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Saccadic Eye Movements Between Strategic, Interceptive, and Non-athletes

Brian Szekely

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SACCADIC EYE MOVEMENTS BETWEEN STRATEGIC, INTERCEPTIVE, AND NON-ATHLETES
by
BRIAN JOSEPH SZEKELY
(Under the Direction of Nicholas Gerald Murray)
ABSTRACT

Introduction: Athletes have differences in object tracking, search strategies, number and duration of fixations, dynamic visual acuity (DVA), and predictive eye movements than non-athletes (NON). However, these eye functions have not been assessed between athlete groups during a task that encompasses antisaccade and DVA characteristics. Purpose: To evaluate the oculomotor control sport paradigm differences between interceptive (INT) and strategic (STR) Division I collegiate athletes, as well as NON with an antisaccade task (AS) and a sport-like dual task (SDT). Methods: Fifty-seven participants (19 STR, 19 INT, and 19 NON) performed 2 trials of an AS and a SDT. Participants stood 55 in away from a monitor with a monocular eye tracker (240Hz) that used eye-to-head integrated to an 8 camera Vicon Motion Capture system (120Hz). Data were exported to MATLAB where a custom smoothing algorithm for AS and SDT resultant distance (RDA and RDSDT) and AS and SDT mean horizontal (MHVA and MHVSDT) velocity were applied. Four one-way ANOVAs measured the differences between groups. Results: There were no significant differences between INT and STR groups in RDA, RDSDT, MHVSDT. For the AS and SDT. The INT and STR had significantly greater RDA and RDSDT than NON (p<0.05). In the AS and, INT and STR exhibited significantly lower MHVA than the NON group (p<0.05). Discussion: RDA and RDSDT in both athlete groups were greater than the NON, while MHVA was lower than the NON. This could suggest that there are no saccadic differences between athlete groups, while the NON may be undershooting their eye movements during both tasks.

INDEX WORDS: Eye tracking, Antisaccade, Sports vision, Dual task
SACCADEIC EYE MOVEMENTS BETWEEN STRATEGIC, INTERCEPTIVE, AND NON-ATHLETES

by

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MASTER OF SCIENCE

STATESBORO, GEORGIA
SACCADIC EYE MOVEMENTS BETWEEN STRATEGIC, INTERCEPTIVE, AND NON-ATHLETES

by

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CHAPTER 1
INTRODUCTION

The evaluation of athletes’ vision was first introduced in the 1930’s (Banister & Blackburn, 1931; Clark & Warren, 1935). Since this time, scientists have been enamored with the physiological effect of sporting activity on vision. The main functions that researchers have assessed are object tracking, search strategies, and anticipatory eye movements. From these investigations, scientists have tried to delineate the differences in eye control strategies between athlete versus non-athlete, as well as expert versus novice athlete.

Expert athletes have the unique ability to learn dynamic complex scenes rapidly due to their superior perceptual skills (Faubert, 2013). This heightened ability could be due to their capacity to resolve spatial dynamic objects during head fixation or movement, as well as allocating their attention more efficiently than non-athletes (Mann, Williams, Ward, & Janelle, 2007; Palidis, Wyder-Hodge, Fooken, & Spering, 2017). This skill is referred to as dynamic visual acuity (Kaufman et al., 2014; Palidis et al., 2017). Dynamic visual acuity is usually tested in two manners: head movement while looking at a stationary object, or no movement fixating on a nonstationary object (Kaufman et al., 2014; Palidis et al., 2017). Athletes have a superior ability to resolve these dynamic objects due to their increased ability to perform catch up saccades to keep the object on the fovea, while simultaneously understanding where their head is in space with the help of their vestibular system (Morrison & Schatz, 2001; Palidis et al., 2017; Purves et al., 2014). A saccade is a burst of sudden eye movement from one point of interest to another (Antoniades et al., 2013; de Brouwer, Yuksel, Blohm, Missal, & Lefèvre, 2002; Purves et al., 2014; Ventura, Balcer, & Galetta, 2014). Not only do athletes have the ability to produce accurate catch up saccades, they can also use a predictive saccade to judge where the object will
be during fast object movement (Regan, 2012).

A saccade requires a cascade of neural mechanisms. The generation of a saccade requires balancing the importance of the stimuli, the goal and the intent of the individual, and the attentional capacity to gain the right amount of information from that stimuli (Mann et al., 2007; Ventura et al., 2014). This process begins when the photoreceptors are stimulated, which is then relayed to the occipital lobe (Purves et al., 2014; Ventura et al., 2014). From here, the neural flow of information goes to the parietal cortex, where reflexive saccades are generated. However, once the neural flow of information has been traveled from the parietal cortex, it can be modulated by the basal ganglia, dorsolateral prefrontal cortex, and thalamus before reaching the superior colliculus, where saccade generation occurs (Kunimatsu & Tanaka, 2010; Pierrot-Deseilligny, Milea, & Müri, 2004; Purves et al., 2014; Ventura et al., 2014). The basal ganglia and the dorsolateral prefrontal cortex play a crucial role in the modulation of the outcome of the saccade (Connolly, Goodale, Menon, & Munoz, 2002; DeSouza, Menon, & Everling, 2003; Srivastava et al., 2014). Their role becomes even more apparent during an antisaccade task. This task involves the suppression of a saccade when a stimulus appears, then looking in the opposite direction of the stimuli (Antoniades et al., 2013; Ventura et al., 2014). The neural flow of information will skip over the parietal eye fields and go straight to the frontal eye fields, specifically the dorsolateral prefrontal cortex in those that are asked to perform an antisaccade task (Connolly et al., 2002; DeSouza et al., 2003; Srivastava et al., 2014). This suggests that the dorsolateral prefrontal cortex is used extensively during attentional and cognitive tasks (Srivastava et al., 2014; Wang et al., 2013). In sports, athletes must perform antisaccadic tasks to maintain focus on the important stimuli, while simultaneously looking away from the distraction objects (Lenoir, Crevits, Goethals, Wildenbeest, & Musch, 2000). Thus, accurate saccades are
imperative in athletics.

Athletes have been observed to have superior control in the inhibition of reflexive saccades than non-athletes (Wang et al., 2013). This observation has also been noted in static head saccadic eye and antisaccadic tasks in baseball and basketball players (Di Russo, Pitzalis, & Spinelli, 2003; Fujiwara et al., 2009; Nakamoto & Mori, 2008a, 2008b). These studies observed that the athletes have faster response time, coupled with fewer errors than non-athletes. This suggests that athletes have a more refined dorsolateral prefrontal cortex due to their superior ability to control their saccadic eye movements during cognitive tasks. However, there are few studies that compare expert athletes of one sport to fellow expert athletes of another (Mann et al., 2007). The researchers operationally distinguished between expert athletes who used a device attached to the athlete (interceptive), such as in tennis, and athletes who have teammates with tactical formations on offense and defense (strategic), such as in soccer. Nonetheless, they made minimal comparisons between the expert athlete groups; only observing that there were with no differences in response time and accuracy between separate athlete groups (Mann et al., 2007).

As aforementioned, there are a number of studies that have assessed the saccadic eye movement capacities of athletes, non-athletes, and less experienced athletes (Jafarzadehpur, Aazami, & Bolouri, 2007; Mann et al., 2007; Nakamoto & Mori, 2008b; Piras, Lobietti, & Squatrito, 2010). However, there have been no studies that have assessed the saccadic eye movement, specifically eye magnitude and velocity differences between two expert athlete groups (strategic vs. interceptive). Traditionally, eye magnitude is assessed in the form of saccadic gain and amplitude analysis (Holmqvist et al., 2011; Radant et al., 2010). There is recent literature that has used use alternative form of amplitude analysis, resultant distance, as a method of analyzing gaze vector mapping (Murray et al., 2017a; Szekely et al., 2017). Szekely
et al. (2017) reported that visually trained athletes did not differ in resultant distance than non-visually trained athletes. However, this investigation was only an abstract, not a published manuscript. To the investigator’s knowledge, only that study evaluated magnitude differences between different sport paradigms. Only a few studies have assessed ocular control during an antisaccadic task that requires both dynamic visual acuity and sport-like postural task between different athlete groups. Yılmaz and Polat (2018) reported that there were no differences in antisaccade velocity between different sports and non-athletes. however, they did not include a sport-like dual task. the sport-like postural task not only requires the dorsolateral prefrontal cortex, but also stimulates of the basal ganglia, which is activated during human voluntary movement (Hikosaka, Takikawa, & Kawagoe, 2000; Purves et al., 2014; Visser & Bloem, 2005). Therefore, the purpose of this thesis was to evaluate the oculomotor control sport paradigm differences between interceptive and strategic Division I collegiate athletes, as well as non-athletes with a static antisaccade task and a sport-like dual task. The current hypothesis is that the interceptive athletes should have lower resultant distance and antisaccade velocities than the other two groups. This is due to their ability to require fewer fixations and faster response times than the other two groups (Mann et al., 2007). Lastly, the interceptive and strategic athletes should have lower resultant distances and antisaccade velocities than the non-athletes that do not participate in a sport (Wang et al., 2013).
CHAPTER 2
METHODOLOGY

2.1 Research Setting

A group of college-aged interceptive Division I athletes (INT), strategic Division I athletes (STR), and non-athletes (NON) were assessed with a cross-sectional design. This methodology allowed the researcher to evaluate the data gathered from the three samples from the same population at one given time point (Thomas, Silverman, & Nelson, 2015). All participants were either INT, STR, or NON from Georgia Southern University. INT was operationally defined as athletes that require coordination between the individual, the parts of the individual’s body, or a handheld device (Mann et al., 2007). STR was operationally defined as those that participate in a sport where teammates are present, with offensive and defensive tactics, while simultaneously allocating attention to a sport specific projectile (Mann et al., 2007). NON was assessed if they were actively performing a minimum of 30 min of moderate physical activity 5 days a week, or 20 min of vigorous physical activity for at least 3 days a week (Haskell et al., 2007). All data collection took place at Georgia Southern University’s Biomechanics Laboratory.

2.2 Participants

Fifty-seven participants (19 STR, 19 INT, and 19 NON; Table 1) agreed to be a part of the study, as well as met all the criteria for inclusion criteria (Table 2). INT athletes were gathered from tennis, baseball, and softball, while STR athletes were gathered from volleyball, soccer, football, and basketball. The sample consisted of both male and female athletes, which were recruited from baseline testing in the summer 2017 and fall 2017 semesters. The NON was recruited from various undergraduate Kinesiology courses. All participants in this study satisfied
the inclusion and exclusion criteria (Table 1). Before participation, all individuals completed a medical questionnaire and informed consent, which was approved by the Georgia Southern University Institutional Review Board.

**Table 1. Demographics of the Strategic, Interceptive, and Non-athletes**

<table>
<thead>
<tr>
<th>Group</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Height (in)</th>
<th>Weight (lbs)</th>
<th>PA (min/week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interceptive</td>
<td>17 M, 2 F</td>
<td>19 ± 1.5</td>
<td>71.4 ± 3.2</td>
<td>186 ± 24.3</td>
<td></td>
</tr>
<tr>
<td>Strategic</td>
<td>10 M, 9 F</td>
<td>19 ± 1.4</td>
<td>70.2 ± 4.4</td>
<td>177.2 ± 48.7</td>
<td></td>
</tr>
<tr>
<td>Non-athletes</td>
<td>7 M, 12 F</td>
<td>21 ± 1.0</td>
<td>67 ± 4.4</td>
<td>156 ± 35.4</td>
<td>291 ± 126</td>
</tr>
</tbody>
</table>

*Note: Demographics of the participants that were included in the data analysis. M= male, F= female, in= inches, lbs= pounds, PA= physical activity. min= minutes. Data are means ± standard deviations.*

**Table 2. Inclusion and exclusion criteria for the non-athletes and athletes**

<table>
<thead>
<tr>
<th>Inclusion</th>
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<tr>
<td>No history of seizures or psychiatric disorder</td>
</tr>
<tr>
<td>No documented concussion inside of 12 months</td>
</tr>
<tr>
<td>Georgia Southern student/athlete</td>
</tr>
<tr>
<td>30 min of moderate activity 5 days a week, or 20 min of vigorous activity 3 days a week (NON)</td>
</tr>
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</table>

*Note: All participants were Georgia Southern University students. Athletes were evaluated during a baseline physical assessment period. Non: Non-athlete*  

### 2.3 Study Design

All participants performed 3 trials of a 62-second sport-like postural dual task (SDT) (Wii Fit Soccer Heading game) and 3 trials of 40 stimuli antisaccades (AS) (Antoniades et al., 2013) in the Georgia Southern University Biomechanics Laboratory while wearing the Applied
Science Laboratory’s (ASL) H7 Eye Tracker (Applied Science Laboratory, Medford, MA, USA). The first trial was a familiarization trial, which was followed by 2 data collection trials. For the AS, 40 blue circular apertures appeared, 20 to the left and 20 to the right in random order. The participants performed 3 trials of this task. The INT and STR performed these 2 assessments during the baseline pre-participation period. Then, the NON participants performed the assessments during the 2017 fall school semester.

3.4 Procedures

The participants first completed a custom antisaccadic task. Each subject stood statically 55 in away from a 55 in LED TV (48.82 × 28.62 in Sharp Aquos HD LED Smart TV, 1920 x 1080 pixels, Mahwah, NJ, USA). While most ocular tests are traditionally given while the participant is seated; it has been observed that eye movement accuracy is not compromised when individuals are standing statically (Boulanger, Giraudet, & Faubert, 2017). The participants performed all tasks standing due to equipment limitations. The participants were instructed to fixate their gaze on a 23 pixel blue circular stimuli (0.5 degrees [°]) that was in the center of the screen (Figure 1) (Antoniades et al., 2013). The blue stimuli then moved 194 pixels to the left or right, with a total movement of 389 pixels (20°) (Antoniades et al., 2013). The individuals were asked to look in the opposite direction of where the blue object appears. Each participant performed 40 antisaccades (20 right, 20 left) with an update rate of 1 s (1 Hz) between the fixation point and the stimuli (Antoniades et al., 2013). The total time of the test was 80 s.

Participants then completed the SDT. The SDT game was performed barefoot on the Wii Fit Balance board. The participants were instructed to stand 55 in away from a 55 in LED TV (48.82 × 28.62 in Sharp Aquos HD LED Smart TV, 1920 x 1080 pixels, Mahwah, NJ, USA) while swaying their body in the mediolateral direction in order to move the on screen avatar in
the same direction (Murray et al., 2017b). No anteroposterior movement is necessary during
game play, however anteroposterior movement may occur. The participants were instructed to
maintain their gaze on the center of the screen, avoiding distraction objects (soccer cleats and
panda heads) and interacting with the cue stimuli (soccer balls). The avoidance of the distraction
objects and interaction with the cue stimuli, allows the SDT to have both prosaccadic and
antisaccadic characteristics. Points were awarded to the participants when they successfully
headed the ball. The visual stimuli were presented to the participants at a rate of 0.8 s (1.25 Hz).
In addition, the visual targets take approximately two seconds to travel 472 pixels (12.50 in) to
the left or right of the on screen avatar. The Wii Fit Soccer Heading game lasted for
approximately 62 s, with a total of 80 soccer balls being presented to the individuals.

The ASL Desktop 7 eye tracker integrated head movement via an 8 camera Vicon Nexus
system (120 Hz, Nexus, Version 1.8.5, Vicon Motion Systems, Oxford, UK). This allows for
head movement during dynamic tasks, mitigating any gaze shifting. The Vicon Nexus system
uses infrared light to detect the reflective markers that are on the posterior side of the ASL eye
tracker. This creates a three dimensional representation of the participant’s head during motion
within the reference frame. The ASL eye tracker itself has one infrared camera and one scene
camera that receive the video. The infrared camera is on top on the anterior, superior portion of
the eye tracker. This camera reflects light off of the monacle into the eye, which then reflects
light off the fovea and pupil (Diaz, Cooper, Kit, & Hayhoe, 2013; Murray et al., 2017b). The
information is then taken back into the eye tracker and recreated in ASL’s EyeTrac7 program
(Argus Science Laboratory, Medford, Massachusetts, USA). Before the AS and SDT, a nine-
point calibration of the TV screen was performed. This calibration digitized the TV screen,
which was then recreated in ASL’s EyeTrac7 (Applied Science Laboratory, Medford, MA,
USA). During both assessments, the scene camera had the point of gaze projected on the recreation of the TV screen, which was deemed as the point of gaze (POG). The POG, with the head coordinates from the Vicon Nexus system, quantified all eye movements and showed the instantaneous eye coordinates in real time. Due to the static head nature of the AS, this quantitative measure produced outputs in degrees (Holmqvist et al., 2011). However, this is not true in during the SDT assessment, due to the exaggerated anteroposterior movement that can occur during this task. Due to this issue, the SDT’s output were given in inches (in).

The ASL Eye tracker, with the head integration from the Vicon Nexus system, tracked the oculomotor efferent output (Murray et al., 2017b). During the SDT game, all stimuli originated from the center of the screen. The participants performed a prosaccade (reflexive eye movement) to the stimuli (soccer balls, shoes, and panda heads), while making antisaccades away from the distraction objects (voluntary eye movement away from stimuli). The TV screen was divided into 3 sections: left, center, right. The left is from the far left of the screen to the left goalpost. The center is the area between the goalposts, and the right is the far right of the TV to the right goalpost (Figure 2). These sections lay the boundaries for normal eye movements (Murray et al., 2017b). Any ocular movement outside the center area of interest are considered a prosaccade error. Prosaccade errors were classified as any directional errors from a target of interest (Murray et al., 2017b; Ventura et al., 2014). During the AS, any movement to the blue circular stimuli that is not in the center were considered a prosaccade error (Figure 1) (Antoniades et al., 2013). However, in this investigation prosaccade errors were not assessed due to the possibility of the participants having attention deficit hyperactivity disorder (ADHD). Individuals with ADHD have been reported to produce more prosaccade errors than their healthy counterparts (Diane C. Gooding & Basso, 2008).
Figure 1. Custom antisaccade task. The participants looked at the center blue stimuli. Next, they looked in the opposite direction of the subsequent blue circle. Any movement to the stimuli is considered a prosaccade error. Furthermore, mean horizontal velocity and resultant distance were used.

Figure 2. The Wii Fit Soccer Heading game with three quadrants. Any eye movements from the center (yellow) are classified as prosaccade errors. In addition, mean horizontal velocity, and resultant distance were analyzed from the data given from the EyeTrac7 software.

2.5 Data Analysis

The instantaneous raw gaze coordinates were exported and analyzed in ASL Results Plus (Applied Science Laboratory, Medford, MA, USA). A custom MATLAB code (MATLAB 2010, MathWorks, Inc., Natick, MA, USA) was used to filter the raw ocular displacement coordinates to calculate resultant distance of the AS (RDA), resultant distance of the SDT (RDSDT, mean
horizontal velocity of the AS (MHVA), and mean horizontal velocity of the SDT (MHVSDT).

The coordinate data were filtered with a Savitzky-Golay filter with a 25-point frame size window (Savitzky & Golay, 1964). This filter smoothed the raw gaze coordinates, which increased the signal-to-noise ratio without significantly compromising the true signal. Once this filter was run, RDA was calculated. This metric was calculated as the square root of the sum of the horizontal and vertical eye movements. Eq (1):

\[
RDA = \sqrt{\sum_{n=1}^{N} (dx^2 + dy^2)}
\]

MHVA and MHVSDT were calculated as the sum of the absolute value of the difference between adjacent points, which was then be divided by the difference between each adjacent data point. Lastly, this then was divided by the number of data points across the whole time series. Eq (2):

\[
MHVA = \frac{\sum_{n=1}^{N-1} |x_{n+1} - x_n|}{N - 1}
\]

The mean horizontal data that were above a 100 °/s were used in the final analysis for the AS. In addition, the mean horizontal velocity data above 100 in/s in the SDT were used in the final analysis. This cutoff was used to remove any smooth motor pursuit velocities (Holmqvist et al., 2011; Spering & Gegenfurtner, 2008).

3.6 Statistical Analysis

Four one-way analysis of variance (ANOVAs) were used to assess RDA, RDSDT, MHVA, and MHVSDT in the three groups (INT, STR, and NON). Post-hoc analyses were run on the differences in the variables of interest of between STR, INT, and NON. According to the
power analysis, a total sample size of 42 was deemed sufficient to determine the significance at
the desired power level (1-\(\beta\) = 0.80). Data were tested for normality with a Shapiro-Wilks test. If
any comparisons violated normality, a Kruskal-Wallis H test was performed. A Holm-Bonferroni
correction was applied for \textit{a priori} comparisons (Holm, 1979). The alpha level was set at 0.05 \textit{a
priori}. All data were run through SPSS v.23 (IBM Inc., Chicago, IL).
CHAPTER 3
RESULTS

All 57 participants (INT = 19, STR = 19, NON = 19) successfully completed both the AS and SDT. Data are summarized in Table 3.

3.1 Antisaccade Task

In the AS, significant omnibus results were noted for RDA ($F_{2,56}=10.71, p<0.001$) and MHVA ($F_{2,56}=24.392, p<0.001$). Follow-up assessments indicated that the INT group (7.31 ± 1.13°; Figure 3) had significantly greater RD than NON (5.74 ± 1.22°, $p<0.001$, $d=1.34$), but significantly slower MHVA than NON (INT: 144.61 ± 12.96°/s, NON: 369.79 ± 195.65°/s, $p<0.001$, $d=1.62$; Figure 4). The STR group (7.23 ± 1.16°) had significantly greater RDA than the NON group (5.74 ± 1.22°, $p<0.001$, $d=1.26$), but significantly lower MHVA than the NON group (STR: 147.50 ± 23.40°/s, NON: 369.79 ± 195.65°/s, $p<0.0001$, $d=1.60$). No significant differences were observed between STR and INT in RDA ($p=0.83$) or MHVA ($p=0.64$, Figure 4).

3.2 Sport-like Dual Task

In the SDT, there were significant omnibus results for RDSDT ($F_{2,56}=7.97, p<0.001$), but not MHVSDT ($F_{2,56}=1.14, p=0.252$). Post-hoc analysis noted that the INT group (4.04 ± 1.66 in) also had significantly greater RDSDT than NON group (2.49 ± 1.08 in, $p=0.001$, $d=1.11$). STR group (3.79 ± 1.02 in) had significantly greater RD than NON (2.49 ± 1.08 in, $p=0.009$, $d=2.18$; Figure 3). No significant differences were noted between INT and STR groups in the RDSDT ($p=0.57$) or MHVSDT ($p=0.80$). Furthermore, there were no significant differences in MHVSDT between INT ($p=0.614$) and STR ($p=0.358$) when compared to NON (Figure 4).
Figure 3. RDA and RDSDT between Interceptive (INT), Strategic (STR), and non-athletes (NON) during an antisaccade (AS) and sport-like dual task (SDT). Data are means ± standard deviations. °= degrees, in= inches.

Figure 4. MHVA and MHVSDT between Interceptive (INT), Strategic (STR), and non-athletes (NON) during an antisaccade (AS) and sport-like dual task (SDT). Data are means ± standard deviations. °/s= degrees divided by seconds, in/s= inches divided by seconds.
CHAPTER 4
DISCUSSION

To evaluate the oculomotor control sport paradigm differences between interceptive (INT) and strategic (STR) Division I collegiate athletes, as well as non-athletes (NON) with a static antisaccade task (AS) and a sport-like dual task (SDT). The hypotheses for this study were partially met. No significant differences were observed between STR and INT in any metric. However, both the STR and INT groups had significantly lower MHVA than NON during both tasks. Furthermore, Both STR and INT had greater RDA and RD than NON in both tasks.

The results indicate that there were no significant differences between the INT and STR group on any metric in the AS or SDT. Prior research has reported conflicting findings between oculomotor control in different sport paradigms (Jafarzadehpur et al., 2007; Piras et al., 2010; Szekely et al., 2017; Yilmaz & Polat, 2018). More recent research has reported differences in prosaccade velocity in tennis players compared to basketball and swimmers (Yilmaz & Polat, 2018). However, there were no differences in antisaccade velocity within any sport group, which was supported in this study. This may explain why there were no differences observed in MHV during the SDT. Since the SDT encompasses both prosaccadic and antisaccadic characteristics, the results may have been different if both the saccadic profiles were analyzed separately. Furthermore, the SDT also utilizes dynamic visual acuity; however, much of the dynamic visual acuity research is between athlete and non-athlete groups (Ishigaki & Miyao, 1993; Palidis et al., 2017; Uchida, Kudoh, Murakami, Honda, & Kitazawa, 2012). This is the first investigation to analyze gaze data in different sport paradigms during a task that utilized dynamic visual acuity. Even though there are reported number of fixation and fixation duration differences between these athlete groups (Mann et al., 2007), these results suggest that there were no other apparent
efferent pathway differences between these athlete types. These results may suggest no neural
differences in these athletes in the frontal eye fields, dorsolateral prefrontal cortex, substantia
nigra, or even the peripheral eye fields, but rather the neural control differences lie in the
structures that control fixations (Pierrot-Deseilligny et al., 2004; Purves et al., 2014). These areas
could include the omnipause neurons in the Raphe Nucleus, which fire very rapidly during
fixation, but cease before the initiation of saccades (Krauzlis, Goffart, & Hafed, 2017). In
addition, the omnipause neurons receive inputs from the intermediate layers of the superior
colliculus (fixation neurons), which increase in their activation rate when potential objects come
across the visual field (Krauzlis et al., 2017). Both of these neuronal structures have been
observed to discharge tonically during fixations, but decrease rapidly during saccadic firing, with
the omnipause decreasing their activation first, with the fixation neurons cessing their activation
over a larger range of time (Everling, Paré, Dorris, & Munoz, 1998). However, when omnipause
neurons have been damaged in primates, via excitotoxic lesions, there were no apparent fixation
differences when compared to primates that did not have any damage to their omnipause neurons
(Kaneko, 1996). It must be noted that some omnipause neurons that survived may have still
influenced the saccade burst generator (Everling et al., 1998). In addition, these monkeys could
have compensated by increasing activity in other fixation centers to reduce the excitatory input
into the saccade burst generator (Everling et al., 1998). These structures may give insight to
future work as to where the eye control mechanism differences may truly be present. At this
point, the eye mechanistic differences between sport paradigms are still unsolved. As noted by
Yılmaz and Polat (Yılmaz & Polat, 2018) on the subject matter, there is a scarcity of literature
that has assessed the antisaccadic and prosaccadic characteristics between different sport
paradigms.
The current results noted that the INT and STR groups had lower velocity in the antisaccade task than NON. Recent previous literature that assessed antisaccadic velocity in athletes and nonathletes, observed both similar and contradictory findings of the current results (Yilmaz & Polat, 2018). The investigators reported that the athletes did not differ in antisaccadic velocity when compared to the non-athletes; however, there was difference in antisaccadic velocity between athlete groups. This group did use a higher sampling frequency in their eye tracker (1000 Hz) than what was used in the current investigation (240 Hz). Previous research that has assessed sampling rate and saccadic velocity noted that if the stimulus is 20° in displacement, a sampling rate greater than 250-300 Hz is needed to accurately assess saccadic velocity (Antoniades et al., 2013; Juhola, Jäntti, & Pyykkö, 1985). Therefore, the saccadic velocity profile may be subject to undersampling, which may have caused a greater difference in displacement over time. If a higher sampling frequency was used, the data points would have been closer over the allotted time, which would not have caused the higher velocities. Be that as it may, the velocity data in previous research, were similar to these current results (Ramchandran et al., 2004; Yilmaz & Polat, 2018), as well as lower than other findings (Babu, Lillakas, & Irving, 2005; Pratt & Trottier, 2005).

The INT and STR groups had greater resultant distance than NON in both the AS and SDT. Only 2 published studies have used RDSDT in the assessment of gaze vector analysis (Murray et al., 2017a; Szekely et al., 2017). Szekely et al. ((Szekely et al., 2017) reported that swimmers did not differ from resultant distance in same SDT that was used in this study. They did not however, assess resultant distance in a traditional static head antisaccade task, nor did they have a control group. Studies that have assessed distance traveled, usually do so in the form of saccadic gain, which is each individual saccadic amplitude divided by distance between
the central point and the stimulus (Holmqvist et al., 2011; Radant et al., 2010). Saccadic gain and other amplitude analyses are a measure of the individual’s ability to accurately perceive the stimuli (Barash & Zhang, 2006; Everling & Fischer, 1998a). Previous literature has reported that humans often undershoot (lower saccadic gain) (Binsted, Chua, Helsen, & Elliott, 2001; Srivastava et al., 2014), with those having pathologies undershooting more than healthy controls (Everling, Krappmann, Preuss, Brand, & Flohr, 1996; Radant et al., 2010). In this investigation, we did not instruct participants to look at the opposite mirrored distance of the cue stimuli and therefore could not assess antisaccadic gain, the current results still follow the trends of saccadic gain research. The non-athletes had significantly lower resultant distance in both tasks when compared to both athlete groups. This could indicate that the non-athletes were undershooting the stimuli (soccer balls) in the SDT and undershooting during the antisaccade task. This concept may also a possible theoretical explanation as to why there was no difference in MHV in the SDT.

One theoretical explanation as to why both athlete groups had lower MHVA, and higher RD, and RDA than the NON, may be due to the increased neural control in the dorsolateral prefrontal cortex and intraparietal areas (Pierrot-Deseilligny et al., 2004). Both of these areas actively participate in either short-term spatial memory, visuospatial attention, and visual integration (Pierrot-Deseilligny et al., 2004). These athletes may be more aware of the distance and velocity required to successfully complete the task based upon the information gathered via the fixations. Furthermore, athletes have been reported to be able to identify the most visual rich areas of the surrounding environment (Mann et al., 2007), thus allowing them to accurately judge the distance that the eye needs to travel and the velocity required to reach there. This could mean that they are making very fast initial saccades, but slower saccades as the time progresses. NON
could be making faster, shorter saccades the entire trial in both the AS and SDT. Future research should assess different time domains of both antisaccadic or prosaccadic task, to better understand the intricate mechanistic differences of initial and catch up saccades between athletes and non-athletes. This may provide insight into microstructure of saccadic eye movements within athlete paradigms.

Several limitations exist in this current thesis that must be addressed in future research. First, as mentioned previously, prosaccade errors were not measured due to the possibility the participants having ADHD. Thus, error velocity was not assessed (Diane C. Gooding & Basso, 2008). Second, the sampling rate may have been too low to accurately capture saccadic velocity. Cue stimuli displacements of 20° must have a sampling rate greater than 250-300 Hz to accurately evaluate saccadic velocity (Antoniades et al., 2013; Juhola et al., 1985). However, as of right now there are no eye trackers above 240 Hz range that allow for eye to head integration with a motion capturing system. Third, the eye-to-head integration of the eye tracking hardware with the Vicon motion capture system, may also cause an additional inaccuracy of 0.5-1.0° (Kredel, Klostermann, & Hossner, 2015). However, this error was minimized by having low image error during the calibration process. Fourth, due to SDT having some anteroposterior movement, the outcome variables had to be assessed with inches, instead of degrees. Lastly, vertical saccades were not assessed, even though there are vertical eye movements present in the SDT. At this time, the horizontal eye saccades are more understood, neurally, than vertical saccades (Purves et al., 2014)
CHAPTER 5

CONCLUSION

In conclusion, this thesis provides the first comparison between athlete paradigms during a SDT, as well one of the first studies to assess the antisaccadic profile of different athlete paradigms (Yilmaz & Polat, 2018). These results suggest that there were no apparent velocity or resultant distance differences between the sport paradigms of STR and INT during an antisaccade task and a SDT. However, both athlete groups had greater resultant distances in both tasks, and greater mean horizontal velocity in the antisaccade task than NON.
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APPENDIX A INFORMED CONSENT

CONSENT TO ACT AS A SUBJECT IN AN EXPERIMENTAL STUDY

1. Title of Project: Identification of Persistent Impairments in Postural Control Following Concussion

   Investigator’s Name: Nicholas Murray, Ph.D.     Phone: (912) 478 - 5268

   Participant’s Name ___________________________ Date:_____________________

   Data Collection Location: Biomechanics Laboratory, Georgia Southern University Campus

2. We are attempting to compare the balance, coordination and bodily control of individuals who have suffered a concussion and compare that to people who have not suffered a concussion. There will be 500 participants in this study, about half whom and half who have not suffered a concussion. The results of this study will help athletic trainers in the evaluation, treatment, and return to play decision making process in individuals who have suffered a concussion.

3. You are being invited to participate in this study because you have recently suffered a concussion or are a control subject. Additionally, you have no history of any nerve, inner ear or balance disorders, metabolic disorders, or significant injury to the lower extremity.

   If you agree to participate in this study you will be asked to attend testing sessions lasting 25 min. You will be tested post-concussion, your return to play day and then every 7 days over the next 2 months. During the session you will be asked to both stand still, on 2 feet and 1 foot, walk at normal pace while solving mental challenges and play the Wii Soccer game. During the session you will stand and walk across force platforms and a carpet which measures the forces you create on the ground. You will also stand on a Wii balance board that is on top of a force platform and wear a headset. Finally, we will record your performance on the balance, cognitive, and neuropsychological testing, and your self-reported symptoms that you complete as part of your normal post-concussion assessment. The balance test will be video recorded.
4. The information we collect on your performance may be sent off campus for analysis, however any information sent will be devoid of identifying characteristics (no one will be able to tell it’s you). The video recordings will not be sent off-campus.

5. Your performance during these tasks will be compared to your performance during your baseline test, if you performed one, when you began playing sports at Georgia Southern University.

6. The risk assumed during the testing is no greater than you experience during your normal daily activities. There is minimal risk of physical injury or mental discomfort while performing this experiment. There is a risk of falling during the gait and balance trials; therefore, a member of the research team will be in close proximity should you lose balance. The headset you will be wearing for the Wii Soccer game does not impair vision and should sit comfortably on your head like a ball cap. If the headset becomes uncomfortable at any time, a member of the research team will immediately remove it. You understand that medical care is available in the event of injury resulting from research but that neither financial compensation nor free medical treatment is provided. You also understand that you are not waiving any rights that you may have against the University for injury resulting from negligence of the University or investigators. Should medical care be required, you may contact Health Services at (912) 478 – 5641.

7. You will likely receive no direct benefit for participating in this study, however you will be provided your results, once calculated, if you so request. The results of this study may be used to better understand and treat individuals who have suffered concussions.

8. You will attend testing sessions over the next 2 months lasting about 25 min.

9. You understand that all data concerning yourself will be kept confidential and available only upon your written request to Nicholas Murray, Ph.D. You understand that any information about your records will be handled in a confidential (private) manner consistent with medical records. Your identity on all records will be indicated by a case number. You will not be specifically mentioned in any publication of research results. However, in unusual cases your research records may be inspected by appropriate government agencies or released to an order from a court of law. All information and research records will be kept for a period of 5 years after the termination of this investigation. The video recordings will be retained for seven years as required by the Georgia Board of Regents policy.
10. If you have any questions about this research project, you may call Nicholas Murray at (912) 478-5268. If you have any questions or concerns about your rights as a research participant in this study it should be directed to the IRB Coordinator at the Office of Research Services and Sponsored Programs at (912) 478-0843.

11. You will not receive compensation for your participation in this project. You will be responsible for no additional costs for your participation in this project.

12. You understand that you do not have to participate in this project and your decision to participate is purely voluntary. At any time you can choose to end your participation by telling the primary investigator, Dr. Murray.

13. You understand that you may terminate participation in this study at any time without prejudice to future care or any possible reimbursement of expenses, compensation, employment status, or course grade except provided herein, and that owing to the scientific nature of the study, the investigator may in his/her absolute discretion terminate the procedures and/or investigation at any time.

14. You understand there is no deception involved in this project.

15. You certify you are 18 years of age or older and you have read the preceding information, or it has been read to you, and understand its contents. Any questions you have regarding the research have been, and will continue to be, answered by the investigators listed at the beginning of this consent form or at the phone numbers given (912) 478 – 5268.

16. You have been provided a copy of this form.

Title of Project: Identification of Persistent Impairments in Postural Control Following Concussion

Principal Investigator          Other Investigator
Nicholas Murray, Ph.D.          Barry Munkasy, Ph.D.
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I, the undersigned, verify that the above informed consent procedure has been followed.
APPENDIX B LITERATURE REVIEW

2.1 Introduction

Half of the brain is directly or indirectly apart of the visual system (Maruta & Ghajar, 2014). The visual system aids in gathering incoming information from the local surroundings and assists in the execution of appropriate motor tasks (Babu et al., 2005). Two major responsibilities of the ocular system is Dynamic visual acuity and gaze stabilization (Kaufman et al., 2014). Dynamic visual acuity is the skill to resolve spatial detail of dynamic objects during head fixation or static objects during dynamic head movement, while gaze stabilization is the ability to maintain a stable gaze on a visual target during the maximum head velocity (Honaker, Criter, Patterson, & Jones, 2015; Palidis et al., 2017). Both of these ocular tasks requires rapid eye movements and processing of those eye movements in order to determine location, orientation, and velocity of the object of focus (Ventura et al., 2014). The visual system uses many various strategies to carry out these variables of visual organization. The ocular system utilizes saccades to gather data around the object of interest in order to gain additional information, and will employ smooth motor pursuit to foveate the object during object motion (Murray et al., 2017b); (Purves et al., 2014).

Object driven athletes, such as those who participate in baseball, basketball, volleyball, and soccer have been shown to have superior dynamic visual acuity than non-athletes (Palidis et al., 2017). Efficient dynamic visual acuity has been purported as being attributed to better oculomotor control (Palidis et al., 2017). Furthermore, it has been suggested that superior dynamic visual acuity is credited to enhanced saccadic eye movements and smooth motor pursuit(Uchida et al., 2012). However, dynamic visual acuity is only part of the equation (Palidis et al., 2017). Palidis et al., (2017) observed that baseball athletes during a free eye movement
condition, baseball players had more efficient eye movements than non-athletes, but not in the fixation condition. They postulated that due to their enhanced dynamic visual acuity, their ability to track the objects was enhanced, not their image processing ability. This could indicate that even though dynamic visual acuity is important, gaze stabilization is of equal or greater importance during dynamic movements. Gaze stabilization fixates the moving object on the fovea during head translation, which is more indicative of response time (Medendorp, Van Gisbergen, & Gielen, 2002).

Gaze stabilization and dynamic visual acuity are commonly assessed with saccades, antisaccades, and smooth motor pursuit examinations, which all are influenced by the vestibulo-ocular reflex (VOR) (D. C. Gooding, Mohapatra, & Shea, 2004; Herdman, Schubert, & Tusa, 2001; Murray et al., 2017b; Murray, Ambati, Contreras, Salvatore, & Reed-Jones, 2014; Palidis et al., 2017; C.-H. Wang et al., 2013). Saccades are quick, straight line ballistic eye movements, mainly in the horizontal direction, which only last tens of milliseconds (Murray et al., 2017b; Purves et al., 2014; Ventura et al., 2014). Antisaccades are saccades made in the opposite direction of a stimulus (Antoniades et al., 2013; Murray et al., 2017b). These eye movements include a wide range of cognitive processes that aids in the gathering of visual stimuli (Ventura et al., 2014). Piras, Lobietti, and Squatrito (2010) reported that professional volleyball athletes perform a visual search strategy that requires fewer fixations of longer durations than non-athletes during a saccadic task where the participants were instructed to look at the visual target when it appeared (prosaccade). This demonstrates that expert volleyball athletes can gather more visual data in a limited amount of time compared to non-athletes. Another common eye tracking tool, that occurs slower than saccades, is smooth motor pursuit. Smooth motor pursuit keeps a moving visual stimuli over the fovea during the trajectory of a moving object (Purves et al.,
All three of these eye movements are involved in VOR movements. The vestibular system will detect brief head movements, and produce catch up saccades to keep the image on the fovea (Purves et al., 2014).

2.2 Eye Movements - Antisaccade And Prosaccade

Saccadic eye movements are the apogee of the neural process of decision making (Schall, 2003). During saccadic eye movements, one must control the amplitude of eye movement, and control the direction of that eye movement (Purves et al., 2014). Prosaccades are reflexive elicited by an onset of a stimulus (Bell, Everling, & Munoz, 2000). While antisaccades have two processes: inhibition of a prosaccade and a voluntary saccade in the opposite direction (Olk & Kingstone, 2003). These eye movements can be broken up into a mathematical hierarchy of physiological properties (Antoniades et al., 2013). This hierarchy includes parameters such as latency period, saccadic velocity, positional errors, and magnitude of movement (Adler, Bala, & Krauzlis, 2002; Antoniades et al., 2013; Babu et al., 2005; Erkelens, 2006; Murray et al., 2017b, 2014; Palidis et al., 2017).

Saccadic eye movements can be reflexive or voluntary. This dichotomy will affect the latency of a saccade. Latency represents the time it takes for an eye to respond to a sudden movement of a target (Figure 1) (Purves et al., 2014). Saccadic latency in humans is approximately 150-250 milliseconds (Adler et al., 2002; Antoniades et al., 2013; Erkelens, 2006; Holmqvist et al., 2011; Krauzlis, 2004; Purves et al., 2014; Yang, Bucci, & Kapoula, 2002). However, Carpenter (Carpenter, 1999) observed that saccadic latency can vary trial-to-trial by 5% outside of 150-300 milliseconds (Figure 2). Furthermore, Adler, Bala, Krauzlis (2002) reported that when participants were given a cue to where an object would appear, the saccadic latency decreased by approximately 40 milliseconds when compared to no cue condition.
Furthermore, Halliday and Carpenter (2010) observed that when demanding cognitive tasks were presented to participants during a prosaccadic task, there were increased saccadic latency. This phenomenon is also observed in those that perform antisaccadic tasks (Everling & Fischer, 1998b). Hallet (1978) first observed ocular performance in a healthy population. Hallet (1978) observed that the latency period increased when the subjects performed the antisaccadic task versus the prosaccadic task. However, during an antisaccade task with a gap between antisaccades (gap effect), the latency period decreases both antisaccades and prosaccades (Everling & Fischer, 1998b; Fischer & Weber, 1992). This increased latency period in antisaccadic tasks is reported to be due to the increased cognition to repress a reflexive saccade, as indicated by functional neuroimaging work (Sweeney et al., 1996). This increased cognitive demand has been further observed to affect antisaccadic velocity (Fischer & Weber, 1992; Hallett, 1978).

Antisaccadic velocity was noted to be slower than prosaccadic velocity first in nonhuman primates (Edelman & Goldberg, 2003). In humans, similar results have been noted (Fischer & Weber, 1992; Hallett, 1978). Fischer and Weber (1992) observed that when subjects performed 200 antisaccades and prosaccades with a range of 8° to the left or right of the fixation point that normalized velocity in the prosaccades (1.047°/s) was greater than antisaccadic velocity (0.966°/s). This increased velocity in antisaccades is due to the increased cognitive demands on working memory to inhibit the reflexive saccade response (J. Wang, Tian, Wang, & Benson, 2013). However, corrective saccades during an antisaccadic task have been reported to be faster than prosaccades (Everling & Fischer, 1998b; Fischer, Gezeck, & Hartnegg, 2000). These corrective saccades are apparent usually when a participant commits a positional error.

Positional errors or prosaccade errors occur during an antisaccade task when an
individual does not suppress the prosaccade reflex (Holmqvist et al., 2011; Douglas P. Munoz & Everling, 2004; Murray et al., 2017b; Pratt & Trottier, 2005). During prosaccadic tasks, individuals seldom make any prosaccadic errors, but will commit prosaccadic errors 5-80% of the time during an antisaccadic task (Everling & Fischer, 1998b; Hallett, 1978). Fischer and Weber (Fischer & Weber, 1992) observed that after 12-15 days of continuous practice of an antisaccade task, participants decreased their error rate from 14 to 11%. This would show that there is a training effect with everyday antisaccade administration. In addition, not only does time affect the error rates of an antisaccadic task, but so does the luminance of the stimulus. Photopic stimuli has been observed to lead to larger angular errors (eye angular movement) in antisaccade tasks compared to prosaccade tasks. However, scotopic luminance will increase prosaccade errors in both antisaccade and prosaccade tasks (Everling & Fischer, 1998b). Furthermore, as the eccentricity (deviating from a circle) of a stimulus increases (1-12°), so too does the amount of prosaccade errors (Fischer & Weber, 1997). This would support the notion that only circles that have less 1° of eccentricity should be used when assessing participants in saccadic tasks. While eccentricity plays a key role in error rates, interweaving prosaccade and antisaccades in the same task causes high error rates (30%) (Weber, 1995). Weber (Weber, 1995) observed that the errors were not only apparent in both the prosaccadic and antisaccadic trials. The analysis indicated that the individuals would make an antisaccade during the prosaccade trial, and a prosaccade during an antisaccade. These findings indicate that cognition is required when make voluntary saccades, even if they are prosaccades.

During both antisaccades and prosaccades, there is no difference in amplitude of eye movement (Kimmig et al., 2001). Saccadic amplitude or gain, is the distance traveled by the eyes during one reflexive or voluntary eye movement (Bahill, Clark, & Stark, 1975; Holmqvist et al.,
2011; Purves et al., 2014; Straube, Fuchs, Usher, & Robinson, 1997). Saccadic amplitude is a measure of saccadic accuracy, typically 4-20°(Ethier, Zee, & Shadmehr, 2008; Holmqvist et al., 2011). Furthermore, in the seminal work of saccadic eye movements, as amplitude increases so too does saccadic duration and average velocity in healthy individuals(Brockhurst & Lion, 1951; Dodge & Cline, 1901; Hyde, 1959). It can be suggested that amplitude of saccades maybe indicative of the overall stability of the eye itself. In diseased populations, saccadic gain is reduced in antisaccadic tasks than in prosaccadic tasks(Srivastava et al., 2014). Thus neither was latency nor, prosaccadic performance affected. However, antisaccadic performance was diminished(Srivastava et al., 2014). This supports that not only is amplitude indicative of overall saccadic performance, but antisaccadic tasks are more efficient in the assessment of saccadic performance.

2.3 Neural Mechanisms Of Saccadic Eye Movements

Much of the information of the saccadic pathways has been carried out in lesion, neurophysiological, neuroanatomical, and brain imaging studies(Srivastava et al., 2014). The cortical and subcortical networks are the main contributors to the planning, initiation, and execution of saccadic eye movements(Srivastava et al., 2014). More specifically, the basal ganglia (BS), superior colliculus (SC), thalamus (TH), brainstem (BR), cerebellum (CB), and cerebral cortex, specifically the parietal and frontal cortices are all involved in saccadic actions (Figure 2)(Srivastava et al., 2014).

The basal ganglia (BS) is vital for the voluntary control of bodily movements and is associated with the initiation and suppression of saccades in human systems(Hikosaka et al., 2000; Purves et al., 2014). The BS is a group of nuclei that are deep within the subcortical white matter of the frontal lobes (Figure 2)(Purves et al., 2014). The BS is comprised of multiple
unique functional groups: caudate, putamen, substantia nigra, and subthalamic nucleus (Hikosaka et al., 2000; Purves et al., 2014). The caudate and putamen are commonly referred to as the striatum or ‘input zone’ (Hikosaka et al., 2000; Purves et al., 2014). Both of these divisions are the destination for all neural input into the BS from the cerebral cortex, frontal eye field, and thalamus (Hikosaka et al., 2000; Purves et al., 2014; Srivastava et al., 2014). In addition, the subthalamic nucleus also receives input from the cerebral cortex (Hikosaka et al., 2000). These structures then lead to the substantia nigra, which is the key in the neural output flow of information (Srivastava et al., 2014). Even though the BS inputs are well-defined, each individual nuclei is connected with a neighboring nuclei, thus it is very difficult to anatomically track the neural input and outputs (Hikosaka et al., 2000).

One possible outcomes of information from the BS’s substantia nigra, is the SC. This structure has an inhibitory effect on the SC (Srivastava et al., 2014). The SC plays a major role in saccadic generation in the midbrain (Srivastava et al., 2014). The SC aids in eye fixations and accurate response of saccadic movements (Hikosaka & Wurtz, 1985; Marino et al., 2012; D. P. Munoz & Wurtz, 1992; Purves et al., 2014). The SC has been shown previously to respond prior and after saccadic eye movements (Srivastava et al., 2014). This has been supported by literature that has reported that upon removal of the SC, saccade generation is inhibited (Schiller, True, & Conway, 1980).

The flow of information from the BS and SC is received by the TH. The TH functions as the gatekeeper for the cerebral cortex (Figure 2) (Tanaka & Kunimatsu, 2011). This includes the frontal eye fields, supplementary eye fields, and dorsolateral prefrontal cortex. Petit, Orssaud, Tzourio, Salamon, Mazoyer, Berthoz (Petit et al., 1993) observed with the use of functional magnetic resonance imaging that during 2 minutes of self-paced voluntary saccades, the nuclei of
the thalamus were activated throughout the whole 2 minutes. Recent literature have shown that
the thalamocortical pathways control the various different types of eye movements; thus the
oculomotor region within the TH has access to all the subcortical areas the aid in the process of
saccades (Tanaka & Kunimatsu, 2011). One unique aspect of the TH is that this structures nuclei
activates before a saccades and exhibits directional preference (Kunimatsu & Tanaka, 2010;
Schlag & Schlag-Rey, 1984; Tanibuchi & Goldman-Rakic, 2003). This means that some of the
TH’s nuclei activate only when the eye will move in a certain direction. In addition, the TH
neurons may even notify the cortical neurons the exact time when visual processing can
commence for the next saccade (Tanaka & Kunimatsu, 2011). The TH is a key structure that
plays a major role in the monitoring of the eye movements and the initiation of voluntary
saccades (Tanaka & Kunimatsu, 2011).

As aforementioned, the TH is the gatekeeper for the cerebral cortices. The frontal
cerebral cortex, specifically the frontal eye fields, work in coordination with the SC to aid in the
accuracy of saccade generation (Figure 2) (Purves et al., 2014). The frontal eye field can activate
distinct neurons within the SC (Purves et al., 2014). This is important because the frontal eye
fields will give the SC information which way the eyes will move: toward the stimuli (saccade),
away from the target (antisaccade), or where the target was (memory guided saccade) (Pierrot-
Deseilligny et al., 2004). Therefore, it can be suggested that much of the voluntary eye
movements must be controlled with the frontal eye fields. However, reflexive eye movements
are initiated by the activation of the parietal eye fields (Figure 3) (Pierrot-Deseilligny et al.,
2004). However, the inhibition is regulated by the frontal eye field, specifically the dorsolateral
prefrontal cortex (Figure 3). The dorsolateral prefrontal cortex is involved in the prediction,
execution, inhibition, and spatial memory of saccadic eye movements (Pierrot-Deseilligny et al.,
2004; Purves et al., 2014). Literature on antisaccades and prosaccades have noted that antisaccades do not travel to the parietal eye fields, but rather the frontal eye fields and dorsolateral prefrontal cortex (Connolly et al., 2002; DeSouza et al., 2003). The dorsolateral prefrontal cortex acts directly on the superior colliculus to inhibit the reflexive nature of saccades (Pierrot-Deseilligny et al., 2004; Purves et al., 2014). This inhibition has an effect on spatial memory. This means that the amplitude during memory guided saccades, guessing where the stimuli appeared after the cessation of the stimuli, and antisaccadic tasks is controlled with the dorsolateral prefrontal cortex (Pierrot-Deseilligny et al., 2004; Purves et al., 2014). During a transcranial magnetic stimulation study, with the use of memory guided saccades, the observers noted that the dorsolateral prefrontal cortex was activated highly during the gap phase of the task, suggesting that this structure is utilized in spatial memory (Muri, Vermersch, Rivaud, Gaymard, & Pierrot-Deseilligny, 1996). This suggests that the frontal eye fields and the dorsolateral prefrontal cortex are involved in tasks that require a higher order of cognition and attention. However, even though the parietal eye fields are used in reflexive saccades, they too have an attentional component. The lateral intraparietal area controls saccadic eye movements and attentional functions (Pierrot-Deseilligny et al., 2004; Purves et al., 2014). This was first noted in monkeys, where low electrical currents would cause a higher activation in this area, whereas with high currents, the monkeys would perform a prosaccade (Cutrell & Marrocco, 2002). Therefore, the parietal eye fields do have some influence on the attentional nature of an individual. However, both the frontal eye fields and dorsolateral prefrontal cortex have the ability to override the parietal cortex, inhibiting the stimulation of the superior colliculus.

2.4 **Saccadic Eye Movements In Athletes**

Athletes in sports where the object is quickly changing require rapid eye movements,
saccades, so that they can meet the attentional demands of their specific sport (Piras et al., 2010). Efficient saccadic eye movements allow for high spatial visual accuracy. Efficiency of the saccades as previously mentioned is determined by prosaccade errors, magnitude of movement, and velocity. In sports, athletes must focus on the most appropriate visual cues in order to perform the correct task (Piras et al., 2010). Therefore, efficient saccades are required are imperative. It is of no surprise then that athletes who are experts in their sports have more accurate and precise saccadic movements (Jafarzadehpur et al., 2007; Lenoir et al., 2000; Piras et al., 2010; Rudin & Sharipan, 2016). Jafarzadehpur, Aazami, Bolouri B (Jafarzadehpur et al., 2007) reported that advanced volleyball athletes could accommodate the visual cues faster after performing a saccade than novice or beginner volleyball players. This ability allowed the advanced volleyball players to perform more accurate saccades in a minute, allowing for more information to be received than the novice or beginner volleyball athletes (Jafarzadehpur et al., 2007). Piras, Lobietti, Squatrito (Piras et al., 2010) reported that experienced volleyball athletes do not follow the ball’s trajectory, but rather the initial movement of the ball, then with a rapid saccade, go to the projected final position of the ball’s path. Furthermore, athletes that have to react quickly to fast moving stimuli have been noted that when prosaccade errors are committed by both athletic populations and nonathletic populations, the athletic population adapt to those errors more rapidly than non-athletes (Babu et al., 2005). Furthermore, athletes who produce small amounts of prosaccade errors also perform saccadic eye movements that are with minimal amplitude movements (Palidis et al., 2017). This shows that athletes that have superior dynamic visual acuity produce short, accurate saccades.

Athletes have been observed to have superior dynamic visual acuity and gaze stability than non-athletes (Ishigaki & Miyao, 1993; Lenoir et al., 2000; Palidis et al., 2017; Uchida et al.,
The apparent differences in velocity, prosaccade errors, and magnitude collectively allow for superior gaze stability and dynamic visual acuity (Ishigaki & Miyao, 1993; Lenoir et al., 2000; Palidis et al., 2017; Uchida et al., 2012). Palidis, Pearson, Wyder-Hodge, Fooken, Spering (Palidis et al., 2017) reported that when athletes and non-athletes were asked to recognize where the gap was in a Landolt C ring test as it moved across a screen at 300 degrees per second, athletes could recognize the smaller gaps in the C ring at higher velocities than the non-athletes. Furthermore, Lenoir, Crevits, Goethals, Wildenbeest, and Musch (Lenoir et al., 2000) reported that an antisaccadic task is more efficient at assessing athletic participation than a saccadic task in an athletic population versus a non-athletic populations. Therefore, combining tasks that require dynamic visual acuity and gaze stabilization, with antisaccadic tasks should be used to assess eye function in athletes, due to the test's ability to mimic the nature of the sport itself.

Figure 5. The red line represents the movement of an object from the left to the right. The blue line represents eye movement across a given time interval. A normal latency period is approximately 200 milliseconds (Purves et al., 2014).
Figure 6. Saccadic flow of information. A: Dorsolateral Prefrontal Cortex; B: Frontal Eye Field; C: Parietal Eye Field; D: Visual Cortex; E: Superior Colliculus; F: Brainstem saccade generators; G: Basal Ganglia; H: Cerebellum; I: Thalamus. Adapted from Srivastava et al. 2014

Figure 7. SEF, supplementary eye field; SFS, superior frontal sulcus; CEF, cingulate eye field; cs, central sulcus; DLPFC, dorsolateral prefrontal cortex; pcs, precentral sulcus; FEF, frontal eye field; IPS, intraparietal sulcus; IFS, inferior frontal sulcus; SMG, supra marginal gyrus; PCC, posterior cingulate cortex; SPL, superior parietal lobe; IPA, intraparietal areas; LS, lateral sulcus; AG, angular gyrus; PEF, posterior eye field; STS, superior temporal sulcus; POS, parieto-occipital sulcus; PHC, parahippocampal cortex; HF, hippocampal formation; SC, superior colliculus; RF, reticular formations (Pierrot-Deseilligny et al., 2004).