----
% This program is designed to plot Gaze vector intersection with the
X-Z
% plane and compare it to target position (calculations done by
Motion
% Monitor).
%
% O'Shea
% Pidcoe (021617 - 031617)
%-----
-----
clear all           %clear all variables
close all          %close all windows and files
prgm = sprintf('PROGRAM = pv9f.m'); %program name for storage
files
sampling_rate = 250; %set to 250Hz
T = 1 / sampling_rate; %period
PLOT = 1; %set plotting flag
RANGE = .01; %fixation range
BIN = 0.005; %bin size for histogram
automation

%-----
-----
% query input file name
%-----
-----
root_name=input('Select File to Run: ','s');
in = strcat(root_name, '.txt'); % append extension
Y=load(in);

frame = Y(:,1); file_len=length(frame);
  head_rotation = Y(:,2);
  Leye_angle_H = Y(:,3); Leye_angle_V = Y(:,4);
  Reye_angle_H = Y(:,5); Reye_angle_V = Y(:,6);

  LEp_x = Y(:,7);  LEp_y = Y(:,8);  LEp_z = Y(:,9);
  LEv_x = Y(:,10); LEv_y = Y(:,11); LEv_z = Y(:,12);
  REp_x = Y(:,13); REp_y = Y(:,14); REp_z = Y(:,15);
  REv_x = Y(:,16); REv_y = Y(:,17); REv_z = Y(:,18);

%-----
-----
% create output file
%-----
-----
out=strcat(root_name, '.out'); %open a file to store % activation
results
fid_out = fopen(out, 'w');
fprintf(fid_out, '%s\r\n',prgm); fprintf(fid_out, '\r\r\n');
fprintf(fid_out, 'FILE = %s\r\n',strcat(root_name, '.txt'));
fprintf(fid_out, '\n');

```

```

%-----
-----
% plot raw data and let user input start and stop points for analysis
%
% NOTE that istart and istop are now created from floating point
values to
% increase the resolution of the selection
%-----
-----
RAW_eye=Leye_angle_H;                                %load horizontal eye
angle                                                %create time array for
xtime = (0:file_len-1)*T;
plotting

if PLOT == 0
    user_begin=1;
    user_end=file_len-1;
end
if PLOT == 1
    scrsz = get(0,'ScreenSize');
    L = scrsz(3)/8;                                %left
    B = scrsz(4)/8;                                %bottom
    W = scrsz(3) - (2*L);                            %width
    H = scrsz(4) - (2*B);                            %height
%     str = sprintf('TRIAL = %d',k);
%     figure('Name',str,'NumberTitle','off',...
%           'Position',[L B W H])                    %title and position figure

figure('Name','RAW Eye Angle Data Window','NumberTitle','off',...
      'Position',[L B W H])                    %title and position figure

%plot raw data
subplot(3,3,1:3);                                %define subplot area
plot(xtime,Leye_angle_H,'b')
hold on;
plot(xtime,Reye_angle_H,'g')
str = sprintf('Left & Right Eye Angle');
title(str)
xlabel('time')
ylabel('angle')

%graphically locate start and stop points for analysis
[x,y] = ginput(2);
user_begin = int32(x(1) * sampling_rate);
if (user_begin < 0) user_begin = 1; end
user_end = int32(x(2) * sampling_rate);
if (user_end < user_begin) user_end = user_begin +
file_len; end
if (user_end > file_len) user_end = file_len; end
end

%display selected values

```



```

VT = zeros(6,1); %define 6 element array to hold vertical start/stop
points
VT(1) = A(1);    %initialize first array locaiton to TOP target BEGIN
k = 2;
isum = 0;        %temporary sum for mean calculation
inum = 0;        %temporary denominator for mean calculation
m = 1;          %temporary index for mean calculation
for i = 2:length(A)
    if ((A(i) - A(i-1)) < 10)
        VT(k) = A(i);
        isum = isum + (z(A(i),1) * z(A(i),2));
        inum = inum + z(A(i),2);
    else
        VTmean(m) = isum / inum;
        isum = 0; inum = 0;    %reset sums
        m = m+1;              %increment index

        k=k+1;
        VT(k) = A(i);
        k=k+1;
    end
end

end
VTmean(m) = isum / inum;

% A
% VT
disp('VTmean = '); disp(VTmean);

%-----
%  overplot range used in calibraiton
%-----
LVSE = zeros(user_end-user_begin,1); %define array
p=1;
for i=1:3
    lowR = VTmean(i) - RANGE;
    highR = VTmean(i) + RANGE;

    for k=user_begin:user_end
        if (Lv(k) > lowR && Lv(k) < highR)
            plot(xtime(k), Lv(k), '.k')
            LVSE(p) = k; %store LeftVerticalStableEye array index
            p = p + 1;
        end
    end
end
end

%-----
%-----
%  find HORIZONTAL target fixations via
%  histogram method
%-----
%-----

```

```

%find target fixations
tarray = Lh(user_begin:user_end);
%   figure(11)
%   hold on
    xx = -.7:BIN:0.7; %bin size subjectively selected
    z = zeros(length(xx),2); z(:,1)=xx(:);
    s = hist(tarray,xx); z(:,2)=s(:);
%   hist(tarray, xx);
%   xlims = [-.7 0.7];
%   xlim(xlims);

%count target fixations and store locations
A = find(s>30); %find eye positions that occurred more than 30 times
HZ = zeros(6,1); %define 18 element array to hold horizontal
start/stop points
HZ(1) = A(1); %initialize first array locaiton to TOP target BEGIN
k = 2;
isum = 0; %temporary sum for mean calculation
inum = 0; %temporary denominator for mean calculation
m = 1; %temporary index for mean calculation
for i = 2:length(A)
    if ((A(i) - A(i-1)) < 10)
        HZ(k) = A(i);
        isum = isum + (z(A(i),1) * z(A(i),2));
        inum = inum + z(A(i),2);
    else
        HZmean(m) = isum / inum;
        isum = 0; inum = 0; %reset sums
        m = m+1; %increment index

        k=k+1;
        HZ(k) = A(i);
        k=k+1;
    end
end
HZmean(m) = isum / inum;

% A
% HZ
disp('HZmean = '); disp(HZmean);

%-----
% overplot range used in calibraiton
%-----
LHSE = zeros(user_end-user_begin,1); %define array
p=1;
for i=1:3
    lowR = HZmean(i) - RANGE;
    highR = HZmean(i) + RANGE;

    for k=user_begin:user_end
        if (Lh(k) > lowR && Lh(k) < highR)
            plot(xtime(k), Lh(k), '.k')
        end
    end
end

```



```

tarray = Rv(user_begin:user_end);
%   figure(10)
%   hold on
    xx = -.7:BIN:0.7; %bin size subjectively selected
    z = zeros(length(xx),2); z(:,1)=xx(:);
    s = hist(tarray,xx); z(:,2)=s(:);
%   hist(tarray, xx);
%   xlims = [-.7 0.7];
%   xlim(xlims);

%count target fixations and store locations
A = find(s>30); %find eye positions that occurred more than 30 times
VT = zeros(6,1); %define 6 element array to hold vertical start/stop
points
VT(1) = A(1); %initialize first array locaiton to TOP target BEGIN
k = 2;
isum = 0; %temporary sum for mean calculation
inum = 0; %temporary denominator for mean calculation
m = 1; %temporary index for mean calculation
for i = 2:length(A)
    if ((A(i) - A(i-1)) < 10)
        VT(k) = A(i);
        isum = isum + (z(A(i),1) * z(A(i),2));
        inum = inum + z(A(i),2);
    else
        VTmean(m) = isum / inum;
        isum = 0; inum = 0; %reset sums
        m = m+1; %increment index

        k=k+1;
        VT(k) = A(i);
        k=k+1;
    end
end

end
VTmean(m) = isum / inum;

% A
% VT
disp('VTmean = '); disp(VTmean);

%-----
% overplot range used in calibraiton
%-----
RVSE = zeros(user_end-user_begin,1); %define array
p=1;
for i=1:3
    lowR = VTmean(i) - RANGE;
    highR = VTmean(i) + RANGE;

    for k=user_begin:user_end
        if (Rv(k) > lowR && Rv(k) < highR)
            plot(xtime(k), Rv(k), '.k')
        end
    end
end

```

```

        RVSE(p) = k; %store RightVerticalStableEye array index
        p = p + 1;
    end
end
end

%-----
% find HORIZONTAL target fixations via
% histogram method
%-----
%find target fixations
tarray = Rh(user_begin:user_end);
% figure(11)
% hold on
xx = -.7:BIN:0.7; %bin size subjectively selected
z = zeros(length(xx),2); z(:,1)=xx(:);
s = hist(tarray,xx); z(:,2)=s(:);
% hist(tarray, xx);
% xlims = [-.7 0.7];
% xlim(xlims);

%count target fixations and store locations
A = find(s>30); %find eye positions that occurred more than 30 times
HZ = zeros(6,1); %define 18 element array to hold horizontal
start/stop points
HZ(1) = A(1); %initialize first array locaiton to TOP target BEGIN
k = 2;
isum = 0; %temporary sum for mean calculation
inum = 0; %temporary denominator for mean calculation
m = 1; %temporary index for mean calculation
for i = 2:length(A)
    if ((A(i) - A(i-1)) < 10)
        HZ(k) = A(i);
        isum = isum + (z(A(i),1) * z(A(i),2));
        inum = inum + z(A(i),2);
    else
        HZmean(m) = isum / inum;
        isum = 0; inum = 0; %reset sums
        m = m+1; %increment index

        k=k+1;
        HZ(k) = A(i);
        k=k+1;
    end
end
end
HZmean(m) = isum / inum;

% A
% HZ
disp('HZmean = '); disp(HZmean);

```



end

```
fprintf(fid_out, '\r\n');
fprintf(fid_out, '\r\n');
fprintf(fid_out, 'Lv = %7.4fx + %7.4f\r\n', LV(1), LV(2));
fprintf(fid_out, 'Rv = %7.4fx + %7.4f\r\n', RV(1), RV(2));
fprintf(fid_out, 'Lh = %7.4fx + %7.4f\r\n', LH(1), LH(2));
fprintf(fid_out, 'Rh = %7.4fx + %7.4f\r\n', RH(1), RH(2));
fprintf(fid_out, '\n');

% HERE

%-----
%-----
% Determine stable eye positions from combination of histogram
defined
% stable eye positions for each eye and each dimension
%-----
%-----
stable_eye = intersect(LVSE, RVSE);
stable_eye = intersect(stable_eye, LHSE);
stable_eye = intersect(stable_eye, RHSE);
stable_eye = stable_eye(2:length(stable_eye)); %remove first element
= 0

% stable_eye = union(LVSE, RVSE);
% stable_eye = union(stable_eye, LHSE);
% stable_eye = union(stable_eye, RHSE);
% stable_eye = stable_eye(2:length(stable_eye)); %remove first
element = 0

%-----
%-----
% Calculate velocity of eye movement (°/s) for average of both eyes
%-----
%-----
% Calculate average magnitude of left and right movements and
% average planar intercept position
%-----
%-----
size = user_end - user_begin + 1;
X_Avg = zeros(size, 1);
Z_Avg = zeros(size, 1);
mag_Avg = zeros(size, 1);

for i = user_begin:user_end
    X_Avg(i) = (Lh(i) + Rh(i)) / 2;
    Z_Avg(i) = (Lv(i) + Rv(i)) / 2;
    temp_H = (Leye_angle_H(i) + Reye_angle_H(i)) / 2;
```

```

        temp_V = (Leye_angle_V(i) + Reye_angle_V(i)) / 2;
        mag_Avg(i) = sqrt(temp_H^2 + temp_V^2);
    end

%-----
% Calculate velocity of eye movement using central difference
method
% and tabulate fixations based on velocity threshold.
%-----
vel_mag = zeros(size,1);

for i = user_begin+1:user_end-1
    vel_mag(i)=abs(((mag_Avg(i+1)-mag_Avg(i-1)))/(2*T));
end
vel_mag(user_begin) = vel_mag(user_begin+1);
vel_mag(user_end) = vel_mag(user_end-1);

subplot(3,3,[5 8]);                %define subplot area
title('Eye Velocity')
% figure('Name','Eye Velocity','NumberTitle','off')    %title
figure
hold on
plot(xtime(user_begin:user_end),
vel_mag(user_begin:user_end),'g');

threshold = .3; %threshold (°/s) to define stable gaze
stable_eye = find(vel_mag(user_begin+1:user_end-1) < threshold);
stable_eyeP = stable_eye + double(user_begin + 1);
plot(xtime(stable_eyeP), vel_mag(stable_eyeP),'.k');

% target values on board
X_tar = [
0.173 0.360 0.552 0.173 0.360 0.552 0.173 0.360 0.552];
Z_tar = [-0.601 -0.601 -0.601 -0.420 -0.420 -0.420 -0.222 -0.222 -
0.222];

%-----
% Plot PoI_X and PoI_Z.
%-----

subplot(3,3,[6 9]);                %define subplot area
% figure('Name','LEFT & RIGHT Stable
Intercepts','NumberTitle','off')    %title figure
hold on

title('Gaze Vector Plane Intercept')
scatter (-X_tar, Z_tar, 'r','filled')
scatter (-Lh(stable_eyeP), Lv(stable_eyeP), 'b')
scatter (-Rh(stable_eyeP), Rv(stable_eyeP), 'g')
xlims = [-.7 -.15];

```

```

xlim(xlimits);
xlabel('PoI_X');
ylabel('PoI_Z');
    axis ij; % reverses vertical axis to match world coordinate system
    axis square; % makes the axis region square

% pause;

%-----
----
% Plot average eye position
%-----
----
subplot(3,3,[6 9]); %define subplot area
% figure('Name','AVERAGE Stable
Intercepts','NumberTitle','off') %title figure
hold on

title('Gaze Vector Plane Intercept')
scatter (-X_tar, Z_tar, 'r','filled')
scatter (-X_Avg(stable_eyeP), Z_Avg(stable_eyeP), 'k','filled')

xlims = [-.7 -.15];
xlim(xlimits);
xlabel('PoI_X');
ylabel('PoI_Z');
    axis ij; % reverses vertical axis to match world coordinate system
    axis square; % makes the axis region square

%-----
----
% Create STABLE EYE data to plot
%-----
----

% TRYING TO REMOVE VALUES OF ZERO FROM THE HISTOGRAM COUNT

% index = find(X_Avg(stable_eye) ~= 0);
% temp_H = X_Avg(index);
% temp_V = Z_Avg(stable_eye);
%
% for i=1:length(temp_H) %(stable_eye)
%     if (temp_H(i) < .21 && temp_H(i) > .13)
%         H(i) = .173;
%     end
%     if (temp_H(i) < .4 && temp_H(i) > .32)
%         H(i) = .360;
%     end
%     if (temp_H(i) < .59 && temp_H(i) > .51)
%         H(i) = .552;
%     end
% end

```

```

% end

% figure(8)
% hold on
% scatter ( -H, -temp_H(1:length(H)), 'r','filled')
%
% figure(9)
% hold on
% xx = -.7:0.005:0;
% s = hist(-X_Avg(stable_eye),xx);
% hist(-X_Avg(stable_eye), xx);
% xlims = [-.7 0];
% xlim(xlims);

%-----
-----
% Plot target positions against stable eye positions as precursor to
% correction equations
%-----
-----
% figure(8)
% hold on
% scatter ( -X_tar, -Lh(stable_eye), 'r','filled')
% scatter (Z_tar, Lv(stable_eye), 'k','filled')
% axis ij; % reverses vertical axis to match world coordinate
system
% axis square; % makes the axis region square
%
% figure(9)
% hold on
% scatter ( -X_tar, -Rh(stable_eye), 'r','filled')
% scatter (Z_tar, Rv(stable_eye), 'k','filled')
% axis ij; % reverses vertical axis to match world coordinate
system
% axis square; % makes the axis region square

```

## APPENDIX B

### MATLAB Code for analyzing Saccade Data

```

%-----
-----

```

```

% This program is designed to plot Gaze vector intersection with the
X-Z
% plane and compare it to target position (calculations done by
Motion
% Monitor) for the horizontal saccade testing with LED's lighting up
as
% targets (L&R).
%
% O'Shea
%
%-----
-----
clear all                %clear all variables
close all                %close all windows and files
prgm = sprintf('PROGRAM = pv7.m'); %program name for storage
files
sampling_rate = 250;    %set to 250Hz
T = 1 / sampling_rate; %period
PLOT = 1;               %set plotting flag
RADIAN=3.14/180;

%-----
-----
% query input file name
%-----
-----
root_name=input('Select File to Run: ','s');
in = strcat(root_name, '.txt'); % append extension
Y=load(in);

frame = Y(:,1); file_len=length(frame);
    head_rotation = Y(:,2);
    LHeye_angle = Y(:,3);
    LVeye_angle = Y(:,4);
    RHeye_angle = Y(:,5);
    RVeye_angle = Y(:,6);
    LEp_x = Y(:,7); LEp_y = Y(:,8); LEp_z = Y(:,9);
    LEv_x = Y(:,10); LEv_y = Y(:,11); LEv_z = Y(:,12);
    REp_x = Y(:,13); REp_y = Y(:,14); REp_z = Y(:,15);
    REv_x = Y(:,16); REv_y = Y(:,17); REv_z = Y(:,18);
    light = Y(:,19);

%-----
-----
% create output file
%-----
-----
% out=strcat(root_name, '.out'); %open a file to store % activation
results
% fid_out = fopen(out, 'w');
% fprintf(fid_out, '%s\r\n', prgm); fprintf(fid_out, '\r\r\n');
% fprintf(fid_out, 'FILE = %s\r\n', strcat(root_name, '.txt'));
% fprintf(fid_out, '\n');

```

```

%-----
-----
% plot raw data and let user input start and stop points for analysis
%
% NOTE that istart and istop are now created from floating point
values to
% increase the resolution of the selection
%-----
-----
RAW_eye=LHeye_angle;           %load horizontal eye
angle
xtime = (0:file_len-1)*T;      %create time array for
plotting

if PLOT == 0
    user_begin=1;
    user_end=file_len-1;
end
if PLOT == 1
    figure('Name','RAW Eye Angle Data
Window','NumberTitle','off') %title figure
    %plot raw data
    plot(xtime,RAW_eye,'b')
    str = sprintf('Left Eye Angle');
    title(str)
    xlabel('time')
    ylabel('angle')

    %graphically locate start and stop points for analysis
    [x,y] = ginput(2);
    user_begin = int32(x(1) * sampling_rate);
    if (user_begin < 0) user_begin = 1; end
    user_end = int32(x(2) * sampling_rate);
    if (user_end < user_begin) user_end = user_begin +
file_len; end
    if (user_end > file_len) user_end = file_len; end
end

%display selected values
hold on;
    istart = single(user_begin) / sampling_rate;
    istop = single(user_end) / sampling_rate;
    x = [istart istart]; plot(x,ylim,'r');           % ylim = axis
limits
    x = [istop istop]; plot(x,ylim,'r');           % ylim = axis
limits

% fprintf(fid_out,'\nSelected data from %.2f to %.2f
sec\n\r\r',istart,istop);

%-----
% plot horizontal eye data vs LED

```

```

%-----
zeroed_eye_angle = zeros(file_len,1);

for i = 1:file_len
    zeroed_eye_angle(i) = LHeve_angle(i)-mean(LHeve_angle);

end

figure(2)
hold on
title('Left Eye horizontal movement & LED signal')
plot(xtime(user_begin:user_end),zeroed_eye_angle(user_begin:user_end),
'b')
plot(xtime(user_begin:user_end),light(user_begin:user_end)-2.5,'g')
xlabel('Time (seconds)')
% ylabel('Horizontal eye movement')

% -----
% compute planar intercept Left eye
% -----
% for i = user_begin:user_end
%     alpha = atan(LEv_z(i)/LEv_y(i));
%     Lv(i) = ((1 + (-LEp_y(i))) * tan(alpha)) + LEp_z(i);
%     beta = atan(LEv_x(i)/LEv_y(i));
%     Lh(i) = ((1 + (-LEp_y(i))) * tan(beta)) + LEp_x(i);
% end
%
%
% figure(3)
% hold on
% title('LEFT vertical/horizontal intercept')
% plot(xtime(user_begin:user_end), Lv(user_begin:user_end), 'r')
% plot(xtime(user_begin:user_end), Lh(user_begin:user_end), 'b')
%
% -----
% compute planar intercept Right eye
% -----
% for i = user_begin:user_end
%     alpha = atan(REv_z(i)/REv_y(i));
%     Rv(i) = ((1 + (-REp_y(i))) * tan(alpha)) + REp_z(i);
%     beta = atan(REv_x(i)/REv_y(i));
%     Rh(i) = ((1 + (-LEp_y(i))) * tan(beta)) + LEp_x(i);
% end
%
% figure(4)
% hold on
% title('RIGHT vertical/horizontal intercept')
% plot(xtime(user_begin:user_end), Rv(user_begin:user_end), 'r')
% plot(xtime(user_begin:user_end), Rh(user_begin:user_end), 'b')
%

```

```

% empirically scale data to fit
% for i = user_begin:user_end
%   Lv(i) = 1.35*Lv(i) + .23;
%   Rv(i) = 1.34*Rv(i) + .25;
%   Lh(i) = 1.21*Lh(i) - .14;
%   Rh(i) = 1.21*Rh(i) - .24;
% end
%
% -----
% Calculation average left and right for cycloplan eye.
% -----
% for i = user_begin:user_end
%   X_Avg(i) = (Lh(i) + Rh(i)) / 2;
%   Z_Avg(i) = (Lv(i) + Rv(i)) / 2;
% end

vel_L = zeros(file_len,1);
vel_E = zeros(file_len,1);
ax_E = zeros(file_len,1);

%-----
% Creating dircectional variables to differentiate between Left and
Right
% Eye movements and LED triggers.
%-----
% directional variables

directiona = zeros(file_len,1);
directionb = zeros(file_len,1);
velT = 10; % set velocity threshold to 10 deg/sec
vel_Lr = zeros(file_len,1);
vel_Ll = zeros(file_len,1);
vel_Er = zeros(file_len,1);
vel_El = zeros(file_len,1);
rcnt = 1;
lcnt = 1;
r=1;f=0;g=0;

for i=user_begin:user_end
    vel_L(i)=((light(i+1)-light(i-1))/(2*T));
    vel_E(i)=((LHeye_angle(i+1)-LHeye_angle(i-1))/(2*T));
end
for i=user_begin:user_end
    ax_E(i)= (abs((vel_E(i+1))-abs(vel_E(i-1)))/(2*T));
    if (vel_L(i) > velT)
        directiona(i) = -500;
        vel_Ll(lcnt) = vel_L(i);
        lcnt = lcnt + 1;
    end
end

```

```

        f=-1;
    end
    if (vel_L(i) < -velT)
        directiona(i) = 500;
        vel_Lr(rcnt) = vel_L(i);
        rcnt = rcnt + 1;
        f=1;
    end
    if (abs(vel_E(i)) > 3*velT)&& f==1 %movement to the right
        if max(abs(vel_E(i:i+10)))>100 %<100 deg/s is a fixation
            directionb(i) = +500; %eye movement
            vel_Er(i) = vel_E(i);
            ax_Er(i) = ax_E(i);
            g=1;
        elseif max(abs(vel_E(i:i+10)))<100 && g==1
            directionb(i) = +500;
            vel_Er(i) = vel_E(i);
            ax_Er(i) = ax_E(i);
        else
            g=0;
        end
    end
    if (abs(vel_E(i)) > 3*velT)&& f==-1 %saccade to the left
        if max(abs(vel_E(i:i+10)))>100
            directionb(i) = -500;
            vel_El(i) = vel_E(i);
            ax_El(i) = ax_E(i);
            g=-1;
        elseif max(abs(vel_E(i:i+10)))<100 && g==-1
            directionb(i) = -500;
            vel_El(i) = vel_E(i);
            ax_El(i) = ax_E(i);
        else
            g=0;
        end
    end
end

end

%-----
%-----
% Find peak, mean and std. dev of left & right saccade velocites
%-----
%-----
flag = 0;
for i = user_begin:user_end
    if directiona(i) ~= 0 && flag == 0
        start_point=i;
        flag = 1;
    end
end
rsac=zeros(100,1);

```

```

lsac=zeros(100,1);
j=1;k=1;cnt1=0;lcnt=0;

for i = start_point:user_end
    if vel_Er(i)~=0
        rsac(j) = i;
        j=j+1;
        rcnt=rcnt+1;
    end
    if vel_Er(i) == 0 && rcnt < 10
        j = j-rcnt;
        rcnt = 0;
    end
    if vel_Er(i) == 0 && rcnt > 10
        rcnt=0;
    end
    if vel_El(i)~=0
        lsac(k) = i;
        k=k+1;
        lcnt=lcnt+1;
    end
    if vel_El(i) == 0 && lcnt < 10
        k = k-lcnt;
        lcnt = 0;
    end
    if vel_El(i) == 0 && lcnt > 10
        lcnt=0;
    end
end
n=0;j=1;k=1;
r_odd=zeros(file_len,1);
r_marker=zeros(10,1);
R_Saccade=zeros(10,1);
max_velR = zeros(10,1);
l_odd=zeros(file_len,1);
l_marker=zeros(10,1);
L_Saccade=zeros(10,1);
max_velL = zeros(10,1);
durationL = zeros(10,1);
durationR = zeros(10,1);
max_axR = zeros(10,1);
max_axL = zeros(10,1);
ax_timeR = zeros(10,1);
ax_timeL = zeros(10,1);
R_Saccade(1) = rsac(1);
L_Saccade(1) = lsac(1);
rdiff = diff(rsac);
ldiff = diff(lsac);
for i = 1:length(rdiff)
    if rdiff(i)~=1
        r_odd(j) =i;
        j=j+1;
    end
end

```

```

end
if rdiff(length(rdiff))==1 % for including last saccade
    r_odd(j)=r_odd(j-1);
    r_odd(j+1)=length(rsac);
end
a = r_odd(1);
R_Saccade(2) = rsac(a);
for i = 1:length(ldiff)
    if ldiff(i)~=1
        l_odd(k) = i;
        k=k+1;
    end
end
if ldiff(length(ldiff))==1 % for including last saccade
    l_odd(k)=l_odd(k-1);
    l_odd(k+1)=length(lsac);
end
b = l_odd(1);
L_Saccade(2) = lsac(b);
j=1;k=1;
for i = 1:length(rdiff)
    if r_odd(i+1) - r_odd(i)>=2
        r_marker(j)= r_odd(i)+1;
        r_marker(j+1)= r_odd(i+1);
        j=j+2;
    end
    % if r_odd(i+1) - r_odd(i)==1
    %     r_marker(j)= r_odd(i+1);
    %     r_marker(j+1)= r_odd(i+1);
    %     j=j+2;
    % end
end
for i = 1:length(ldiff)
    if l_odd(i+1) - l_odd(i)>=2
        l_marker(k)= l_odd(i)+1;
        l_marker(k+1)= l_odd(i+1);
        k=k+2;
    end
    % if l_odd(i+1) - l_odd(i)==1
    %     l_marker(k)= l_odd(i+1);
    %     l_marker(k+1)= l_odd(i+1);
    %     k=k+2;
    % end
end
j=3;k=3;
for i=1:2:length(r_marker)
    a = r_marker(i);
    b = r_marker(i+1);
    R_Saccade(j) = rsac(a);
    R_Saccade(j+1)=rsac(b);
    j=j+2;
end
for i=1:2:length(l_marker)

```

```

    c = l_marker(i);
    d = l_marker(i+1);
    L_Saccade(k) = lsac(c);
    L_Saccade(k+1)=lsac(d);
    k=k+2;
end
j=1;k=1;
for i = 1:2:length(R_Saccade)
    start = R_Saccade(i);
    stop = R_Saccade(i+1);
    max_velR(j) = max(abs(vel_Er(start:stop)));
    max_axR(j) = max(ax_Er(start+1:stop));
    durationR(j) = (stop-start)/250;
    for q = start:stop
        if ax_Er(q) == max_axR(j)
            ax_timeR(j) = (q-start)/250;
        end
    end
    j=j+1;
    avg_max_velR = mean(max_velR);
    std_max_velR = std(max_velR);

end
for i = 1:2:length(L_Saccade)
    start = L_Saccade(i);
    stop = L_Saccade(i+1);
    max_velL(k) = max(abs(vel_El(start:stop)));
    max_axL(k) = max(ax_El(start+1:stop));
    durationL(k) = (stop-start)/250;
    for q = start:stop-1
        if ax_El(q) == max_axL(k)
            ax_timeL(k) = (q-start)/250;
        end
    end
    k=k+1;
    avg_max_velL = mean(max_velL);
    std_max_velL = std(max_velL);

end

% figure(16)
% hold on
% plot(rsac,'g.')
% plot(lsac,'b.')

%fprintf(fid_out,'\nSelected data from %.2f to %.2f
sec\n\r\r',istart,istop);
% fprintf(fid_out,'\nMax Velocity Saccade Left = %.2f deg/s\n\r',
max_velL);

%-----
% Plot of Left and Right Directions with LED triggers.

```

```

%-----
-----

figure(3)
hold on
title('Onset of LED illumination(Green) & Eye Velocity(Blue)')
plot (-vel_L(:,1),'g')
plot (vel_E(:,1),'b')
% plot (directiona(:,1),'r')    % plot velocity direction array to test
% plot (directionb(:,1),'k')
xlabel('Frames');
ylabel('LED blinks / Eye velocity')

figure(4)
hold on
title('Left Saccade velocity(Green) & Right Saccade Velocity(Blue)')
plot (frame*T,vel_El(:,1),'g')
plot (frame*T,vel_Er(:,1),'b')
xlabel('Time');
ylabel('Eye Velocity (deg/sec)')

% target values on board
X_tar = [0.173 0.36 0.552 0.173 0.36 0.552 0.173 0.36 0.552];
Z_tar = [-0.601 -0.601 -0.601 -0.42 -0.42 -0.42 -0.222 -0.222 -0.222];

%-----
-----
% Time Lag Calculation (latency)
%-----
-----

LED_blink = zeros(file_len,1);
Eye_fix = zeros(file_len,1);
led_blink = zeros(file_len,1);
eye_fix = zeros(file_len,1);
j=1;k=1;

for i=user_begin:user_end
    if abs(directiona(i)) == 500
        led_blink(j)=i;
        j=j+1;
    end
    if abs(directionb(i)) == 500 && abs(mean (directionb(i:i+5)))==500
        eye_fix(k)=i;
        k=k+1;
    end
end
LED_blink(1) = led_blink(1);
j=2;k=1;l=2;
for i=2:user_end-1
    if led_blink(i+1)-led_blink(i) >1

```

```

        LED_blink(j) = led_blink(i+1);
        j=j+1;
    end
    if eye_fix(i)>led_blink(1)
        eye_fix(k) = eye_fix(i);
        k=k+1;
    end
end
Eye_fix(1) = eye_fix(1);
for i=2:user_end-1
    if eye_fix(i+1)-eye_fix(i) >1
        Eye_fix(1) = eye_fix(i+1);
        l=l+1;
    end
end
% -----
% Settling Time Calculation.
% -----

Eye_set = zeros(40,1);
time_lag = zeros(40,1);
L_time_lag = zeros(17,1);
R_time_lag = zeros(17,1);
settle_time = zeros(39,1);
settle_timeR = zeros(20,1);
settle_timeL = zeros(19,1);
saccade_number = (1:1:20);
set_ampL = zeros(19,1);
set_ampR = zeros(19,1);
set_amp = zeros(38,1);
for i=1:39
    time_lag(i)= ((Eye_fix(i)-LED_blink(i))*T);
end
j = 1;
for i = 1:2:39
    R_time_lag(j) = time_lag(i);
    L_time_lag(j) = time_lag(i+1);
    j = j+1;
end

k = 1;
for i=1:user_end
    if eye_fix(i+1)- eye_fix(i)~=1
        Eye_set(k) = eye_fix(i);
        k = k+1;
    end
end

for i = 1:39
    settle_time(i) = (Eye_set(i)-Eye_fix(i))*T;
end

```

```

j=1;

query = input('LED_R or LED_L? R/L =', 's');

if query == 'r'
    for i = 1:2:38
        settle_timeR(j) = settle_time(i);
        settle_timeL(j) = settle_time(i+1);
        j=j+1;
    end

elseif query == 'l'
    for i = 1:2:38
        settle_timeR(j) = settle_time(i+1);
        settle_timeL(j) = settle_time(i);
        j=j+1;
    end
end

for i = 1:length(L_time_lag)
    j = L_time_lag(i);
    set_ampL(i) = j;
    j=j+1;
end
for i = 1:length(R_time_lag)
    k = L_time_lag(i);
    set_ampR(i) = k;
    k=k+1;
end
for i = 1:length(time_lag)
    l = time_lag(i);
    set_amp(i) = l;
    l=l+1;
end

avg_settle_timeL = mean(settle_timeL);
avg_settle_timeR = mean(settle_timeR);
std_settle_timeL = std(settle_timeL);
std_settle_timeR = std(settle_timeR);
Left_Latency = mean(L_time_lag);
Right_Latency = mean(R_time_lag);
std_Left_Latency = std(L_time_lag);
std_Right_Latency = std(R_time_lag);

figure(5)
hold on
title('Time Delay for Left(Green) & Right(Blue) Saccades')
plot (saccade_number,L_time_lag,'.g')
plot (saccade_number,R_time_lag,'.b')
xlabel('Saccade Number');
ylabel('Time Delay');

```

```

%-----
% calculate error between POG and LED
%-----

% compute planar intercept Left eye

for i = user_begin:user_end
    alpha = atan(LEv_z(i)/LEv_y(i));
    Lv(i) = ((1 + (-LEp_y(i))) * tan(alpha)) + LEp_z(i);
    beta = atan(LEv_x(i)/LEv_y(i));
    Lh(i) = ((1 + (-LEp_y(i))) * tan(beta)) + LEp_x(i);
end

% compute planar intercept Right eye

for i = user_begin:user_end
    alpha = atan(REv_z(i)/REv_y(i));
    Rv(i) = ((1 + (-REp_y(i))) * tan(alpha)) + REp_z(i);
    beta = atan(REv_x(i)/REv_y(i));
    Rh(i) = ((1 + (-LEp_y(i))) * tan(beta)) + LEp_x(i);
end

%----- Input calibration equations-----%

clear a
clear b
clear c
clear d

a = 1.1194; %Lv
ai = .1142;
b = 1.2046; %Rv
bi = .1389;
c = 1.1557; %Lh
ci = -.1074;
d = 1.1084; %Rh
di = -.1975;

% empirically scale data to fit
for i = user_begin:user_end
    Lv(i) = a*Lv(i) + ai;
    Rv(i) = b*Rv(i) + bi;
    Lh(i) = c*Lh(i) + ci;
    Rh(i) = d*Rh(i) + di;
end

figure(6)
hold on
title('RIGHT vertical/horizontal intercept')
plot(xtime(user_begin:user_end), Rv(user_begin:user_end), 'r')
plot(xtime(user_begin:user_end), Rh(user_begin:user_end), 'b')

```

```

figure(7)
hold on
title('LEFT vertical/horizontal intercept')
plot(xtime(user_begin:user_end), Lv(user_begin:user_end), 'r')
plot(xtime(user_begin:user_end), Lh(user_begin:user_end), 'b')

% Calculation average left and right for combined POG.

for i = user_begin:user_end
    pog_x(i) = (Lh(i) + Rh(i)) / 2;
    pog_z(i) = (Lv(i) + Rv(i)) / 2;
    pog_y(i) = (REv_y(i) + LEv_y(i)) / 2;
end

% target values on board
X_tar = [0.173 0.36 0.552 0.173 0.36 0.552 0.173 0.36 0.552];
Z_tar = [-0.601 -0.601 -0.601 -0.42 -0.42 -0.42 -0.222 -0.222 -0.222];

RX_error=zeros(file_len,1);
RY_error=zeros(file_len,1);
RZ_error=zeros(file_len,1);
LX_error=zeros(file_len,1);
LY_error=zeros(file_len,1);
LZ_error=zeros(file_len,1);
% pog_X=zeros(file_len,1);
% pog_Y=zeros(file_len,1);
% pog_Z=zeros(file_len,1);
LXZ_error=zeros(file_len,1);
RXZ_error=zeros(file_len,1);
X_fov=zeros(file_len,1);
Z_fov=zeros(file_len,1);
X_fov_r=zeros(file_len,1);
Z_fov_r=zeros(file_len,1);
X_fov_l=zeros(file_len,1);
Z_fov_l=zeros(file_len,1);
    %compute error between POG and LED location

for i=user_begin:user_end
    if directionb(i) == 500
        RX_error(i) = pog_x(i) - 0.173;
        RY_error(i) = pog_y(i) - 1;
        RZ_error(i) = pog_z(i) + 0.42;    %.409
        RXYZ_error(i) =
sqrt(RX_error(i)^2+RZ_error(i)^2+RY_error(i)^2);
%         if atan(sqrt((pog_x(i)-0.173)^2)) < 0.0332 %&&
atan(sqrt((pog_z(i) + 0.42)^2)) < 0.0332 %1.64    % 1.9deg degrees =
1(fovea)+0.03(target)+0.5(eyelink)+0.1(motion monitor)...double it to
count for errors during head movement.
%             X_fov_r(k) = pog_x(i);
%             Z_fov_r(k) = pog_z(i);
%             k = k+1;
%         end
end

```

```

%         if X_fov_r(j)~=0
%             foveated_r = foveated_r +1;
%         end
%         if Z_fov_r(j)~=0
%             foveated_rz = foveated_rz +1;
%         end
end

    if directionb(i) == -500
        LX_error(i) = pog_x(i) - 0.552; % .554
        LY_error(i) = pog_y(i) - 1;
        LZ_error(i) = pog_z(i) + 0.42; % .409
%         LXYZ_error(i) =
sqrt(LX_error(i)^2+LY_error(i)^2+LZ_error(i)^2);
%         if atan(sqrt((pog_x(i)-0.552)^2)) < 0.0332 %&&
atan(sqrt((pog_z(i) + 0.42)^2)) < 0.0332 %1.64 % 1.9 degrees =
1(fovea)+0.03(target)+0.5(eyelink)+0.1(motion monitor)...double it to
count for errors during head movement.
%             X_fov_l(n) = pog_x(i);
%             Z_fov_l(n) = pog_z(i);
%             n = n+1;
%         end
%         if X_fov_l(j)~=0
%             foveated_l = foveated_l +1;
%         end
%         if Z_fov_l(j)~=0
%             foveated_lz = foveated_lz +1;
%         end
end

end

-----
% Target Foveation
%-----
-----

eye_fix_diff = zeros(500,1);
fix_period = zeros(40,1);

count=0;
flag_eye = 0;
move_start = eye_fix(1);

for i = 1:499
    eye_fix_diff(i) = eye_fix(i) - eye_fix(i+1);
    if eye_fix_diff(i) > 0 && flag_eye == 0
        move_end = eye_fix(i)+20;
        flag_eye =1;
    end
end

clear k
k = 1;
foveated_r = 0;

```

```

foveated_l = 0;
for i = move_start:move_end
    if directionb(i) == 0
        fix_period(k) = i;
        k = k+1;
    end
end

clear n
clear k
n = 1;
k = 1;
for i = move_start:move_end
    if directionb(i) ==0
        if atan(sqrt((pog_x(i)-0.552)^2))*180/pi < 1.9 %&&
atan(sqrt((pog_z(i) + 0.42).^2))*180/pi < 1.9 %1.64 % 1.9 degrees =
1(fovea)+0.03(target)+0.5(eyelink)+0.1(motion monitor)
            X_fov_l(n) = pog_x(i);
            Z_fov_l(n) = pog_z(i);
            n = n+1;
        end
        if atan(sqrt((pog_x(i)-0.173)^2))*180/pi < 1.9 %&&
atan(sqrt((pog_z(i) + 0.42).^2))*180/pi < 1.9 %1.64 % 1.9deg degrees
= 1(fovea)+0.03(target)+0.5(eyelink)+0.1(motion monitor)
            X_fov_r(k) = pog_x(i);
            Z_fov_r(k) = pog_z(i);
            k = k+1;
        end
    end
end

count = length(fix_period);
foveated_l = 0;
foveated_r = 0;
for i = 1:file_len
    if X_fov_l(i)~=0
        foveated_l = foveated_l +1;
    end
    if X_fov_r(i)~=0
        foveated_r = foveated_r +1;
    end
end
clear j
j = 1;
% rfix_total = 0;
% lfix_total = 0;
% for k = user_begin:user_end
%     if directionb == 0
%         for i = 2:2:36
%             rfix_count(j) = R_Saccade(i+1)-R_Saccade(i);
%             %rfix_total = rfix_total + rfix_count(j);
%             j = j+1;

```

```

%         end
%         rfix_total = sum(rfix_count);
%
%         clear j
%         j = 1;
%
%         for i = 2:2:36
%             lfix_count(j) = L_Saccade(i+1)-L_Saccade(i);
%             %lfix_total = lfix_total + lfix_count(j);
%             j = j+1;
%         end
%         lfix_total = sum(lfix_count);
%     end
% end
%
FF = (foveated_l + foveated_r)/count*100; %target foveation at
percentage of total stablization points collected
FF_left = (foveated_l/ (count/2))*100;
FF_right = (foveated_r/ (count/2))*100;

LED_positionLX=zeros(file_len,1);
LED_positionLZ=zeros(file_len,1);
LED_positionRX=zeros(file_len,1);
LED_positionRZ=zeros(file_len,1);

X_cyc=zeros(file_len,1);
Y_cyc=zeros(file_len,1);
Z_cyc=zeros(file_len,1);
X_cal=zeros(file_len,1);
Z_cal=zeros(file_len,1);
Int_err_X=zeros(file_len,1);
Int_err_Z=zeros(file_len,1);
XZ_error=zeros(file_len,1);
X_left=zeros(file_len,1);
Z_left=zeros(file_len,1);
X_right=zeros(file_len,1);
Z_right=zeros(file_len,1);
L_Int_err_X=zeros(file_len,1);
R_Int_err_X=zeros(file_len,1);
L_Int_err_Z=zeros(file_len,1);
R_Int_err_Z=zeros(file_len,1);
L_XZ_error=zeros(file_len,1);
R_XZ_error=zeros(file_len,1);
XL_eye=zeros(file_len,1);
XR_eye=zeros(file_len,1);
ZL_eye=zeros(file_len,1);
ZR_eye=zeros(file_len,1);
XRR = zeros(file_len,1);
ZRR = zeros(file_len,1);
XRL = zeros(file_len,1);
ZRL = zeros(file_len,1);

```

```

XLL = zeros(file_len,1);
ZLL = zeros(file_len,1);
XLR = zeros(file_len,1);
ZLR = zeros(file_len,1);
yL=ones(file_len,1);
yR=ones(file_len,1);
frameL = zeros(file_len,1);
frameR = zeros(file_len,1);
ampL = zeros(100,1);
ampR = zeros(100,1);

for j = user_begin:user_end
    if light(j) < 0 % Right LED negative Left LED positive
        LED_positionRX(j) = 0.552; %.554
        LED_positionRZ(j) = 0.42; %.409
    end
    if light(j) > 0
        LED_positionLX(j) = 0.173;
        LED_positionLZ(j) = 0.42; %.409
    end

    % Calculating Cyclopan Eye;
    X_cyc(j)= (LEp_x(j)+ REp_x(j))/2;
    Z_cyc(j)= (LEp_z(j)+ REp_z(j))/2;
    Y_cyc(j)= (LEp_y(j)+ REp_y(j))/2;

    r = (1 - Y_cyc(j))/(pog_y(j) - Y_cyc(j));
    X_cal(j)= X_cyc(j) + r*(pog_x(j)-X_cyc(j));
    Z_cal(j)= Z_cyc(j) + r*(pog_z(j)-Z_cyc(j));
    X_left(j)= Lh(j)+ r*(pog_x(j)- Lh(j)); % left eye xcoord gaze
intercept
    X_right(j)= Rh(j)+ r*(pog_x(j)- Rh(j)); % right eye xcoord
gaze intercept
    Z_left(j) = Lv(j) + r*(pog_z(j)-Lv(j));
    Z_right(j) = Rv(j) + r*(pog_z(j)-Rv(j));
    L_Int_err_X(j) = X_left(j)-LED_positionLX(j);
    R_Int_err_X(j) = X_right(j)-LED_positionRX(j);
    L_Int_err_Z(j) = Z_left(j)-LED_positionLZ(j);
    R_Int_err_Z(j) = Z_right(j)-LED_positionRZ(j);

    L_XZ_error(j) = sqrt(L_Int_err_X(j)^2+L_Int_err_Z(j)^2); %left
eye left LED error
    R_XZ_error(j) = sqrt(R_Int_err_X(j)^2+R_Int_err_Z(j)^2);
%right eye right LED error

end

% Separating Left and Right direction POG errors with left and right
LEDs

```

```

light = round(light)-1;
clear k
clear n
clear p
k = 1;
n = 1;
p = 1;
for j = user_begin:user_end
    if light(j) < 0 %Right LED negative
        XR_eye(k) = X_right(j);
        ZR_eye(k) = Z_right(j);
        XL_eye(k) = X_left(j);
        ZL_eye(k) = Z_left(j);
        XRR(k)=XR_eye(k)-3.5*mean(XR_eye(2:100));% zeroed value[1]-
3.5;2)-3.3;3)-3.3;4)-1]
        ZRR(k)=ZR_eye(k); %zPOI right eye, right LED
        XRL(k)=XL_eye(k)-3.5*mean(XL_eye(2:100));% zeroed value[1]-
3.5;2)-3.3;3)-3.3;4)-1]
        ZRL(k)=ZL_eye(k); %
%         if k == 1
%             frameR(k) = 1;
%         else
%             frameR(k) = frameR(k-1)+1;
%         end
% %         if XRR(k)==0
% %             frameR(k)=0;
% %         end
        k = k +1;
    end

    if light(j) > 0 %Left LED positive
        XL_eye(k) = X_left(j);
        ZL_eye(k) = Z_left(j);
        XR_eye(k) = X_right(j);
        ZR_eye(k) = Z_right(j);
        XLL(k) = XL_eye(k)-1*mean(XL_eye(2:100));% zeroed value[1]-
1;2)-1;3)-1;4)-0.3]
        ZLL(k) = ZL_eye(k);
        XLR(k) = XR_eye(k)-1*mean(XR_eye(2:100));% zeroed value[1]-
1;2)-1;3)-1;4)-0.3]
        ZLR(k) = ZR_eye(k);
%         if k == 1
%             frameL(k) = 1;
%         else
%             frameL(k) = frameL(k-1)+1;
%         end
% %         if XLR(k)==0
% %             frameL(k)=0;
% %         end
        k = k +1;
    end
end
if light(j) < 0 %Right LED negative
    if n == 1

```

```

        frameR(n) = 1;
    else
        frameR(n) = frameR(n-1)+1;
    end
    n = n+1;
end
if light(j) > 0 %Left LED positive
    if p == 1
        frameL(p) = 1;
    else
        frameL(p) = frameL(p-1)+1;
    end
    p = p+1;
end
end
end

x_Rerror_R = zeros(40,1);
z_Rerror_R = zeros(40,1);
x_Rerror_L = zeros(40,1);
z_Rerror_L = zeros(40,1);
z_Lerror_R = zeros(40,1);
x_Lerror_R = zeros(40,1);
x_Lerror_L = zeros(40,1);
z_Lerror_L = zeros(40,1);

clear k
clear l
clear m
clear p
k = 1;
l = 1;
m = 1;
p = 1;
for i= user_begin:user_end
    if directionb(i) == 0 && X_right(i) < .36
        x_Rstable_R(k) = X_right(i);
        z_Rstable_R(k) = Z_right(i);
        x_Rerror_R(k) = abs(0.173 - X_right(i));
        z_Rerror_R(k) = abs(-0.42 - Z_right(i));
        k = k+1;
    end
    if directionb(i) == 0 && X_right(i) > .36
        x_Rstable_L(l) = X_right(i);
        z_Rstable_L(l) = Z_right(i);
        x_Rerror_L(l) = abs(.552- X_right(i));
        z_Rerror_L(l) = abs(-0.42- Z_right(i));
        l = l+1;
    end
    if directionb(i) == 0 && X_left(i) < 0.36
        x_Lstable_R(m) = X_left(i);
        z_Lstable_R(m) = Z_left(i);
        x_Lerror_R(m) = abs(0.173 - X_left(i));

```

```

        z_Lerror_R(m) = abs(-0.42 - Z_left(i));
        m = m+1;
    end
    if directionb(i) == 0 && X_left(i) > 0.36
        x_Lstable_L(p) = X_left(i);
        z_Lstable_L(p) = Z_left(i);
        x_Lerror_L(p) = abs(0.552 - X_left(i));
        z_Lerror_L(p) = abs(-0.42 - Z_left(i));
        p = p+1;
    end
end

figure (8)
hold on
title('LED position Vs Point of Interception (PoI) [blue=left eye,
green=right eye]')
xlabel('X co-ordinate');
ylabel('Z co-ordinate');
plot(XL_eye,-ZL_eye,'.b')
plot(XR_eye,-ZR_eye,'.g')
plot(x_Lstable_L,-z_Lstable_L,'.b')
plot(x_Lstable_R,-z_Lstable_R,'.b')
plot(x_Rstable_L,-z_Rstable_L,'.g')
plot(x_Rstable_R,-z_Rstable_R,'.g')
plot (0.552, 0.42, 'rs', 'LineWidth',2, 'MarkerSize' ,5) %0.554, 0.42
plot (0.173, 0.42, 'rs', 'LineWidth',2, 'MarkerSize' ,5)

%    clear k
%    k = 1;
for j = 1:(user_end-user_begin)
    yL(j) = 0.552*yL(j)-1*mean(XL_eye(2:100));% zeroed value[1]-1;2)-
1;3)3)-1;4)-0.3]
    yR(j) = 0.173*yR(j)-3.5*mean(XR_eye(2:100));% zeroed value[1]-
3.5;2)-3.3;3)-3.3;4)-1]
    %    k = k + 1;
end

plot (frameL*T,yL,'r')
plot (frameR*T,yR,'r')
axis([0,500*T,-0.7,0.7])

j=1;k=1;
for i = 1:user_end
    if XLR(i) ~= 0 %xcoord Left LED right eye
        ampL(j) = XLR(i); %degree span
        j = j+1;
    end
    if XRL(i) ~= 0 %xcoord Right LED left eye
        ampR(k) = XRL(i);
        k = k+1;
    end
end
end

```

```

avg_ampL = mean(ampL);
std_ampL = std(ampL);
avg_ampR = mean(ampR);
std_ampR = std(ampR);
max_ampL = max(ampL);
min_ampL = min(ampL);
min_ampR = max(ampR);
max_ampR = min(ampR);
no_of_saccades = (length(settle_time)-1)/2;
%-----
-----
% calculate eye angles while staring target
%-----
-----
L_Eye_angle = zeros(39,1);
%R_Eye_angle = zeros(39,1);
L_Eye_angleL = zeros(18,1);
L_Eye_angleR = zeros(18,1);
%R_Eye_angleR = zeros(file_len,1);
%R_Eye_angleL = zeros(file_len,1);

avg_L_Eye_angleL = mean(L_Eye_angleL);
avg_L_Eye_angleR = mean(L_Eye_angleR);
% avg_R_Eye_angleL = mean(R_Eye_angleL);
% avg_R_Eye_angleR = mean(R_Eye_angleR);

figure(11)
hold on
title('Eye(blue) LED(green) plot EyeVel saccade onset(black)')
xlabel('Frames');
ylabel('Eye Angle(degrees)/LED switching pattern');
plot(-LHeye_angle(:,1), 'b')
plot(light(:,1), 'g')
plot (vel_El(:,1), 'k')
plot (vel_Er(:,1), 'k')

%-----
-----
% calculate saccadic error
%-----
-----
Error_R=zeros(20,1);
er_R=zeros(file_len,1);
Error_L=zeros(20,1);
er_L=zeros(file_len,1);
Max_sac_velR=zeros(20,1);
Max_sac_velL=zeros(20,1);
Sac_ampR=zeros(20,1);
Sac_ampL=zeros(20,1);

clear n

```

```

clear m
n = 1;
m = 1;
for i = user_begin:user_end
    if directionb(i)==0 && X_right(i) < 0.36 %xcoord right LED right
eye gaze intercept
        er_R(1)= abs(X_right(i)-.173);
        %n = n +1;
    end
    if directionb(i)==0 && X_right(i) > 0.36 %xcoord right LED right
eye gaze intercept
        er_R(i)= abs(X_right(i)-.552);
        %n = n +1;
    end
    if directionb(i)==0 && X_left(i) < 0.36
        er_L(i)= abs(X_left(i)-.173);
        %m = m+1;
    end
    if directionb(i)==0 && X_left(i) > 0.36
        er_L(i)= abs(X_left(i)-.552);
        %m = m+1;
    end
end
end

k=1;l=1;
for i = 1:2:length(R_Saccade-1)
    start = R_Saccade(i);
    stop = R_Saccade(i+1);
    Max_sac_velR(k) = max(abs(vel_Er(start:stop)));
    %Sac_ampR(k) = abs((LHeye_angle(stop)-LHeye_angle(start)));
    Sac_ampR(k) = atan(abs((Rh(stop)-Rh(start))/2))*180/pi *2;
    %Error_R(k)= (mean(er_R(stop+1:startb))); %*1000;
    k=k+1;
end
for i = 1:2:length(L_Saccade-1)
    start = L_Saccade(i);
    stop = L_Saccade(i+1);
    Max_sac_velL(l) = max(abs(vel_El(start:stop)));
    %Sac_ampL(l) = abs((LHeye_angle(stop)-LHeye_angle(start))); %
degree span of eye movement during saccade
    Sac_ampL(l) = atan(abs((Lh(stop)-Lh(start))/2))*180/pi*2;
    %Error_L(l)= (mean(er_L(stop+1:startb-1))); %*1000
    l=l+1;
end

x_Error_Reye_Rled = mean(x_Rerror_R);
x_std_Reye_Rled = std(x_Rerror_R);
x_Error_Reye_Lled = mean(x_Rerror_L);
x_std_Reye_Lled = std(x_Rerror_L);

z_Error_Reye_Rled = mean(z_Rerror_R);
z_std_Reye_Rled = std(x_Rerror_R);
z_Error_Reye_Lled = mean(z_Rerror_L);

```

```

z_std_Reye_Lled = std(x_Lerror_L);

x_Error_Leye_Rled = mean(x_Lerror_R);
x_std_Leye_Rled = std(x_Lerror_R);
x_Error_Leye_Lled = mean(x_Lerror_L);
x_std_Leye_Lled = std(x_Lerror_L);

z_Error_Leye_Rled = mean(z_Lerror_R);
z_std_Leye_Rled = std(z_Lerror_L);
z_Error_Leye_Lled = mean(z_Lerror_L);
z_std_Leye_Lled = std(z_Lerror_L);

% for i = 1:length(Sac_ampLm)
%     Sac_ampL(i) = atan(Sac_ampLm(i))*2;
% end
% for i = 1:length(Sac_ampRm)
%     Sac_ampR(i) = atan(Sac_ampRm(i))*2;
% end

average_Error_L = mean(Error_L);
average_Error_R = mean(Error_R);
std_Error_L = std(Error_L);
std_Error_R = std(Error_R);

%-----
% Plot saccadic error
%-----
% if Z == 1
    sac_markL=zeros(20,1);
    sac_markR=zeros(20,1);
    flag1=0;flag2=0;
    j=1;k=1;
    for i = start_point+1: user_end
        if XRR(i)~=0 && flag1==0;
            sac_markR(j) = i;
            flag1=1;
            j=j+1;
        end
        if XRR(i)==0 && flag1 == 1
            sac_markR(j)= i-1;
            flag1 = 0;
            j = j+1;
        elseif i == user_end && flag1 == 1
            sac_markR(j) = i;
        end
    end
    for i = start_point+1: user_end
        if XLR(i)~=0 && flag2==0;
            sac_markL(k) = i;
            flag2=1;

```

```

        k=k+1;
    end
    if XLR(i)==0 && flag2 == 1
        sac_markL(k)= i-1;
        flag2 = 0;
        k = k+1;
    elseif i == file_len && flag2 == 1
        sac_markL(k) = i;
    end
end
end

```

```

figure(14)
hold on
title('Time Duration for Left(Green) & Right(Blue) Saccades Vs
Amplitude')
plot (Sac_ampL(1:18),durationL(1:18),'.g')
plot (Sac_ampR(1:18),durationR(1:18),'.b')
xlabel('Amplitude');
ylabel('Time Duration');

```

```

figure(15)
hold on
title('Peak Velocity for Left(Green) & Right(Blue) Saccades Vs
Amplitude')
plot (Sac_ampL(1:18),max_velL(1:18),'.g')
plot (Sac_ampR(1:18),max_velR(1:18),'.b')
xlabel('Amplitude');
ylabel('Peak Velocity');

```

## APPENDIX C

### MATLAB Code for analyzing VOR

```

%-----
-----
% This program is designed to plot (1) raw temporal data, (2) the
head
% angle vs eye angle, and (3) head v. eye velocities (along with
separate
% VOR gains.
%
% Hegde (circa 2009)
% Pidcoe 022017
% O'Shea
%-----
-----

clear all %clear all variables
close all %close all windows and files
prgm = sprintf('PROGRAM = pv7.m'); %program name for storage
files
sampling_rate = 250; %set to 250Hz
T = 1 / sampling_rate; %period
PLOT = 1; %set plotting flag

%-----
-----
% query input file name
%-----
-----
root_name=input('Select File to Run: ','s');
in = strcat(root_name, '.txt'); % append extension
Y=load(in);

frame = Y(:,1);
file_len=length(frame);
    head_angle = Y(:,2);
    LHeye_angle = Y(:,3);
    RHeye_angle = Y(:,5);
    LEp_x = Y(:,7); LEp_y = Y(:,8); LEp_z = Y(:,9);
    LEv_x = Y(:,10); LEv_y = Y(:,11); LEv_z = Y(:,12);
    REp_x = Y(:,13); REp_y = Y(:,14); REp_z = Y(:,15);
    REV_x = Y(:,16); REV_y = Y(:,17); REV_z = Y(:,18);

%-----
-----
% create output file
%-----
-----
% out=strcat(root_name, '.out'); %open a file to store % activation
results
% fid_out = fopen(out, 'w');
% fprintf(fid_out, '%s\r\n', prgm); fprintf(fid_out, '\r\n');
% fprintf(fid_out, 'FILE = %s\r\n', strcat(root_name, '.txt'));
% fprintf(fid_out, '\n');

```

```

%-----
-----
% plot raw data and let user input start and stop points for analysis
%
% NOTE that istart and istop are now created from floating point
values to
% increase the resolution of the selection
%-----
-----
RAW_eye = LHeye_angle;           %load horizontal eye
angle
xtime = (0:file_len-1)*T;       %create time array for
plotting

if PLOT == 0
    user_begin=1;
    user_end=file_len-1;
end

if PLOT == 1
    figure('Name','RAW Eye Angle Data
Window','NumberTitle','off')    %title figure
    %plot raw data
    plot(xtime,RAW_eye,'b')
    str = sprintf('Left Eye Angle');
    title(str)
    xlabel('time')
    ylabel('angle')

    %graphically locate start and stop points for analysis
    [x,y] = ginput(2);
    user_begin = int32(x(1) * sampling_rate);
    if (user_begin < 0) user_begin = 1; end
    user_end = int32(x(2) * sampling_rate);
    if (user_end < user_begin) user_end = user_begin +
file_len; end
    if (user_end > file_len) user_end = file_len; end
end

%display selected values
hold on;
    istart = single(user_begin) / sampling_rate;
    istop = single(user_end) / sampling_rate;
    x = [istart istart]; plot(x,ylim,'r');           % ylim = axis
limits
    x = [istop istop]; plot(x,ylim,'r');           % ylim = axis
limits

% fprintf(fid_out,'\nSelected data from %.2f to %.2f
sec\n\r\r',istart,istop);

pog_x = zeros(1,file_len);
pog_y = zeros(1,file_len);

```

```

pog_z = zeros(1,file_len);
lv = zeros(1,file_len);
lh = zeros(1,file_len);
rv = zeros(1,file_len);
rh = zeros(1, file_len);
X_fov=zeros(file_len,1);
Z_fov=zeros(file_len,1);

for i = 1:file_len
    alpha = atan(LEv_z(i)/LEv_y(i));
    Lv(i) = ((1 + (-LEp_y(i))) * tan(alpha)) + LEp_z(i);
    beta = atan(LEv_x(i)/LEv_y(i));
    Lh(i) = ((1 + (-LEp_y(i))) * tan(beta)) + LEp_x(i);
end

% compute planar intercept Right eye

for i = 1:file_len
    alpha = atan(REv_z(i)/REv_y(i));
    Rv(i) = ((1 + (-REp_y(i))) * tan(alpha)) + REp_z(i);
    beta = atan(REv_x(i)/REv_y(i));
    Rh(i) = ((1 + (-LEp_y(i))) * tan(beta)) + LEp_x(i);
end
-----
%
%                               Input Calibration Equations
%
-----

clear a
clear b
clear c
clear d

a = 1.1194; %Lv
ai = .1142;
b = 1.2046; %Rv
bi = .1389;
c = 1.1557; %Lh
ci = -.1074;
d = 1.1084; %Rh
di = -.1975;

% empirically scale data to fit
for i = 1:file_len
    Lv(i) = a*Lv(i) + ai;
    Rv(i) = b*Rv(i) + bi;
    Lh(i) = c*Lh(i) + ci;
    Rh(i) = d*Rh(i) + di;
end

```

```

% Calculation average left and right for combined POG.

for i = user_begin:user_end
    pog_x(i) = (Lh(i) + Rh(i)) / 2;
    pog_z(i) = (Lv(i) + Rv(i)) / 2;
    pog_y(i) = (REv_y(i) + LEv_y(i)) / 2;
end

% target values on board
X_tar = [0.173 0.36 0.552 0.173 0.36 0.552 0.173 0.36 0.552];
Z_tar = [-0.601 -0.601 -0.601 -0.42 -0.42 -0.42 -0.222 -0.222 -0.222];

% Horizontal Eye angle calibration
cor_eyeangle = zeros(file_len,1);

for i = user_begin:user_end
    cor_eyeangle(i) = c*LHeye_angle(i) + ci;
end

%-----
% create arrays
%-----

zeroed_head_angle = zeros(file_len,1);
zeroed_eye_angle = zeros(file_len,1);

%-----
%-----
% Calculation of Mean
%-----
%-----

for i = 1:file_len
    zeroed_head_angle(i) = head_angle(i)-mean(head_angle);
    zeroed_eye_angle(i) = cor_eyeangle(i)-mean(cor_eyeangle);
end

%-----
%-----
% Plot of Zeroed Eye and Head angles
%-----
%-----

figure(1)
    hold on
    title('Eye Angle')
    plot(xtime, cor_eyeangle)
    xlabel('Time (seconds)');
    ylabel('Eye Angle (degrees)');

figure(2)
    hold on
    title('Zeroed Eye and Head angles plot')
    plot(xtime(user_begin:user_end),
zeroed_head_angle(user_begin:user_end,1), 'b')

```

```

        plot(xtime(user_begin:user_end),
zeroed_eye_angle(user_begin:user_end,1), 'g')
        xlabel('Time (seconds)');
        ylabel('Eye Angle (degrees)');
%-----
-----
% Calculation of Head Angle Vs Eye Angle
%-----
-----
figure(3)
hold on
title('Head Angle Vs Eye Angle')
plot (zeroed_head_angle, zeroed_eye_angle, '.g')
xlabel('Head Angle(degrees)');
ylabel('Eye Angle(degrees)');

% PEP -- NEED TO SCALE X AXIS TO EQUAL TOTAL TIME xlim of xtime

%-----
-----
% create indices for L and R head ANGLES -- NOTE: need to add
user_begin to
% left_head and right_head arrays to properly index the data
%-----
-----
deadzone = 1;
left_head = find (zeroed_head_angle(user_begin:user_end) > deadzone);
right_head = find (zeroed_head_angle(user_begin:user_end) < -
deadzone);

% left_head = find (zeroed_head_angle > deadzone);
% right_head = find (zeroed_head_angle < -deadzone);

% user_begin add offset
left_head = left_head + double(user_begin);
right_head = right_head + double(user_begin);

%-----
-----
% create temporary arrays from indices and plot directional movements
of
% eye and head moving towards the left. Used to verify data.
%-----
-----
a = zeroed_head_angle(left_head); b = zeroed_eye_angle(left_head);
c = zeroed_head_angle(right_head); d = zeroed_eye_angle(right_head);

figure(4)
hold on
title('Left eye and head data Vs time')

```

```

    plot(a, 'r')
    plot(b, 'k')
    xlabel('Time');
    axis square;

figure(5)
    hold on
    title('Right eye and head data Vs time')
    plot(c, 'r')
    plot(d, 'k')
    xlabel('Time');
    axis square;

figure(6)
    hold on
    title('Head Angle Vs Eye Angle')
    plot(a, b, 'r.')
    plot(c, d, 'k.')
    %plot(xtime(user_begin:user_end),
zeroed_head_angle(user_begin:user_end,1), 'b')
    xlabel('Head Turn Angle(degrees)');
    ylabel('Eye Angle(degrees)');
    axis square;

%-----
%-----
% create linear regression data fits and plot
%-----
%-----

rL = polyfit(a,b,1); %1st order fit of L eye velocities
rR = polyfit(c,d,1); %1st order fit or R eye velocities

% create and plot arrays
for i=1:length(a)
    e(i) = (rL(1)*a(i)) + rL(2);
end
    plot (a,e, 'b')

clear e;

for i=1:length(c)
    e(i) = (rL(1)*c(i)) + rL(2);
end
    plot (c,e, 'b')

% Annotate the VOR gain into the figure
str = sprintf('Lm= %s',num2str(rL(1)));
text(mean(a),0,str, 'HorizontalAlignment', 'center')

str = sprintf('Rm= %s',num2str(rR(1)));
text(mean(c),0,str, 'HorizontalAlignment', 'center')
%
```

```

% fprintf(fid_out,'\nSelected data from %.2f to %.2f
sec\n\r\r',istart,istop);
% fprintf(fid_out,'VOR Left Gain = %s \n\r',num2str(rL(1)));
% fprintf(fid_out,'VOR Right Gain = %s \n\r',num2str(rR(1)));
%
% % Find average VOR gain (both Left and Right directions)
%
% gain = [rL(1); rR(1)];
% avg_gain = mean(gain);
%
% fprintf(fid_out,'VOR Total Gain = %s \n\r',avg_gain);

%-----
----
% Calculation of Head Velocity Vs Eye Velocity
%-----
----
vel_H = zeros(file_len,1);
vel_E = zeros(file_len,1);
sample_freq = 250;
sample_rate = 1/sample_freq;
for i=user_begin + 2:user_end-1
    vel_H(i)=((zeroed_head_angle(i+1)-zeroed_head_angle(i-
1))/(2*sample_rate));
    vel_E(i)=((zeroed_eye_angle(i+1)-zeroed_eye_angle(i-
1))/(2*sample_rate));
end

%-----
----
% create indices for L and R head VELOCITIES
%-----
----
deadzone = 5;
left_head = find(vel_H(user_begin:user_end) > deadzone);
right_head = find(vel_H(user_begin:user_end) < -deadzone);

% user_begin add offset
left_head = left_head + double(user_begin);
right_head = right_head + double(user_begin);

%-----
----
% create temporary arrays from indices and plot
%-----
----
a = vel_H(left_head); b = vel_E(left_head);
c = vel_H(right_head); d = vel_E(right_head);

figure(7)
    hold on

```

```

    title('Head Velocity Vs Eye Velocity')
    plot (a, b, 'b.', c, d, 'g.')
    xlabel('Head Velocity(degrees/sec)');
    ylabel('Eye Velocity(degrees/sec)');
    axis square;

vel_lh = mean(a);
vel_rh = mean(abs(c));

vel_mean = (vel_rh + vel_lh)/2 ;

% fprintf(fid_out, 'Mean Left Velocity= %s \n\r', vel_lh);
% fprintf(fid_out, 'Mean Right Velocity = %s \n\r', vel_rh);
% fprintf(fid_out, 'Mean Total Velocity = %s \n\r', vel_mean);

% clear k
% clear j
% k = 1;
%
% for i = 1:file_len
%     if left_head(i+1)-left_head(i)<10
%         vel_l(k) = vel_H(i)
%         k = k+1
%     end
%
%     if right_head(i+1) - left_head(i) < 10
%
%
%-----
%-----
% create linear regression data fits and plot
%-----
%-----
pL = polyfit(a,b,1); %1st order fit of L head velocities
pR = polyfit(c,d,1); %1st order fit or R head velocities

% create and plot arrays
for i=1:length(a)
    f(i) = (pL(1)*a(i)) + pL(2);
end
    plot (a,f, 'r')

clear f;

for i=1:length(c)
    f(i) = (pL(1)*c(i)) + pL(2);
end
    plot (c,f, 'r')

```

```

% Annotate the VOR gain into the figure
str = sprintf('Lm= %s',num2str(pL(1)));
text(mean(a),0,str,'HorizontalAlignment','center')

str = sprintf('Rm= %s',num2str(pR(1)));
text(mean(c),0,str,'HorizontalAlignment','center')

% fprintf(fid_out,'\nSelected data from %.2f to %.2f
sec\n\r\r',istart,istop);
% fprintf(fid_out,'Velocity VOR Left Gain = %s \n\r',num2str(pL(1)));
% fprintf(fid_out,'Velocity VOR Right Gain = %s \n\r',num2str(pR(1)));

% Find average VOR gain (both Left and Right directions)
velgain = [pL(1); pR(1)];
velavg_gain = mean(velgain);

% fprintf(fid_out,'Velocity VOR Total Gain = %s \n\r',velavg_gain);

%-----
%-----
% Target Foveation
%-----
%-----

for j =user_begin:user_end
    if atan(sqrt((pog_x(j)-0.36)^2))*180/pi < 3.8 %&&
atan(sqrt((pog_z(j) + 0.42)^2))*180/pi < 3.8 %3.26 % in degrees =
1(fovea)+0.03(target)+0.5(eyelink)+0.1(motion monitor)...double it to
count for errors during head movement.
        X_fov(j) = pog_x(j);
        Z_fov(j) = pog_z(j);
    end
end

foveated = 0;
for j = user_begin:user_end
    if X_fov(j)~=0
        foveated = foveated +1;
    end
end
count = length(user_begin:user_end);

end
FF = foveated/count*100;

```

## APPENDIX D

### MATLAB Code for Analyzing VORC Data

```

%-----
-----
% This program is designed to plot (1) raw temporal data, (2) the
head
% angle vs eye angle, and (3) head v. eye velocities (along with
separate
% VOR gains.
%
% Hegde (circa 2009)
% Pidcoe 022017
% O'Shea
%-----
-----

clear all %clear all variables
close all %close all windows and files
prgm = sprintf('PROGRAM = pv7.m'); %program name for storage
files
sampling_rate = 250; %set to 250Hz
T = 1 / sampling_rate; %period
PLOT = 1; %set plotting flag

%-----
-----
% query input file name
%-----
-----
root_name=input('Select File to Run: ','s');
in = strcat(root_name, '.txt'); % append extension
Y=load(in);

frame = Y(:,1); file_len=length(frame);
head_angle = Y(:,2);
LHeye_angle = Y(:,3);
RHeye_angle = Y(:,5);
LEp_x = Y(:,7); LEp_y = Y(:,8); LEp_z = Y(:,9);
LEv_x = Y(:,10); LEv_y = Y(:,11); LEv_z = Y(:,12);
REp_x = Y(:,13); REp_y = Y(:,14); REp_z = Y(:,15);
REv_x = Y(:,16); REv_y = Y(:,17); REv_z = Y(:,18);

%-----
-----
% create output file
%-----
-----
% out=strcat(root_name, '.out'); %open a file to store % activation
results
% fid_out = fopen(out, 'w');
% fprintf(fid_out, '%s\r\n', prgm); fprintf(fid_out, '\r\r\n');
% fprintf(fid_out, 'FILE = %s\r\n', strcat(root_name, '.txt'));
% fprintf(fid_out, '\n');

```

```

%-----
-----
% plot raw data and let user input start and stop points for analysis
%
% NOTE that istart and istop are now created from floating point
values to
% increase the resolution of the selection
%-----
-----
RAW_eye = LHeye_angle;           %load horizontal eye
angle
xtime = (0:file_len-1)*T;       %create time array for
plotting

if PLOT == 0
    user_begin=1;
    user_end=file_len-1;
end

if PLOT == 1
    figure('Name','RAW Eye Angle Data
Window','NumberTitle','off')    %title figure
    %plot raw data
    plot(xtime,RAW_eye,'b')
    str = sprintf('Left Eye Angle');
        title(str)
        xlabel('time')
        ylabel('angle')

    %graphically locate start and stop points for analysis
    [x,y] = ginput(2);
        user_begin = int32(x(1) * sampling_rate);
            if (user_begin < 0) user_begin = 1; end
        user_end = int32(x(2) * sampling_rate);
            if (user_end < user_begin) user_end = user_begin +
file_len; end
            if (user_end > file_len) user_end = file_len; end
end

%display selected values
hold on;
    istart = single(user_begin) / sampling_rate;
    istop = single(user_end) / sampling_rate;
    x = [istart istart]; plot(x,ylim,'r');           % ylim = axis
limits
    x = [istop istop]; plot(x,ylim,'r');           % ylim = axis
limits

% fprintf(fid_out,'\nSelected data from %.2f to %.2f
sec\n\r\r',istart,istop);

%-----
-----

```

```

%                               Input Calibration Equations
%
-----

pog_x = zeros(1,file_len);
pog_y = zeros(1,file_len);
pog_z = zeros(1,file_len);
lv = zeros(1,file_len);
lh = zeros(1,file_len);
rv = zeros(1,file_len);
rh = zeros(1, file_len);
X_fov=zeros(file_len,1);
Z_fov=zeros(file_len,1);

for i = 1:file_len
    alpha = atan(LEv_z(i)/LEv_y(i));
    Lv(i) = ((1 + (-LEp_y(i))) * tan(alpha)) + LEp_z(i);
    beta = atan(LEv_x(i)/LEv_y(i));
    Lh(i) = ((1 + (-LEp_y(i))) * tan(beta)) + LEp_x(i);
end

% compute planar intercept Right eye

for i = 1:file_len
    alpha = atan(REv_z(i)/REv_y(i));
    Rv(i) = ((1 + (-REp_y(i))) * tan(alpha)) + REp_z(i);
    beta = atan(REv_x(i)/REv_y(i));
    Rh(i) = ((1 + (-LEp_y(i))) * tan(beta)) + LEp_x(i);
end
clear a
clear b
clear c
clear d

a = 1.1194; %Lv
ai = .1142;
b = 1.2046; %Rv
bi = .1389;
c = 1.1557; %Lh
ci = -.1074;
d = 1.1084; %Rh
di = -.1975;

% empirically scale data to fit
for i = 1:file_len
    Lv(i) = a*Lv(i) + ai;
    Rv(i) = b*Rv(i) + bi;
    Lh(i) = c*Lh(i) + ci;
    Rh(i) = d*Rh(i) + di;
end

```

```

% Calculation average left and right for combined POG.

for i = user_begin:user_end
    pog_x(i) = (Lh(i) + Rh(i)) / 2;
    pog_z(i) = (Lv(i) + Rv(i)) / 2;
    pog_y(i) = (REv_y(i) + LEv_y(i)) / 2;
end

cor_eyeangle = zeros(file_len,1);

for i = user_begin:user_end
    cor_eyeangle(i) = c*LHeve_angle(i) + ci;
end

%-----
% create arrays
%-----

zeroed_head_angle = zeros(file_len,1);
zeroed_eye_angle = zeros(file_len,1);

%-----
%-----
% Calculation of Mean
%-----
%-----

for i = 1:file_len
    zeroed_head_angle(i) = head_angle(i)-mean(head_angle);
    zeroed_eye_angle(i) = cor_eyeangle(i)-mean(cor_eyeangle);
end

%-----
%-----
% Plot of Zeroed Eye and Head angles
%-----
%-----

figure(1)
    hold on
    title('Eye Angle')
    plot(xtime, cor_eyeangle)
    xlabel('Time (seconds)');
    ylabel('Eye Angle (degrees)');

figure(2)
    hold on
    title('Zeroed Eye and Head angles plot')
    plot(xtime(user_begin:user_end),
zeroed_head_angle(user_begin:user_end,1), 'b')
    plot(xtime(user_begin:user_end),
zeroed_eye_angle(user_begin:user_end,1), 'g')
    xlabel('Time (seconds)');
    ylabel('Eye Angle (degrees)');

%-----
%-----

```

```

% Calculation of Head Angle Vs Eye Angle
%-----
-----
figure(3)
hold on
title('Head Angle Vs Eye Angle')
plot (zeroed_head_angle, zeroed_eye_angle, '.g')
xlabel('Head Angle(degrees)');
ylabel('Eye Angle(degrees)');

% PEP -- NEED TO SCALE X AXIS TO EQUAL TOTAL TIME xlim of xtime
%-----
-----
% create indices for L and R head ANGLES -- NOTE: need to add
user_begin to
% left_head and right_head arrays to properly index the data
%-----
-----
deadzone = 1;
left_head = find (zeroed_head_angle(user_begin:user_end) > deadzone);
right_head = find (zeroed_head_angle(user_begin:user_end) < -
deadzone);

% left_head = find (zeroed_head_angle > deadzone);
% right_head = find (zeroed_head_angle < -deadzone);

% user_begin add offset
left_head = left_head + double(user_begin);
right_head = right_head + double(user_begin);

%-----
-----
% create temporary arrays from indices and plot directional movements
of
% eye and head moving towards the left. Used to verify data.
%-----
-----
a = zeroed_head_angle(left_head); b = zeroed_eye_angle(left_head);
c = zeroed_head_angle(right_head); d = zeroed_eye_angle(right_head);

figure(4)
    hold on
    title('Left eye and head data Vs time')
    plot(a, 'r')
    plot(b, 'k')
    xlabel('Time');
    axis square;

figure(5)

```

```

    hold on
    title('Right eye and head data Vs time')
    plot(c, 'r')
    plot(d, 'k')
    xlabel('Time');
    axis square;

figure(6)
    hold on
    title('Head Angle Vs Eye Angle')
    plot(a, b, 'r.')
    plot(c, d, 'k.')
    %plot(xtime(user_begin:user_end),
zeroed_head_angle(user_begin:user_end,1), 'b')
    xlabel('Head Turn Angle(degrees)');
    ylabel('Eye Angle(degrees)');
    axis square;

%-----
%-----
% create linear regression data fits and plot
%-----
%-----

rL = polyfit(a,b,1); %1st order fit of L eye velocities
rR = polyfit(c,d,1); %1st order fit or R eye velocities

% create and plot arrays
for i=1:length(a)
    e(i) = (rL(1)*a(i)) + rL(2);
end
    plot (a,e, 'b')

clear e;

for i=1:length(c)
    e(i) = (rL(1)*c(i)) + rL(2);
end
    plot (c,e, 'b')

% Annotate the VOR gain into the figure
str = sprintf('Lm= %s', num2str(rL(1)));
text(mean(a),0,str, 'HorizontalAlignment', 'center')

str = sprintf('Rm= %s', num2str(rR(1)));
text(mean(c),0,str, 'HorizontalAlignment', 'center')

% fprintf(fid_out, '\nSelected data from %.2f to %.2f
sec\n\r\r', istart, istop);
%fprintf(fid_out, 'VOR Left Gain = %s \n\r', num2str(rL(1)));
%fprintf(fid_out, 'VOR Right Gain = %s \n\r', num2str(rR(1)));

% Find average VOR gain (both Left and Right directions)

```

```

gain = [rL(1); rR(1)];
avg_gain = mean(gain);

%fprintf(fid_out,'VOR Total Gain = %s \n\r',avg_gain);

%-----
----
% Calculation of Head Velocity Vs Eye Velocity
%-----
----
vel_H = zeros(file_len,1);
vel_E = zeros(file_len,1);
sample_freq = 250;
sample_rate = 1/sample_freq;
for i=user_begin + 2:user_end-1
    vel_H(i)=((zeroed_head_angle(i+1)-zeroed_head_angle(i-
1))/(2*sample_rate));
    vel_E(i)=((zeroed_eye_angle(i+1)-zeroed_eye_angle(i-
1))/(2*sample_rate));
end

%-----
----
% create indices for L and R head VELOCITIES
%-----
----
deadzone = 5;
left_head = find(vel_H(user_begin:user_end) > deadzone);
right_head = find(vel_H(user_begin:user_end) < -deadzone);

% user_begin add offset
left_head = left_head + double(user_begin);
right_head = right_head + double(user_begin);

%-----
----
% create temporary arrays from indices and plot
%-----
----
a = vel_H(left_head); b = vel_E(left_head);
c = vel_H(right_head); d = vel_E(right_head);

figure(7)
    hold on
    title('Head Velocity Vs Eye Velocity')
    plot (a, b,'b.', c, d, 'g.')
    xlabel('Head Velocity(degrees/sec)');
    ylabel('Eye Velocity(degrees/sec)');
    axis square;

vel_lh = mean(a);

```

```

vel_rh = mean(abs(c));

vel_mean = (vel_rh + vel_lh)/2 ;

% clear k
% clear j
% k = 1;
%
% for i = 1:file_len
%     if left_head(i+1)-left_head(i)<10
%         vel_l(k) = vel_H(i)
%         k = k+1
%     end
%
%     if right_head(i+1) - left_head(i) < 10
%
%
%-----
%-----
% create linear regression data fits and plot
%-----
%-----
pL = polyfit(a,b,1); %1st order fit of L head velocities
pR = polyfit(c,d,1); %1st order fit or R head velocities

% create and plot arrays
for i=1:length(a)
    f(i) = (pL(1)*a(i)) + pL(2);
end
    plot (a,f, 'r')

clear f;

for i=1:length(c)
    f(i) = (pL(1)*c(i)) + pL(2);
end
    plot (c,f, 'r')

% Annotate the VOR gain into the figure
str = sprintf('Lm= %s',num2str(pL(1)));
text(mean(a),0,str,'HorizontalAlignment','center')

str = sprintf('Rm= %s',num2str(pR(1)));
text(mean(c),0,str,'HorizontalAlignment','center')

% fprintf(fid_out,'\nSelected data from %.2f to %.2f
sec\n\r\r',istart,istop);
% fprintf(fid_out,'Velocity VOR Left Gain = %s \n\r',num2str(pL(1)));
% fprintf(fid_out,'Velocity VOR Right Gain = %s \n\r',num2str(pR(1)));

% Find average VOR gain (both Left and Right directions)

```

```

velgain = [pL(1); pR(1)];
velavg_gain = mean(velgain);

% fprintf(fid_out,'Velocity VOR Total Gain = %s \n\r',velavg_gain);

%-----
-----
% Compute intercept error
%-----
-----
X_cyc=zeros(file_len,1);
Y_cyc=zeros(file_len,1);
Z_cyc=zeros(file_len,1);
X_cal=zeros(file_len,1);
Z_cal=zeros(file_len,1);
Int_err_X=zeros(100,1);
X_left=zeros(file_len,1);
Z_left=zeros(file_len,1);
X_right=zeros(file_len,1);
Z_right=zeros(file_len,1);
L_Int_err_X=zeros(100,1);
R_Int_err_X=zeros(100,1);
X_fov=zeros(file_len,1);
Z_fov=zeros(file_len,1);
nLaserX=zeros(file_len,1);
nzeroed_head_angle=zeros(100,1);
nzeroed_eye_angle=zeros(100,1);
check = zeros(10,1);

% compute planar intercept Left eye

figure(6)
hold on
title('RIGHT vertical/horizontal intercept')
plot(xtime(user_begin:user_end), Rv(user_begin:user_end), 'r')
plot(xtime(user_begin:user_end), Rh(user_begin:user_end), 'b')

figure(7)
hold on
title('LEFT vertical/horizontal intercept')
plot(xtime(user_begin:user_end), Lv(user_begin:user_end), 'r')
plot(xtime(user_begin:user_end), Lh(user_begin:user_end), 'b')

% Calculation average left and right for combined POG.

for i = user_begin:user_end

```

```

    pog_x(i) = (Lh(i) + Rh(i)) / 2;
    pog_z(i) = (Lv(i) + Rv(i)) / 2;
    pog_y(i) = (REv_y(i) + LEv_y(i)) / 2;
end

for j = user_begin:user_end
    % Calculating Cyclopedian Eye;
    X_cyc(j)= (LEp_x(j)+ REp_x(j))/2;
    Z_cyc(j)= (LEp_z(j)+ REp_z(j))/2;
    Y_cyc(j)= (LEp_y(j)+ REp_y(j))/2;

    % Calculating Point of Interception (based on target depth 1m);
    r = (1 - Y_cyc(j))/(pog_y(j) - Y_cyc(j));
    X_cal(j)= X_cyc(j) + r*(pog_x(j)-X_cyc(j));% - offsetx
    Z_cal(j)= Z_cyc(j) + r*(pog_z(j)-Z_cyc(j));% - offsetz
    X_left(j)= LEp_x(j)+ r*(pog_x(j)- LEp_x(j)) ;
    X_right(j)= REp_x(j)+ r*(pog_x(j)- REp_x(j));
    Z_left(j) = LEp_z(j) + r*(pog_z(j)-LEp_z(j));
    Z_right(j) = REp_z(j) + r*(pog_z(j)-REp_z(j));

end
%-----
%-----
%Laser Motion display
%-----
%-----
% i = 1;
% for j = user_begin:user_end
%     X_cal (i) = X_cal(j);
%     i = i+1;
% end

nocheck=zeros(10,1);
LaserX = zeros(file_len,1);
Laserox = zeros(file_len,1);
X_Cal=zeros(10,1);
for j=1:length(X_cal)
    nocheck(j) = isfinite(X_cal(j));
end
i=1;
for j=1:length(nocheck)
    if nocheck(j) == 1
        X_Cal(i) = X_cal(j);
        i=i+1;
    end
end
end
Lx = mean(X_Cal(user_begin+50:user_end+100));
stdxcal=std(X_Cal(user_begin+50:user_end+100));
j=1;
for i = user_begin:user_end
    LaserX(i)= Lx - (1-LEp_y(i))*tan(zeroed_head_angle(i)*pi/180);
    Laserox(j) = LaserX(i);
end

```

```

        j=j+1;
end

i=1;
for j = user_begin+100:user_end
    lx = mean (Laserx);
    if (lx+0.1524) < lx < (lx-0.1524) %Choosing an area of interest
(the center foot of the screen)
        nLaserX(i) = LaserX(j);
        nzeroed_head_angle(i) = zeroed_head_angle(j);
        nzeroed_eye_angle(i) = zeroed_eye_angle(j);
        i=i+1;
    end
end

i=1;
for j=user_begin:user_end
    Int_err_X(i) = X_Cal(j)-LaserX(j);
    L_Int_err_X(i) = X_left(j)-LaserX(j);
    R_Int_err_X(i) = X_right(j)-LaserX(j);
    i=i+1;
end
%-----
%Eliminating NaNs
%-----
Int_err=zeros(10,1);
for j=1:length(Int_err_X)
    check(j) = isfinite(Int_err_X(j));
end
i=1;
for j=1:length(check)
    if check(j) == 1
        Int_err(i) = Int_err_X(j);
        i=i+1;
    end
end

std_Int_err_X = std(Int_err);
avg_Int_err_X = mean(Int_err);
std_zeroed_head_angle = std(zeroed_head_angle);

figure(8)
hold on
title('Head Angle Vs Eye Angle (blue=area of interest)')
plot (zeroed_head_angle, zeroed_eye_angle, '.g')
plot (nzeroed_head_angle, nzeroed_eye_angle, '.b')
xlabel('Head Angle(degrees)');
ylabel('Eye Angle(degrees)');

```

```

figure (9)
hold on
title('Scatter plot (Laser Target(red) vs. point-of-gaze(blue))(green
= area of interest)')
xlabel('X co-ordinate');
ylabel('-Z co-ordinate');
plot(X_Cal(user_begin:user_end),-Z_cal(user_begin:user_end),'.b')
plot(LaserX(user_begin:user_end),-Z_cal(user_begin:user_end),'.r')
plot(nLaserX(user_begin:user_end),-Z_cal(user_begin:user_end),'.g')
axis ([-1.0,1.2,-0.15,0.65]);

%-----
%
% Target Foveation
%-----
%
%-----
for j =user_begin:user_end
    if atan(sqrt((pog_x(j)-LaserX(j))^2))*180/pi < 3.8 %3.26 % in
degrees = 1(fovea)+0.03(target)+0.5(eyelink)+0.1(motion
monitor)...double it to count for errors during head movement.
        X_fov(j) = pog_x(j);
        Z_fov(j) = pog_z(j);
    end
end
foveated = 0;
for j = user_begin:user_end
    if X_fov(j)~=0
        foveated = foveated +1;
    end
end
count = length(user_begin:user_end);

end
FF = foveated/count*100;

```

VITA

Brittany Lin O'Shea was born on March 16, 1990 in Woodbridge, Virginia and is an American citizen. She graduated Cosby High School, Midlothian Virginia in 2008. In 2012, she received a Bachelor of Science in Mechanical Engineering and a minor in Biomedical Engineering from the University of Virginia, Charlottesville, Virginia and subsequently worked as a Mechanical Engineer for 3 years before starting graduate school.