Investigation of vision strategies used in a dynamic visual acuity task

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Masters of Science
in
Vision Science

Waterloo, Ontario, Canada, 2017

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Purpose: Dynamic visual acuity (DVA), the ability to resolve fine details of a moving target, requires spatial resolution and accurate oculomotor control. Individuals who engage in activities in highly dynamic visual environments are thought to have superior dynamic visual acuity and utilize different gaze behaviours (fixations, smooth pursuits, and saccades). This study was designed to test the hypothesis that athletes and video game players (VGPs) have superior DVA to controls. Furthermore, the study was designed to investigate why DVA may be different between groups.

Methods: A pre-registered, cross-sectional study examined static visual acuity (SVA), DVA, smooth pursuit gains, and gaze behaviours (fixations, smooth pursuits, and saccades) in 46 emmetropic participants (15 athletes, 11 VGPs, and 20 controls). Athletes were members of varsity teams (or equivalent) who played dynamic sports (such as hockey, soccer, and baseball) for more than 1 year with a current participation of more than 6 hours per week. VGPs played action video games four times per week for a minimum of one hour per day. Controls did not play sports or video games. SVA (LogMAR) was tested with an Early Treatment Diabetic Retinopathy Study (ETDRS) chart. DVA (LogMAR; mov&, V&mp Vision Suite) was tested with Tumbling E optotypes that moved either horizontally (left to right) or randomly (Brownian motion) at 5°/s, 10°/s, 20°/s, or 30°/s. Task response time was measured by averaging the amount of time it took to respond to each letter per trial (i.e random 30°/s, horizontal 10°/s, etc.) which indicated the time it took for a motor response to occur. Smooth pursuit gains were tested with El-Mar eye tracker while participants

completed a step-ramp task with the same respective velocities as the DVA task. A one-way independent measures ANOVA was used to analyze smooth pursuits. Relative duration of gaze behaviours were measured with the Arrington eye tracker while participants performed the DVA task. A one-way independent measures ANOVA was used to test for group differences in SVA. A one-way ANOVA was used to test for group and speed differences in DVA. A repeated-measures two-way ANOVA was used to compare gaze behaviours of the first five and last five letters of 30°/s velocity.

Results: SVA was not significantly different between groups (p=0.595). Random motion DVA at 30°/s was significantly different between groups (p=0.039), specifically between athletes and controls (p=0.030). Thus, athletes were better than controls at random 30°/s. Horizontal motion DVA at 30°/s was also significantly between groups (p=0.031). Post-hoc analysis revealed a significant difference between athletes and VGPs (p=0.046). This suggests that athletes were better than VGPs at horizontal 30°/s. DVA task response time per letter was not significantly different between groups for horizontal motion at 30°/s (p=0.707) or random motion at 30°/s (p=0.723). Therefore, the motor response times were similar between groups at both motion types. Smooth pursuit gains were not significantly different between group at 30°/s (p=0.100) which indicates similar physiological eye movements. Eye movement gaze behaviours of horizontal motion at 30°/s were not significant between each groups for fixations (p=0.598), smooth pursuits (p=0.226), and saccades (p=0.523). Similarly, there was no significant difference in gaze behaviours for random motion at 30°/s between groups, for fixation (p=0.503), smooth pursuits (p=0.481), and saccades (p=0.507). Thus, gaze behaviours for horizontal and random motion were similar for all groups.

Conclusion: Athletes exhibited superior DVA for randomly moving targets compared to controls, and superior DVA for horizontally moving targets compared to VGPs. The task response times, gaze behaviours and smooth pursuit gains of each group were not significantly different. Therefore task response times, smooth pursuit gains and gaze behaviours cannot explain the superior DVA displayed by the athletes. Further research is required in order to determine why DVA in athletes is superior at 30°/s.

Acknowledgements

- I would like to thank my supervisor Dr. Kristine Dalton for her guidance and support in order for me to complete this work successfully. I have been inspired by the amount dedication and passion for her work.
- I would like to thank my committee members Dr. Benjamin Thompson for helping me with the statistics and Dr. Daphne McCulloch for helping me to shape the project to what it is now.
- I would like to thank Dr. Elizabeth Irving and Linda Lillakas for letting me use their equipment and teaching me the analysis tool.
- I would like to thank Amy Willms for writing the Arrington analysis software code.
- I would like to thank all the study participants for making this happen.
- I would like to thank the graduate coordinator Stephanie Forsyth for her amazing help in keeping graduate students on track.
- Thank you to the graduate students (GIVS), staff, and faculty members for all their support and making this a delightful environment.
- Finally, I would like to thank Dr. Martin J. Steinbach, mentor, colleague, friend, who inspired me into vision research. You will not be forgotten.

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Chapter 1. Introduction

Vision is one of the most dominant senses used by humans. When visual targets move, humans are able to track them with a variety of eye movements. Being able to use a variety of eye movements is often necessary and important in navigating through the environment. For the visual processing system to work optimally, the input or information obtained through the eyes must be clear. Perceiving motion accurately and optimally is critical to humans' daily activities such as driving a car, walking down the street, or catching a ball. Once perceived, visual information must be interpreted in a meaningful way before any subsequent motor action can take place. This process, known as visual-motor integration is a complex process that needs to be better understood because it is a key component in interpreting how information from the environment is processed. One way to study visual-motor integration is to break the process down into smaller steps, such as the visual step or cognitive step. The purpose of this study is to examine the first step of this process, the visual step, since the integration process cannot function normally without first obtaining the proper input from the eyes.

1.1 Static Visual Acuity (SVA)

The first aspect of visual information processing is sensory input.[1] The ability to resolve precise details can be an important factor in perceptual processing if the details contain visual information relevant to the task. Visual acuity can include detection, resolution or the recognition of a target. One of the most basic visual functions is static visual acuity (SVA).[2]

SVA is used to describe the sharpness of vision, and the smallest detail that can be identified. SVA is typically measured using stationary, high contrast targets (i.e. black letters on a white background). In the clinical setting, acuity is measured with letter charts to assess recognition and discrimination abilities.

Laby et al. (1996) studied the visual function of professional baseball players from the Los Angeles Dodgers between 1992 to 1995, and found that the vast majority of professional baseball players had visual acuities better than -0.12 LogMAR, with a large number better than -0.20 LogMAR. The study used a computerized monitor with Snellen letter optotypes to test static visual acuity of each eye separately at 20 feet. The static visual acuity of athletes were between -0.35 LogMAR to 0.70 LogMAR with an average of -0.13 LogMAR.[3] No specific control data were given in this study, however the static visual acuity of a non-athlete 18-24 year old group has been previously shown to be approximately -0.13 LogMAR.[4] Laby et al. (1996) conclude that the visual acuity of professional baseball players was better than that of non-athletes in the general population, however based on the control data presented above, the visual acuities of high-level athletes may in fact be very similar to the normal population.

Similarly, in another well-trained population, Green & Bavelier (2007) demonstrated that video game players (VGPs) have better visual acuity thresholds than non-video game players (non-VGPs). While they did not use a traditional static visual acuity task to measure visual acuity thresholds, Green & Bavelier (2007) used a spatial resolution task that measured the crowding of targets by determining whether participants were able to discriminate between a normal T shape or an inverted T shape as the distance between the target object increased or decreased while there were distractor T shapes above and below the target.[5] This test was completed centrally and over a broad range of eccentricities. Compared with non-VGPs, action VGPs had the ability to complete the task with smaller target-distractor distances, thus Green & Bavelier concluded that the spatial resolution required for visual processing was enhanced in the VGPs across all eccentricities. This was also observed in non-VGPs who were trained on action video games, which lead the authors to conclude that video-game play could help improve spatial resolution.[5]

Two additional studies have not found a difference in SVA between athletes and non-athletes.[6,7] Christenson and Winkelstein (1988) used numerous clinical optometric tests to measure the visual abilities required in sports of athletes and non-athletes. They found that athletes had significantly better vergence, saccades, visual reaction time, and peripheral awareness.[6] However, no significant differences in SVA between athletes and non-athletes were found using a Snellen chart. In a more recent study, Hoshina et al., (2013) examined the static, kinetic, and dynamic visual acuity of Japanese professional baseball players. They found that SVA was not statistically significantly different between professional baseball players and a normal group of individuals. A kinetic visual acuity meter AS-4 was used to measure SVA.[7]

1.2 Dynamic Visual Acuity (DVA)

Stationary targets have been used extensively to test SVA from clinical to research settings, however, visual acuity may also be measured when following moving targets with the eyes.[8] Measuring visual acuity with moving targets is important because traditional SVA measurements may not be a good representation of the visual demands of our daily environment or activities. The term dynamic visual acuity (DVA) was first introduced by Ludvigh and Miller (1953), and refers to the ability of the visual system to resolve the fine details of a target when there is motion between the target and the observer whether the target or the observer is moving.[9] DVA studies have used many parameters for testing, such as type of letter, target speed, colour, or direction. Traditionally, most DVA tasks have used Landolt C rings,[10–14] followed by Snellen optotype E targets, also known as tumbling Es.[15,16] The Landolt C consists of a ring that has a gap in it. The gap can be at various positions, typically left, right, up, or down, and the individual's task is to decide which orientation the gap is located. The tumbling E task requires individuals to decide what direction the legs of the E are pointing in (i.e. up, down, left or right).

In their initial studies, Ludvigh and Miller (1953) determined that high movement velocities of a target across the retina at high velocities could produce imperfect pursuit eye movements and a loss in acuity compared with static images.[9] Later, Ludvigh and Miller (1958) found that dynamic visual acuity varied significantly between individuals with similar static visual acuities. This finding was supported by Long & Riggs (1991), who demonstrated that dynamic and static visual acuities vary markedly among individuals and that static visual acuity was not a good predictor of DVA.[13]

While static visual acuity may not be a good indication of DVA performance, DVA performance may be correlated with task performance instead.[17] This lead the Committee on Vision of the National Research Council (1985) to state that the visual measurements of DVA have considerable promise as a new technique for assessing a component of visual performance which was traditionally overlooked by other tests.[18] The increasing interest in studying DVA is that in many everyday activities, such as driving, flying, and ball playing, discrimination of moving objects (or of stationary objects while one is moving) plays a key role.

Being able to perceive motion is often crucial for athletic performance. Athletes need to receive, process and integrate information accurately before quickly reacting to the environment. For this reason, high-level baseball players, like many other object tracking sports have been suggested to be suitable subjects for studying the relationships between visual functions, such as dynamic visual acuity and performance.[19]

Video-game players, specifically, action VGPs who play first-person-shooter games such as, Counter-strike, Unreal Tournament, and Call of Duty, are also an excellent model for studying visual function and performance.[5] VGPs are consistently interacting with a dynamic environment getting feedback from the displays and being able to perform precise eye movements and motor responses.[20] Furthermore, other critical elements of the visual system (such as visual acuity, attention, and visual search) may be trained through video-game experience and practice,[20] however DVA has not yet been studied in VGPs.

Previous studies in athletes have indicated that better DVA performance was associated with sports that require a ball or target for object tracking such as volleyball and basketball,[21] baseball,[12] tennis and badminton,[14] motorsports,[22] and catching tasks.[23] Furthermore, studies in baseball, tennis, and badminton have demonstrated that athletes have superior DVA to non-athletes (Table 1).[11,12,14,24–26] Many of these studies have suggested that the superior DVA performances of athletes were due to their superior ability in utilizing saccades effectively in order to track fast moving objects[11,24,25] although the DVA mechanism is not yet well understood. It is possible that athletes may have an innate superior ability to complete DVA tasks, or that this ability has developed through repeated training.[12] However, further research is required as to whether or not the differences may indicate a learned behaviour. Despite significant differences in methods for measuring DVA, all but three of these studies[13,22,27] found DVA to be better in athletes.

Table 1.1 Summary of all DVA studies conducted in athletes to date

Study	**Sport**	**DVA Method (target type; head fixed or free)**	**Stimulus Characteristics (Target gap size)**	**Results**	**Significant**
Morris & Kreighbaum (1977)[21]	Basketball, Volleyball	Checkerboard pattern Free head	Horizontal motion (left to right across a 180 deg cylindrical screen): 10 revolutions per minute (rpm) – 1.31 vs 1.16 min arc. 20 rpm – 1.62 vs 1.41 min arc	No significance for 10 and 20 rpm target for high and low percentage shooters	ns
Rouse et al., (1988)[12]	Baseball	Landolt C Free head	Horizontal motion: 1.26 min of arc	Angular velocity of target: athlete 82.35°/s, controls 69.90°/s	$p<0.05$
Long & Riggs (1991)[13]	Baseball, Hockey, Tennis, Soccer	Landolt C Free head	Horizontal motion: 60°/s to 150°/s letter size threshold	No significance between DVA of athletes and controls	ns
Ishigaki & Miyao (1993)[14]	Baseball, Tennis, Badminton	Landolt C Fixed head	Horizontal motion: 8 and 10 min of arc	Angular velocity of Landolt C target: athlete 254°/s, controls 245.2°/s	$p<0.05$
Schneiders et al., (2010)[22]	Motorsport	Tumbling E. Fixed head	Head moved in horizontal metronome of 150°/s Letter size threshold	DVA of athletes (1.41 min of arc) and controls (1.48 min of arc)	ns
Uchida et al., (2012)[24]	Baseball	Landolt C Fixed head	Horizontal motion: 8 and 42 min of arc	Angular velocity of Landolt C target: athlete 404°/s, controls 315°/s	$p<0.05$
Palidis et al., (2017)[26]	Baseball	Landolt C Fixed head	Horizontal motion: 24 min of arc	Minimum position error and frequency of reverse saccades (50 and 70°/s)	$p<0.05$

1.2.1 Summary – Dynamic Visual Acuity

Differences in DVA between athletes and non-athletes may suggest underlying differences in perceptual ability. DVA may indicate a learned behaviour (i.e. athletes develop DVA as a skill in response to training). Professional baseball pitchers were able to throw a fastball at speeds of 150km/h and the physiological capabilities of the eyes should not be able to track the fastballs.[24] Even the more experienced baseball batters cannot keep their eyes on the ball at those speeds, but somehow professional batters were consistently able to strike the ball.[28,29] There is a greater need to understand what visual mechanisms allow professionals to have a superior DVA.

1.3 Eye Movements

Eye movements play a critical role in the visual system. The functions of eye movements are to locate visual targets and aid to stabilize the image of the target on the retina. Eye movements can be grouped into three main categories: fixations, saccades, and smooth pursuits.

1.3.1 Fixations

Fixations are eye movements that helps stabilize the eye on a selected stationary target,[30] which allows the images to fall on the fovea in order to have highest visual acuity possible.[31–33] The mechanism controlling visual fixations has been studied intensively within the last century. Interestingly, fixations are not stationary eye movements but very slow drifts in eye position during attention to stationary targets.[34] Yarbus (1967) suggested that fixations may be a form of smooth pursuits but suppression of the smooth pursuit system may help to reduce slow drifts from the eyes,[31] whereas Luebke & Robinson (1988) suggested it might be due to an independent visual fixation system.[35] More recently, Leigh & Zee (1999) proposed that fixations were used to correct for any error which could influence the image quality due to slow drifts of the eyes.[36] Irrespective of the underlying mechanisms of fixational eye movement, fixations play a crucial role in all types of visual acuity.[37]

1.3.2 Smooth Pursuits

Smooth pursuits are used for tracking and following discrete moving objects in our environment,[38,39] and ensure the highest possible visual acuity of the object.[40] Smooth pursuit eye movements are slower eye movements compared to saccades because smooth pursuits help keep the moving target steady during eye tracking and correct for any velocity error between the eyes and the target.[34,41]

Smooth pursuits have been measured by dividing smooth eye velocity by target stimulus velocity in order to obtain a value for pursuit gain.[42] During ideal pursuit tracking, the smooth pursuit gain is close to 1.0, which indicates that the eye do not lag behind the target. Inaccurate smooth pursuit movements have been known to cause a loss of ability to maintain a stationary image on the retina and results in decreased visual acuity.[12]

1.3.3 Saccades

Saccades are fast eye movements used to scan the environment and locate objects of interest for a broad range of purposes, ranging from relatively simple information gathering to the more complex identification, discrimination, and perception of objects.[39,43,44]

Saccadic latencies were used as one potential way to assess saccadic eye movements and represent the time from the beginning of a non-predictable target movement to the start of the saccade.[39] Typically, saccadic latencies were measured with an eye tracker to determine the distance and target travel speed between the onset of the stimulus to the end position of the stimulus. Saccades can reach up to 1000°/s and typically their durations are very short (30-80 ms).[41]

Another way to assess saccadic eye movements was to quantify the relationship between saccades of various amplitudes and their respective peak velocities.[39] The amplitude is the size of the saccade and it determines the saccade accuracy or gain. The gain is the ratio, typically less than 1, from the saccade amplitude of the observer divided by the desired saccade amplitude. The velocity of a saccadic eye movement increases as a function of its amplitude, and the peak velocity of a saccade is the highest velocity reached during the eye movement. The relationship between saccade amplitude and velocity has been called the main sequence and can be plotted as saccade amplitude vs. peak velocity.[45] Saccade amplitude is determined by the peak velocity, which makes it is possible for shorter duration saccades to have a higher peak velocity than longer duration saccades

1.3.4 DVA and Eye Movements

Although DVA was thought to be related to ocular pursuits of moving targets,[10,11] a recent study by Kohmura et al. (2008) investigating the relationship between DVA and eye movements using electrooculography found that DVA had a strong relationship with saccadic latency rather than the peak velocity of saccadic eye movements.[2] Kohmura et al. (2008) used Landolt C rings at a speed of 300°/s and measured eye movement velocities up to 600°/s, and concluded that the most important factor for target discrimination was the latency of saccadic eye movements.[2]

Uchida et al. (2012), found that Japanese college baseball players had superior DVA compared to the general population when athletes were in the free eye movement condition but not for the fixation condition. In this particular study, a target randomly appeared on the right or left side of the monitor. Participants were asked to focus their eye on the central fixation of the screen and track the target either left or right. The results suggest that athletes were better at perceiving a blurred image of the moving targets, and indicated that the superior DVA of athletes was mainly due to their improved ability to track moving targets with their eyes.[24]

1.3.5 Athletes Eye Movements

In ball sports such as baseball,[29] basketball,[46] cricket,[43] and squash,[47] athletes rely on a combination of saccadic and smooth pursuit eye movements to track a moving ball. Bahill and LaRitz (1984) created a device of a ball attached to a string in order to mimic a baseball pitch. The ball speed was between 60 and 100 mph. The research was to identify the saccadic, vestibule-ocular, vergence, and smooth pursuit eye movements used during object tracking. Baseball batters head and eye movements while hitting a simulated fastball were examined. Horizontal eye movements were recorded with a photoelectric system using infrared emitters and photodetectors while head movements were monitored with a video camera from the ceiling.[29] Subjects consisted of graduate students, the Carnegie-Mellon University baseball team, and a professional baseball player. Though no specific sample size was given, all had 20/20 uncorrected visual acuities. The maximum smooth-pursuit velocity for both eyes of college level athletes was 50°/s. At the same moment, the maximum head velocity was 20°/s. Professional baseball player, Brian Harper, was recorded to have a smooth pursuit velocity of 120°/s and head velocity of 30°/s.[29] In addition to having faster smooth-pursuit eye movements and better head-eye coordination while tracking the ball compared to the other subjects, Bahill and LaRitz (1984) found that unlike the other subjects, the major league baseball player made anticipatory saccades when the velocity of the ball travelling towards the bat exceeded the upper limit of smooth-pursuit eye movements. These anticipatory saccades appear to have little value in directing the bat, because the swing is committed as much as 0.2s before ball contact but they appear to be useful in helping predict the ball's location at contact.[29] If professional baseball players can be taught to use anticipatory saccades in order to see the ball as it hits a bat, then it may possible that this learning can be generalizable to other populations and other tasks as well.

Lenoir et al. (2000) assessed how saccadic eye movements may potentially enhance sports performance.[48] More specifically, they studied prosaccadic and antisaccadic eye movements, as the hypothesized these gaze mechanisms gave skilled athletes their advantage in their sport.[48] Prosaccades have been known to be important in gaze strategies. The ball's velocity often exceeds the smooth pursuit eye movement capabilities thus shifting the eyes slightly ahead of the balls location allows for crucial information. On the other hand, antisaccades help to suppress the reflexive prosaccades, in order to shift gaze in the opposite direction of the stimulus. During this study, Lenoir et al. (2000) measured eye movements in athletes from various ball sports (basketball, soccer, volleyball, handball and tennis). Participants were asked to fixate at the center of the screen followed by a square appearing to the left or right from the center of the screen. Depending on the trial block, participants were asked to either follow the target (prosaccade) or look in the opposite location of the target (antisaccade). Their findings suggests that prosaccadic eye movements use a reflexive response mechanism while antisaccadic eye movements require voluntary cognitive suppression.[48] They conclude that antisaccades play a more important role than prosaccades to gaze behaviour and visual performance.

Contrary to Lenoir et al., (2000), Babu et al., (2005) found that racquet sport athletes responded to positive positional errors at a faster rate than non-athletes. Babu and colleagues (2005) looked at dynamic saccadic adaptation between a population of racquet sport athletes and non-athletes in order to determine what saccadic adaptation characteristics were most significant.[33] Their stimuli were also on a horizontal plane with a fixation at the center. The targets moved either right or left, and positional errors were assessed to determine how well participants could continue to track stimuli that moved in either the same, or the opposite direction of the target's current motion. A positive positional error meant the target moved one direction and then made a quick step of 3° in the same direction while a negative positional error had the target step in the opposite direction by 3°. Positive positional error measured how well participants could continue to track stimuli that were displaced in the same direction as the target's current motion, whereas negative positional error measured how well participants could track stimuli that were displaced in the opposite direction of the target's current motion. The only difference between groups found was that racquet sport athletes were able to interpret positive positional errors at a faster rate. Athlete's responses to positive positional errors suggest that a strategic learned component may influence gaze behaviours.[33] Whether saccadic eye movements are a learned behaviour due to the environment is still in debate.

1.3.6 Video Game Players Eye Movements

Action video games also rely significantly on the accuracy of saccadic eye movements.[25] Typical games that require fast eye movements and reaction times are First-Person Shooter (FPS) games. FPS games are played from the character's perspective and often involve many movement controls (e.g. shooting, jumping, and crouching). A recent study by Mack and Ilg (2014) looked at the possible effects of playing video games by measuring the saccades of VGPs and non-VGPs in two oculomotor tasks, the double-step task and an anti-saccade task.[49] The objective of the oculomotor tasks was to measure the reaction time and accuracy of the participant's saccadic eye movements, and the results demonstrated that VGPs have a significantly shorter saccadic reaction time compared to non-NVGPs.

1.4 Vision Strategy

A vision search strategy is the combination of eye movements (fixations, saccades, and smooth pursuits) used in order to extract information from a scene. The term gaze behaviour is used to describe eye movements when the subject's head and eye system move naturally compared to traditional eye movement recordings where the head position is fixed in place.[50] Athletes and VGPs have spent tremendous hours training in their environment and have been found to exhibit better vision strategies than the general population in their specific environments.[43,50–54] It may be possible that these vision strategy differences may enhance performance on other visual function tasks (such as dynamic visual acuity).

1.4.1 Athletes Vision Strategy

Previous research on vision strategy in athletes had found that experts and near experts used different gaze behaviors in their sports.[43,50–54] In particular, the differences in gaze behaviour were seen with eye movement (fixation, smooth pursuit duration, saccade) durations, and locations of gaze at critical moments.[50–52] Novices, who were much less skilled, had difficulty determining where to locate information about the task they are doing, and the distribution of fixations used by novices to collect information was less efficient than the experts.[52] Investigations during play have revealed that the vision strategies used to extract visual information can differentiate elite and novice performance (i.e. skilled or unskilled) as well as successful or unsuccessful outcomes.[43,50–54]

1.4.1.1 *Information Acquisition by Athletes*

Ripoll and colleagues (1986) analyzed the jump shot of professional basketball athletes and a control group. The aim of the study was to investigate the role of eye and head position during the jump shot relative to the target location (basketball net) and level of expertise of basketball players. Participant's eye and head movements were monitored using video-tape samples and a NAC eye movement recorder while participants completed a variety of shots. Ten participants (average age 22.5 years) completed this study. Five participants were national level basketball players and the other five participants had little to no experience in basketball. Ripoll and colleagues demonstrated that being able to locate the target was a key factor for gaze stability, and found that the stability of head and eye movements significantly contributed to the success of a jump shot.[46] Finally, Ripoll and colleagues found that skilled players were able to 1) orient their gaze toward the basket sooner, and 2) maintain their gaze on the target longer than less skilled individuals.[46]

Ripoll and Fleurance (1988) examined whether or not expert table tennis players followed their coaches instruction to "keep one's eye on the ball" during play,[54] by examining the gaze behaviours of five international table tennis players while they performed basic strokes. A video-oculographic eye recorder apparatus (Nac Eye Mark Recorder IV) was used to measure the vision strategy during the time between ball contact with the opponent's bat and ball contact with the subject's bat. The parameters analyzed were 1) total temporal duration and mean temporal duration (ms) of visual pursuit of the ball and 2) total temporal duration and mean temporal duration (ms) of eye-head stability during the strike. Ripoll and Fleurance (1988) found that the experts did not track the ball for the full duration, but preferred to track the ball at the beginning of its trajectory, and concluded that this behavior was associated with their high levels of success.[54]

Similar to Ripoll and Fleurance's work in table tennis players, Land and McLeod (2000) conducted a study of gaze behaviours in cricket players. Land and McLeod (2000) tried to determine what information was available to professional cricket batsmen (n=3) as the ball approached them by monitoring their eye movements, specifically their predictive saccades. A 50 Hz eye tracker with a single head-mounted video camera recorded the scene ahead and an image of the left eye. Land and McLeod found that batsmen use fixations as cues to get early trajectory information during the first 100-150 ms of the ball's flight and then make a predictive saccade to the location of where the ball may land.[43] The fixation began at the pitcher's point of release, followed by an anticipatory saccade ahead of where the ball may land and then an anticipatory saccade ahead of where the ball would land. The vestibulo-ocular reflex response of athletes likely helped keep their gaze positions (eye and head) in a relatively stable position.[43] No control participants were used during this study, and the three participants ranged from professional to amateurs, however this was a significant study because eye movements of batters were recorded in their natural environment.

Williams et al., (2002) expanded on the work of Ripoll and Fleurance, and demonstrated that skilled tennis players had superior visual search behaviours than less experienced players. The study examined anticipation skill of eight skilled and eight less skilled male tennis players using a back-projected image in order to mimic an opponent in front of each participant. Participants were on two pressure plates and four extra pressure plates were positioned surrounding the participant (one plate left, right, up, and behind). Eye movements were recorded with an ASL 5000SU eye tracker that allowed for body movements within 1.22 m. Participants were asked to perform simulated tennis strokes based on the projected player's groundstrokes. Skilled tennis players used more fixations of the head-shoulder and hip-trunk regions than less skilled tennis players.[55] The gaze behaviour between racket and ball of less skilled players were more variable than skilled players. The findings conclude that skilled players were able to use visual search behaviours more effectively than less skilled players.

Finally, McKinney and colleagues (2008) tracked the eye movements of four skilled squash players and no controls using a RIT lightweight wearable eye tracker. McKinney and colleagues found that before the players hit the ball, they would make an anticipatory saccade to the front wall which would allow their eyes to arrive 152±28 ms before contacting the ball.[47] To any other sides of the wall, an anticipatory saccade would be made 220 ms ahead of its location. The study showed that skilled squash players use a combination of highly accurate anticipatory saccade as well as gaze stability to collect visual information when both player and object moved rapidly.

1.4.1.2 Information Interpretation by Athletes

Vickers (1992) had investigated the vision strategy of golfers using eye tracking equipment. The gaze of low handicap (n=5) and high handicap (n=7) participants were tested. A low handicap in golf means a higher skill level. The mean ages were 42 years for low handicap and 45 years for high handicap. Participants wore an ASL 3001H Eye View monitor, which was a monocular corneal reflection eye tracking system that measured participant's gaze during putts. Low handicapped golfers were able to use longer fixations on the ball and target compared to high handicap golfers.

Vickers (1996) identified a quiet eye period, which was the final fixation between the preparation phase and the pre-shot phase of motor related tasks in sports including golf, basketball, volleyball, and ice hockey.[50–52,56] During the quiet eye period, athletes maintain a fixation or stable gaze on the target, and the findings of Vickers' numerous studies indicate a longer final fixation and quiet eye from the expert group compared to novices.[50–52,56] Based on these findings, the quiet eye has been suggested to link the information collection and processing strategies from the sensory input to the motor output which would allow for the completion of a specific task.

1.4.2 Video Game Players Vision Strategy

Castel et al., (2005) examined if long term video game experience could influence visual search and the inhibition of return. The inhibition of return means that people are sometimes slower to respond to a stimulus when it is presented at a previously stimulated location compared to a new location, and is a measure of visual attention.[57] Being able to quickly allocate attention to a new location is critical to video game players and real life situations like driving. Visual search was quantified with a fixation at the center of the screen and distractors surrounding it. Easy visual searches would consist of a letter D among 8 letter K's while a hard search would consist of a letter D among 8 different letters. For both easy and hard visual searches, expert VGPs had significantly faster reaction times than non-VGPs, but both groups were equally good at inhibiting the return of attention to previously cued locations.[58] Castel et al.'s findings suggest VGPs and non-VGPs use similar visual attention mechanisms. However, since the reaction times of expert VGPs was faster, Castel et al. concluded that the expert VGPs stimulus-response mapping was faster than that of the non-VGPs.

Similar to Castel et al. (2005), Bialystok (2006) found that the reaction times of VGPs were shorter than those of non-VGPs when using the Simon task. The Simon task typically has participants exhibit a faster stimulus response to the target when it is moving in the same direction as the response regardless of how relevant the information may be to the actual task.[59] The study found that expert VGPs were able to respond faster than non-VGPs on the Simon task. The reaction time differences on the Simon task indicate that experience may influence performance and that the expert VGPs may have an enhanced ability to make faster and more accurate motor responses to visual stimuli than less experienced VGPs.[20]

Hubert-Wallander et al., (2011) also found that expert VGPs had shorter reaction times, and were capable of quicker visual search than non-VGPs. Hubert-Wallander et al., (2011) used two hard visual search tasks in their study. One task measuring reaction time and the other task measuring accuracy in order to determine whether visual search was influenced by video game play. All of the visual search tasks required participants to find a random target letter among a number of distractor letters.[58] The first visual search task was similar to Castel et al. (2005). The second task used a modified Posner cuing paradigm. A Posner cuing paradigm typically had a cue flash in one location to prime attention before the onset of the target. One of four locations would be cued, and an invalid cue may make the task more difficult. A reaction time difference was expected between the valid and invalid cued targets in VGPs compared to non-VGPs, and it was hypothesized that an invalid cue should not affect VGPs as much. Similar to Castel et al., (2005), Hubert-Wallander et al. found that expert VGPs were faster than non-VGPs on the visual search task. Also, the Posner cuing paradigm showed that expert VGPs were better able to disengage their attention faster than non-VGPs.[58]

Most recently, Green et al., (2010) determined that VGPs used their sensory information more efficiently to help the decision making process than non-VGPs. A drift diffusion model was used to collect responses on a visual motion task.[60] The model required subjects to view a random dot display. The random dots were set at different levels, which indicated dot movement coherency, which was the difficulty setting of the task. The different levels of movement coherency were 50%, 25%, and 0% and the dot array moved either left or right.

The length of time participants took to respond (their reaction time) was considered to be an indication of the amount of time needed to integrate the visual sensory information. Using this paradigm, Green et al. found that VGPs were able to integrate visual sensory information at a faster rate than non-VGPs, which allowed for more rapid inferences to be made. The difference in response time between VGPs and non-VGPs was most pronounced at lower coherence levels.[60]

1.4.3 Summary – Vision Strategy

Highly efficient visual search strategies appear to be a critical component of high level performance in athletes and VGPs. Given the amount of hours athletes and video gamers spend training in their dynamic environments, perhaps they have learned to use a vision strategy that is more efficient than the normal population, particularly as there appears to be a link between eye movements, visual perception and motor control in elite performers.[13,43,50,52,56,58,59] Further studies are needed in order to determine whether the difference in visual search strategies are a result of the time these experts spend training, or if they are related to underlying differences in physiology between the experts and controls.

1.5 Purpose

In the past, DVA studies have been conducted using a variety of different methods, motion trajectories and optotypes as there has been no standardized or validated DVA task developed. While the previous studies have attempted to quantify and explain the differences in DVA performance between experts and novices, it has been difficult to draw conclusions from this research because the methods used were so different. Therefore, the primary purpose of this thesis was to examine the dynamic visual acuity of athletes, VGPs, and non-athletes, non-VGPs with a novel DVA task that has been standardized and validated. The secondary purpose of the thesis was to begin to determine why differences in DVA exist. Are differences in DVA caused by physiological differences of the eye or are there factors related to their eye movements? To examine the other factors, exploratory analyses of the eye movements (fixations, smooth pursuits, and saccades) and gaze behaviours were carried out.

The DVA task chosen for the current study was a Tumbling E task (moV&, V&MP Vision Suite), which is similar to the Landolt C task. The moV& software was chosen, because this software platform was recently validated and uses standardized measures of visual acuity thresholds (LogMAR).[16] Two different motion types, horizontal (predictable) and random walk (unpredictable) were used to try and gain a better understanding of whether or not differences in processing dynamic visual information exist. Additionally, participants were required to complete a second, standard eye movement task known as a step-ramp task to measure smooth pursuits, in order to facilitate the comparison of physiological eye movements between groups. Finally, participants' gaze behaviours were recorded while they completed the DVA tasks so that vision strategies could be compared between groups. It is important to understand how dynamic visual information is collected and processed because this understanding will begin to help inform how motion processing and visual-motor integration occur in individual's daily lives. Subsequently, this may potentially contribute to the development of methods for enhancing motion perception in individuals who struggle in dynamic environments.

1.6 Hypotheses

1. Athletes and VGPs performance on the DVA task are hypothesized to be better than non-athletes at a velocity of 30°/s.
2. Athletes and VGPs smooth pursuit gains are hypothesized to be similar to controls at a velocity of 30°/s.
3. The vision strategies that athletes and VGPs use include significantly higher proportion of fixations and smooth pursuits while performing the DVA task than the vision strategies used by controls.

A velocity of 30°/s was chosen for the primary research outcome, because previous research used very high velocities and 30°/s was the closest representation of what had been done before.

Chapter 2. Methods

Prior to data collection, this study was pre-registered with the Open Science Framework. Pre-registering the study was a way to help outline the details of the study and set up research questions before carrying out the study to limit the amount of bias. Details of the pre-registration can be found at http://osf.io and have been included in this thesis as Appendix A. Ethics approval for the study was granted by the Office of Research Ethics (ORE #21515) at the University of Waterloo.

2.1 Sample Size Calculation

Please refer to Appendix A (9.1 Sample Size Rationale).

2.2 Participants

Three groups of participants were recruited for this study: dynamic sport athletes, action video game players and controls (non-athletes, non-VGPs). Based on the sample size calculation, the decision was made to recruit 20 participants for each group. Participants were recruited from the University of Waterloo Games Institute, the University of Waterloo Warrior Athletics program, and the University of Waterloo Optometry Program and the Kitchener-Waterloo community.

2.2.1 Inclusion Criteria

All participants were healthy adults between 18-26 years of age with monocular distance static acuities of 0.0 LogMAR or better in each eye. Participants were eligible to participate in the study if they were emmetropic, if they fit into one of the three participant groups defined below, and they gave consent to participate.

2.2.1.1 Athletes

For the purposes of this study, athletes who played dynamic sports (e.g. hockey, soccer, basketball) at a varsity level (or equivalent) were recruited. Athletes had to have played their sport for a minimum of 5 years, had to be a member of a varsity team (or equivalent) for more than 1 year, and had to currently participate in their sport for more than 6 hours per week.[33]

2.2.1.2 Video Game Players

Video game players had to play action video games (e.g. Call of Duty, Counterstrike, League of Legends, Overwatch). Video game players had to play an action video game at least 4 times a week for a minimum of 1 hour per day, and had have done so for at least the previous 6 months.[58]

2.2.1.3 Controls

Control participants were non-athletes and non-VGPs. This meant that they had never played a sport at a varsity level (or equivalent), they played less than 3 hours of recreational sports per week,[33] and they played action video games less than 1 hour per month.[58]

2.2.2 Exclusion Criteria

Exclusion criteria for all participants, regardless of group were as follows:

1) Monocular static visual acuity worse than 0.0 LogMAR in either eye

2) A difference of 0.1 LogMAR or greater in static visual acuity between eyes
3) Spherical refractive error less than -0.50D or greater than +0.50D and / or cylindrical refractive error greater than 0.50D. (Note: In recognition of the fact that auto refractors can create an artificial stimulus to accommodation, participants with measured spherical refractive errors of -1.50D or less who had a distance static visual acuity of 0.0 LogMAR or better were still considered eligible to participate)
4) Contact lens or spectacle wear
5) Self-reported history of an ocular health anomaly that had the potential to impact visual acuity in either eye
6) Presence of an obvious binocular vision defect (e.g. nystagmus, strabismus, amblyopia).

2.2.3 Eligibility

Participant's eligibility was confirmed by asking them to complete a personal history questionnaire. Additionally, their refractive error was assessed using a Topcon KR-1 Auto Kerato-Refractometer (Topcon Medical Systems Inc., Oakland, NJ, USA), and participant's monocular static visual acuities were measured using the Early Treatment Diabetic Retinopathy Study (ETDRS) charts.

2.3 Protocol

The participants were asked to attend one study visit that was approximately 1.5 hours long and were reimbursed for their time. All of the measurements listed below were collected during this single study visit.

2.3.1 Static Visual Acuity

Static visual acuity was measured with the Early Treatment Diabetic Retinopathy Study (ETDRS) charts (Precision Vision, Woodstock, IL, USA). The ETDRS chart is a LogMAR chart that has 5 letters on every line. Every line change is equal to 0.1 LogMAR units thus each letter scored was 0.02 LogMAR units. The ETDRS static visual acuity was measured binocularly at a distance of 4 metres with three different ETDRS charts respectively (monocular right, monocular left, and binocular). For participants to continue in the study, static visual acuity had to be better than 0.0 LogMAR in each eye, and the difference in static visual acuity between the right and left eyes had to be <0.1 LogMAR units.

2.3.2 Dynamic Visual Acuity

The moV& (V&mp Vision Suite, Waterloo, Canada) dynamic visual acuity test was used for all DVA testing. The target was always a black, tumbling E on a white background, which was presented in one of four orientations with the prongs facing right, left, up, or down. Targets were displayed on a large television monitor (visual angle: horizontal 15.5°, vertical 9.1°) and the display was always set at a contrast value of at least 90%. Participants sat 4 metres from the monitor and DVA testing began 0.5 LogMAR above each participant's binocular static visual acuity threshold.

Two motion types were examined in this study: random motion, which was unpredictable and horizontal motion, which followed a predictable path. For the random motion, the target motion was Brownian so that the target position could not be anticipated at any point in time.

The target was shown for a maximum 20 seconds or until participants respond to the orientation of the letter E by button presses on a control pad. The arrow keys (up, down, left, and right) on the control pad corresponded to the perceived orientation. For horizontal motion, the target moved from the left side of the monitor to the right side in only one pass. The target only moved once across the screen and did not loop. The maximum time the target remained on the screen was 0.52s for 30°/s to 3.10s for 5°/s. Horizontal motion was necessary for comparing the existing literature which has used Landolt C targets in a horizontal motion.[2,11–14] For random motion, the letter disappeared when the participant responded and for both motion types, the next trial started immediately after the participant responded.

The dynamic acuity measurement threshold was determined similar to SVA. Participants who got 3/5 letters correct for a LogMAR line would move 0.1 LogMAR down to the next line until they could not get 3/5 letters correct. Participants' binocular dynamic visual acuity was measured at four different target speeds for each motion type (8 DVA tests in total). The four speeds were: 0.35, 0.71, 1.46, 2.31 m/s which correspond to 5, 10, 20, and 30°/s respectively. Participants were required to wear the Arrington Research Viewpoint Binocular eye tracker while completing all of the DVA measurements (Figure 2.1).

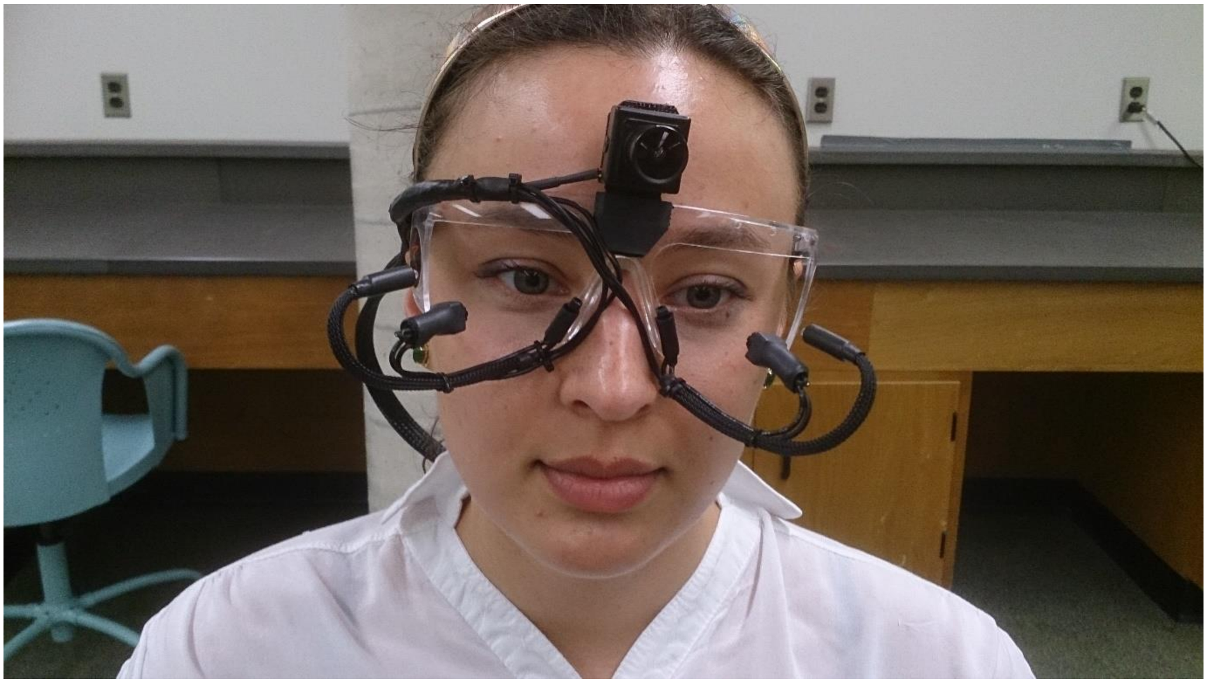


Figure 2.1. Arrington Research Viewpoint Binocular eye tracker mounted. Informed consent was given for the use of this photograph.

2.3.3 Arrington Eye Tracker

The ViewPoint binocular eye tracker (Arrington Research Ltd., Scottsdale, USA) was used to measure vision strategy during the DVA task in this study. The ViewPoint eye tracker allowed for the tracking of gaze position in the real world through the scene camera video. The calibration of this eye tracker was with respect to the scene camera that moves with the subject. No additional head tracking was done during this study, so participants were asked to minimize their head movements to allow the study to target eye movement strategies.[61] This eye tracker consisted of two eye cameras and one scene camera mounted on a plastic frame without lenses (Figure 2.2). One eye camera was situated in front of each eye and the scene camera was mounted just on the bridge of the nose between the eyes. The eye cameras record eye position at 60 Hz (from each eye individually) and the scene camera records at 30 Hz.

A 23° field of view scene camera lens which corresponds to a horizontal FOV (20.2°) and vertical FOV (15.4°) was used for all recordings because it allowed the entire monitor to be viewed during the DVA task, while also allowing for some margin of error if the head (and subsequently the scene camera) were to move.

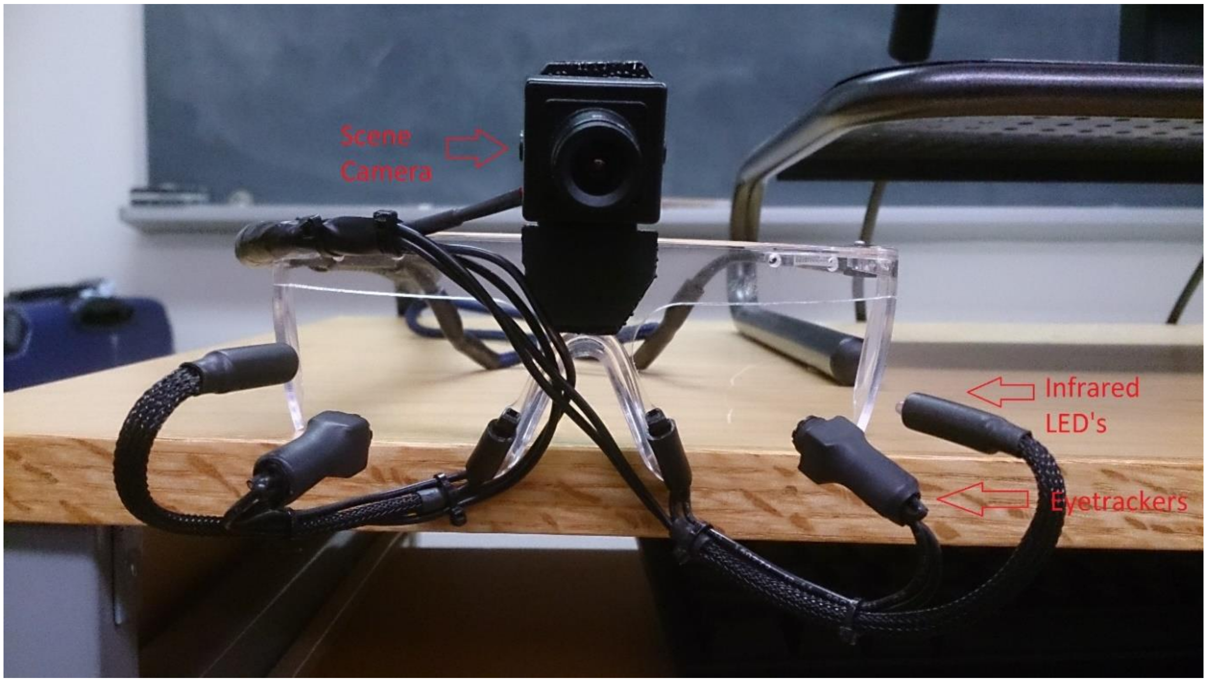


Figure 2.2 Arrington eye tracker. Scene camera located above the nasal bridge; eye tracking cameras and infrared LEDs located in front of each eye

The pupil-glint method was used to track eye position and was set to Video AutoImage and Positive-Lock Threshold as recommended by Arrington Research Ltd. (Figure 2.3). This method relies on measurement of the vector difference between the pupil and the corneal reflection in order to determine the position of the eyes.[61] The camera and the infrared LED of each eye were adjusted such that the pupil of the eye was tracked properly. The infrared illuminator and camera systems provided by Arrington Research were designed to be within the safe limits of exposure. [61]

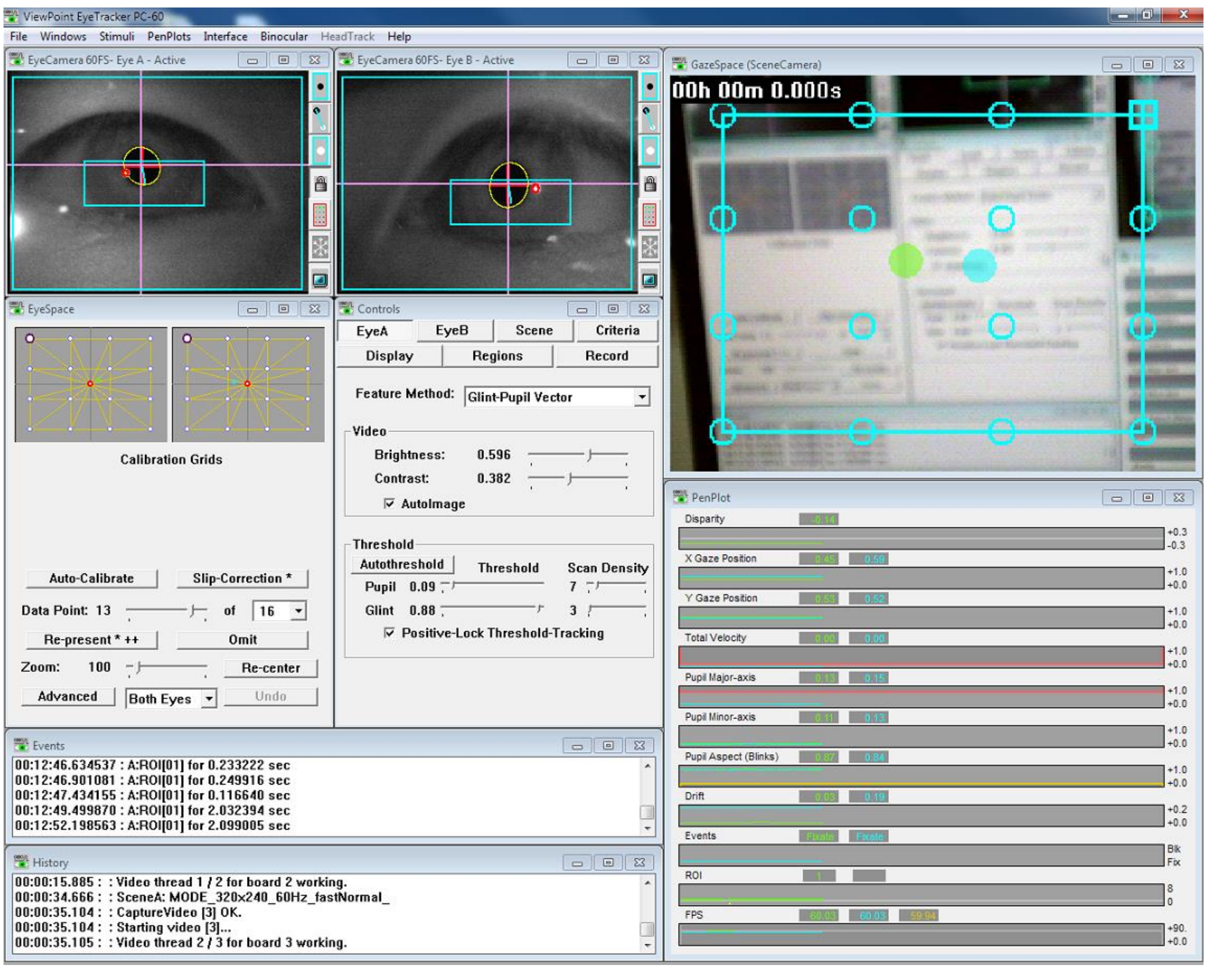


Figure 2.3. The glint-pupil vector method was selected to track eye position. The top left shows Eye A (right eye), and Eye B (left eye). The bottom left is the EyeSpace indicating the calibration grid. The top right was the GazeSpace which was connected to the scene camera. The bottom right was the pen plot where x and y gaze points and velocity were recorded

2.3.4 Arrington Eye Tracker Analysis

Eye tracking data were analyzed using software developed at the University of Waterloo in the Vision & Motor Performance (VAMP) lab.[62]

The eye tracking analysis software used a method known as Velocity and Movement Pattern Identification (I-VMP) which has been used in previous studies.[30,63] The I-VMP method segregates eye movements into different groups: fixations, smooth pursuits and saccades. In order to segregate eye movements, specific criteria need to be met for this to happen. The first criterion was the saccade velocity threshold (S), followed by a temporal window size (T_w) and finally a movement threshold (M).

The saccade velocity threshold (S) helps to determine how saccades are classified. The I-VMP algorithm had set the saccade velocity threshold to 70°/s and supported by previous research as being the optimal threshold.[30,63] Eye movement velocities above 70°/s were considered saccadic eye movements, and removed from the data that was considered for smooth pursuit and fixation analysis. The next steps were to distinguish between smooth pursuits and fixations.

The temporal window and movement threshold were an important step in distinguishing smooth pursuits and fixations. The temporal window (T_w) was the time frame between pairs of adjacent data points and used to determine the average movement vector. The optimal fixed temporal window (T_w) was set to 130 ms. When the temporal window was set to 130 ms, 520 ms of data would result in 4 average movement vectors (4 data points) that would be compared to the movement threshold. There were no unit values but the magnitude of the vectors were between 0 and 1. A larger movement vector (i.e. 0.8) would indicate a trend in the data points moving towards a particular direction. If eye movements were trending towards a particular direction, it was likely to be a smooth pursuit eye movement rather than fixation. A smaller movement vector would indicate more variability in the data points and thus be classified as a fixation. For this study, an optimal movement threshold was set at 0.2. If the data points had a movement vector less than *M* (less than 0.2) the eye movement would be classified as a fixation. Any data points with *M* greater than 0.2 would be classified as a smooth pursuit.

The field of view of the scene camera lens had no effect on the calculation of the movement threshold because the calculation was done using unit direction vectors, which meant each direction vector used in the calculation was normalized to have a magnitude of 1. Thus, the distance of the eye movement was ignored and only the direction was considered.

Digital markers were used to indicate specific time points of interests in a data file. There were different markers available such as *preparation, action, critical action, post action,* and *action end.* The number of the current video frame was inserted next to the marker. There were no differences in which markers were selected except that each marker gave a unique code for identification in the output file. Two markers were always inactive, *data start* and *data end.* After selecting the first data point, *data start* would be marked 60 frames before it.

Similarly, *data end* would be marked 60 frames after the last marker. The *add* button allows for numerous *action* phases to be inputted. In this study, *action* phase markers were used to indicate when the presentation of the first tumbling E appeared on the screen as well as the presentations of the first and last five tumbling Es. *Action end* was used to mark the end of the presentation of the last tumbling E.

2.3.5 Smooth Pursuits

A step-ramp stimulus was used to measure smooth pursuits and assess participant's physiological eye movements.

The step-ramp stimulus consisted of a white target dot moving with a constant velocity on a black background. Participants were asked to follow the white dot with their eyes. The step-ramp stimulus was presented at velocities of 5, 10, 20, 30°/s and moved in a horizontal direction (left to right or right to left). Each speed and direction combination were presented 5 times for a total of 40 trials. During the step-ramp stimulus task, participants wore the El-Mar eye tracker in order to measure smooth pursuit gains.

2.3.6 El-MAR Eye Tracker

The El-MAR eye tracker is a binocular recording video based system (Series 2020 binocular CCD; El-Mar, Toronto, Canada). The eye tracker has a 120 Hz sampling rate making it more suitable to measure smooth pursuit velocities and gains. The El-MAR has two individual eye trackers, which simultaneously measure binocular eye position (Figure 2.4). For accurate measurements, two corneal reflections should be visible during calibration. Prior to recording, the El-Mar was calibrated for each individual participant at a 2 meter viewing distance.[33,44]

Smooth pursuit velocities (5°/s, 10°/s, 20°/s, 30°/s) were tested along the horizontal axis using the step ramp stimulus. These velocities also had negative values (-5°/s, -10°/s, -20°/s, -30°/s). The positive and negative values were used to indicate the direction of the ramp (i.e. a negative value meant a step to the right while ramping left back to the fixation position). The step ramp stimulus consisted of the dot moving quickly to either the left or right side of the display and then moving back to the center at one of the four pursuit velocities. The four velocities (5°/s, 10°/s, 20°/s, 30°/s) and two directions had a fixed time on the screen (4s, 2s, 1s, 0.65s) respectively. There was a one second fixation between each stimulus (i.e. the end of each ramp).

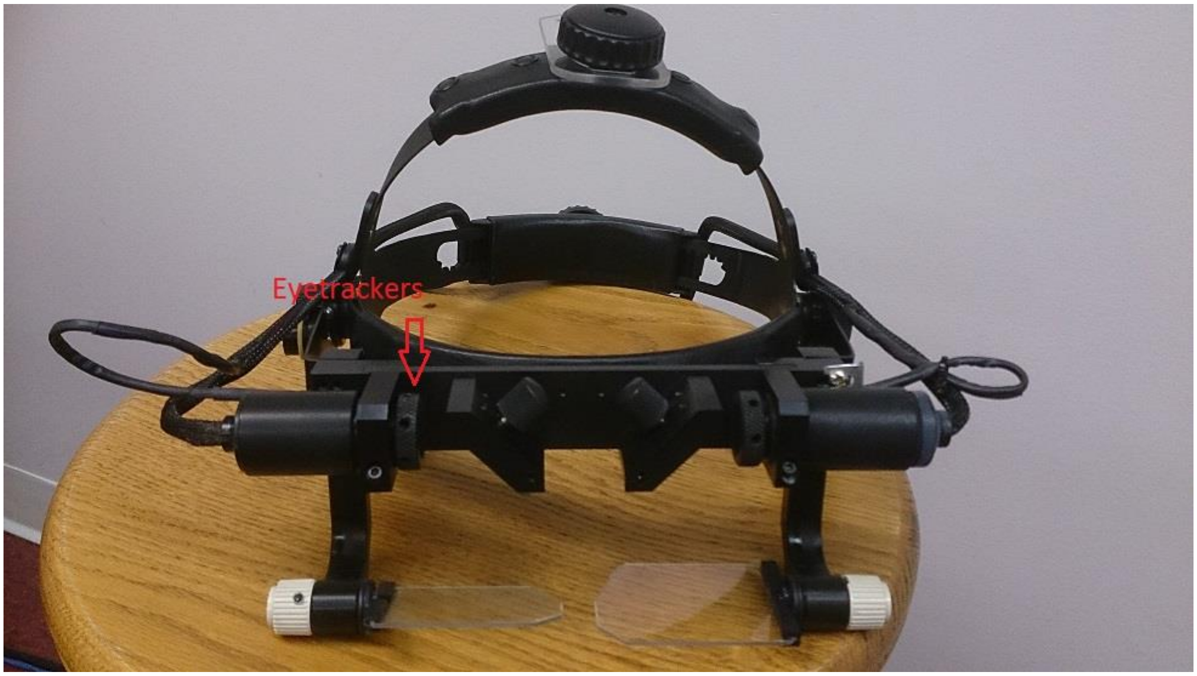


Figure 2.4. El-Mar eye tracker

2.3.7 El-MAR Eyespy Analysis

The analysis for the smooth pursuit step-ramp task required the program Matlab (MathWorks, Natick, MA, USA). Within Matlab, a custom-made eye movement application called Eyespy was used to analyze the smooth pursuit gains for all velocities tested.

To filter out data, Eyespy requires that a saccade be a certain duration. Eyespy may find something that was similar to a saccade and checks the velocity. The default setting was set at a minimum duration of 0.05s and a maximum sampling rate of 250 Hz for recording smooth pursuits. If the duration of the eye movement was too short or fast then the data were omitted. For the current study, the default setting was ideal for smooth pursuit eye movements and not saccades.

Markers were used in this analysis to manually mark the start and end of each individual trial (at each velocity). This analysis program generates a number of different parameters of the data, including mean velocity, stimulus velocity and gain. To calculate smooth pursuit gain, a weighted average was taken using the mean velocity of the smooth pursuits and the number of sample points for that given stimulus velocity. Smooth pursuit gain is a measure of how accurately the eyes followed the stimulus. A gain of 1 meant that the eye moved exactly the same time as the target, whereas a gain of less than 1 meant that the eye undershot the target.

2.4 Statistical Analysis

All statistical analyses for this thesis were conducted using IBM SPSS Statistic for Windows, Version 24.0 (Armonk, NY, USA) and GraphPad Prism 6.00 for Windows (La Jolle, CA, USA).

The following statistical analyses were conducted. Please see Appendix A (18. Statistical Models).

1. Static visual acuity of both eyes (OU) was tested with a one-way independent measures ANOVA. A factor of group was tested.
2. Static visual acuity comparing each eye (OD, OS) were tested with a two-way independent measures ANOVA. The factors of eye and subject were tested.
3. Dynamic visual acuity was tested with a one-way independent measures ANOVA. A factor of speed was tested.

4. The DVA task duration per letter for horizontal and random 30°/s were analyzed with a one-way independent measures ANOVA. A factor of group was tested.
5. Smooth pursuit gain analysis at 30°/s velocity was tested with a one-way independent measures ANOVA. A factor of group was tested.
6. The vision strategies of 30°/s were analyzed by comparing gaze behaviours of the first five and last five letters using a two-way repeated measures ANOVA. The factors of time (within-subjects) and group (between-subjects) were tested.

Chapter 3. Results

3.1 Population Demographics

The study anticipated a sample size of 20 per group for a total of 60 participants. However, recruitment challenges such as the strict criteria in refractive error reduced the target sample size. The actual sample size and population demographics are listed below.

Table 3.1 Population demographics of each group

	Age (years, mean ± SD)	Gender (n)	Background (n)	Sphere/Cylinder (D)	Hours/week (mean ± SD)
Athlete (n = 15)	21.5 ± 2.6	M = 8 F = 7	Volleyball (1), Baseball (1), Basketball (1), Football (3), Hockey (2), Soccer (3), Field Hockey (2) Squash (1) Tennis (1)	OD 0.03/-0.35 OS 0.06/-0.36	13.4 ± 6.9
VGP (n = 11)	21.4 ± 2.7	M = 9 F=2	League of Legends (4) Counterstrike (2) Call of Duty (3) Overwatch (2)	OD 0.02/-0.34 OS 0.09/-0.36	13.4 ± 7.1
Control (n = 20)	21.7 ± 2.8	M = 7 F = 13	N/A	OD 0.01/-0.35 OS 0.05/-0.34	N/A

3.2 Static Visual Acuity

Static visual acuities were measured monocularly and binocularly with the ETDRS chart. Binocular results were compared between groups with a one-way ANOVA. The SVA means and standard error means (SEM) were listed in Figure 3.1 and subsequent figures. Binocular SVA was not statistically significant between the groups ($F(2.43) = 0.526$, $p = 0.595$). The results suggest that the three groups have similar ocular properties with regards to the optics of the eye. This was supported by the strict inclusion/exclusion criteria of the refractive error. Follow up analysis was done in regards to the right and left eye.

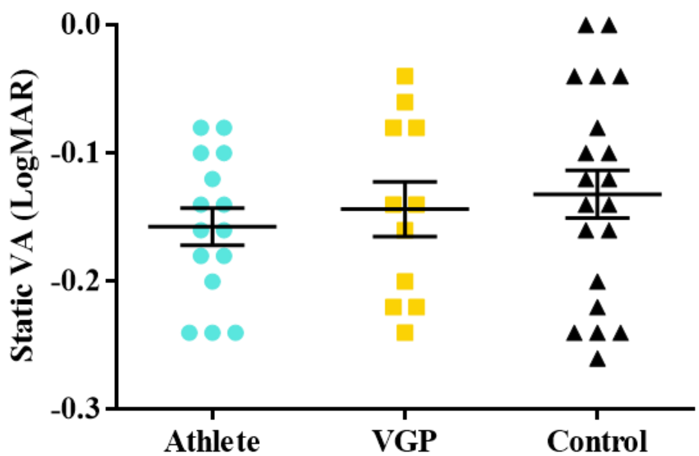


Figure 3.1 Binocular SVA (mean ± SEM) of athletes (mean=-0.16±0.01 LogMAR), VGPs (mean=-0.14±0.02 LogMAR), and controls (mean=-0.13±0.02 LogMAR)

Right eye (OD) and left eye (OS) were compared within subjects to determine if there were any differences of eye on the SVA test. There were no significant differences between eyes ($F(1,86) = 0.086$, $p = 0.772$) and no interaction between eye and subjects ($F(2,86) = 0.261$, $p = 0.7706$) (Figure 3.2). The results suggest that overall, there were no differences between right eye and left eye. However, it should be noted that athletes' OD VA was on average four letters better than controls and athletes' OS VA was approximately two letters better than controls (Table 3.2).

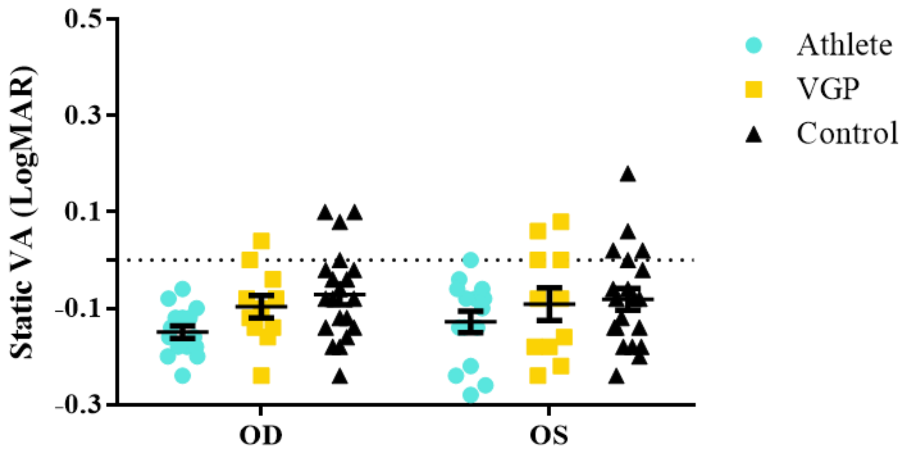


Figure 3.2 SVA of right eye (OD) and left eye (OS) for each group

Table 3.2. SVA means and SEM of right eye (OD) and left eye (OS)

	OD	OS
	Mean ± SEM (LogMAR)	Mean ± SEM (LogMAR)
Athlete	-0.15 ± 0.01	-0.13 ± 0.02
VGP	-0.10 ± 0.02	-0.10 ± 0.03
Control	-0.07 ± 0.02	-0.08 ± 0.02

3.3 Dynamic Visual Acuity – Random Motion

Random motion dynamic visual acuity was tested at four velocities (5°/s, 10°/s, 20°/s, 30°/s). The velocities of each group were analyzed and there was a significant effect of speed within the athlete group ($F(3,56) = 7.84$, $p = 0.0002$) (Figure 3.3). A post-hoc analysis of athletes were significantly different between speeds of 5°/s and 10°/s ($p = 0.005$), 5°/s and 20°/s ($p = 0.001$), and 5°/s and 30°/s ($p = 0.014$). The DVA of VGPs were not significant between speeds ($F(3,40) = 2.12$, $p = 0.11$). The DVA of controls were significant between speeds ($F(3,76) = 7.28$, $p = 0.0002$) (Table 3.3). A post-hoc analysis revealed that controls were significantly different between speeds of 5°/s and 10°/s ($p = 0.05$), 5°/s and 20°/s ($p = 0.01$), and 5°/s and 30°/s ($p = 0.0009$) (Table 3.3). The results showed that the athletes and controls DVA velocities were significantly worse at higher velocities compared with 5°/s. Overall, DVA performance seems to plateau as speed increases.

Table 3.3. DVA of each velocity

	5°/s	10°/s	20°/s	30°/s
	Mean ± SEM (LogMAR)	Mean ± SEM (LogMAR)	Mean ± SEM (LogMAR)	Mean ± SEM (LogMAR)
Athlete	-0.06 ± 0.02	0.06 ± 0.02	0.1 ± 0.03	0.05 ± 0.03
VGP	-0.01 ± 0.03	0.08 ± 0.03	0.09 ± 0.05	0.1 ± 0.04
Control	0.01 ± 0.03	0.13 ± 0.03	0.15 ± 0.02	0.15 ± 0.02

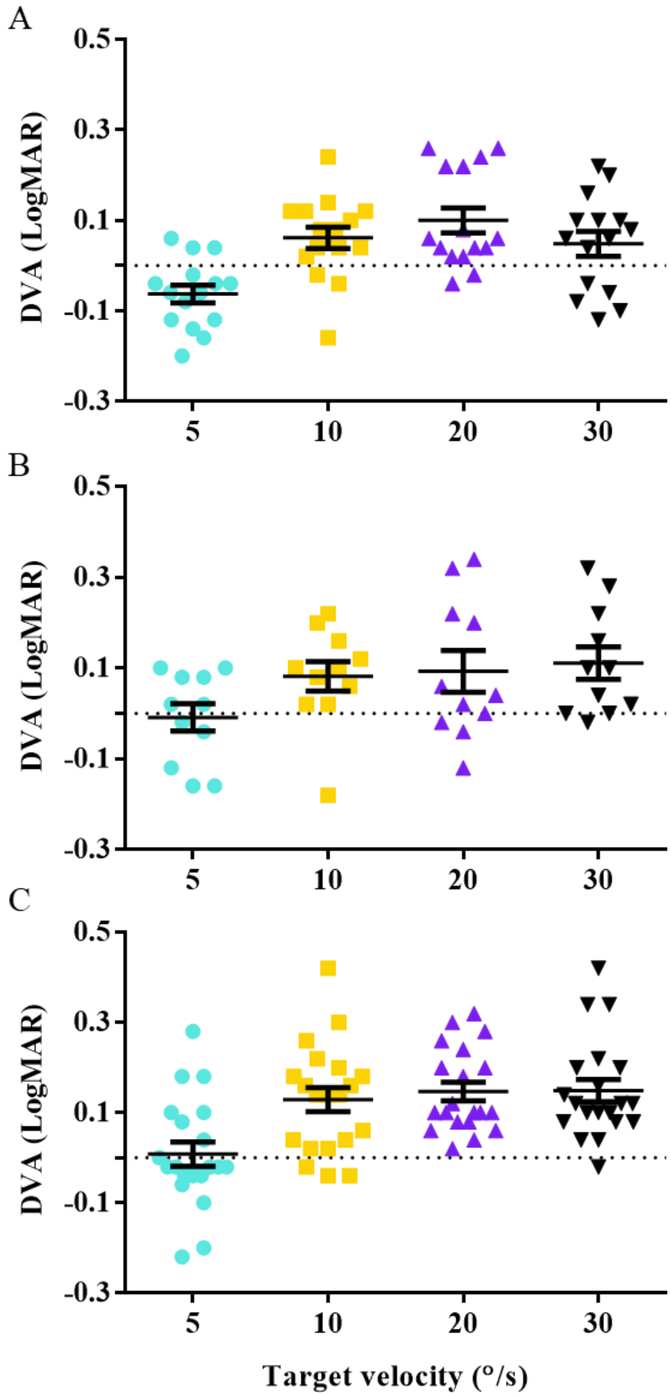


Figure 3.3 Random motion DVA according to target velocities of each group. A. Athlete group. B. VGP group. C. Control group.

Based on the study pre-registration, a velocity of 30°/s was hypothesized to be significantly different between groups. A one-way independent measures ANOVA was used to test this hypothesis. A velocity of 30°/s revealed a significant difference between groups ($F(2,43) = 3.52$, $p = 0.039$). Post-hoc tukey HSD revealed that athletes (mean = 0.05 ± 0.03 LogMAR) had a significantly lower DVA compared to the control group (mean = 0.15 ± 0.02 LogMAR, p=0.03). No differences were found between athletes and VGPs (mean = 0.1 ± 0.04 LogMAR, $p = 0.339$) or VGPs and controls ($p = 0.637$). On average, athletes were approximately one line better than controls while the target moved 30°/s. In conjunction with Figure 3.3, Figure 3.4 supports the fact that DVA performance of athletes was significantly better than controls. Smooth pursuit gains and gaze behaviour analyses were used to examine why there was a difference at 30°/s between athletes and controls.

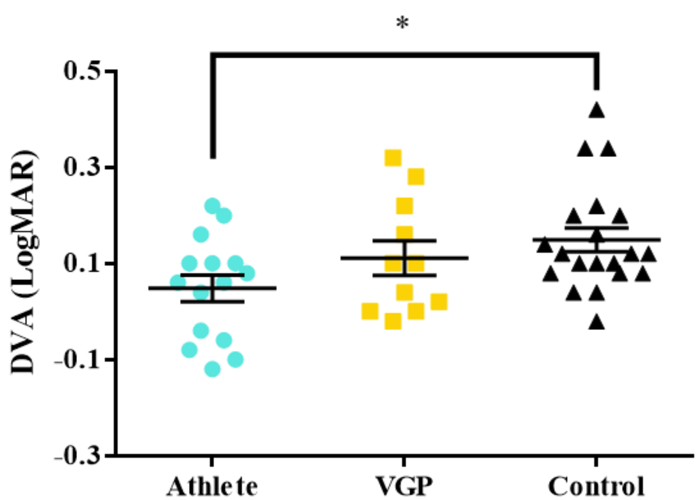


Figure 3.4. DVA performance at 30°/s for each group

3.4 Dynamic Visual Acuity - Horizontal Motion

Horizontal dynamic visual acuity was tested at four velocities (5°/s, 10°/s, 20°/s, 30°/s). There was a significant main effect of speed for athletes ($F(3, 56) = 15$, $p = 0.0001$), VGPs ($F(3,40) = 17.5$, $p = 0.0001$), and controls ($F(3,76) = 17.81$, $p = 0.0001$). The velocities within each group were analyzed and compared (Figure 3.5). The athlete group had a significant difference of speed between 5°/s and 20°/s ($p = 0.0001$), 5°/s and 30°/s ($p = 0.0001$), 10°/s and 20°/s ($p = 0.004$), and 10°/s and 30°/s ($p = 0.0004$) (Table 3.4). There were significant differences of speed for VGPs between 5°/s and 20°/s ($p = 0.0002$), 5°/s and 30°/s ($p = 0.0001$), 10°/s and 20°/s ($p = 0.003$), and 10°/s and 30°/s ($p = 0.0001$). Finally, speed was also significantly different for the control group between 5°/s and 20°/s ($p = 0.0001$), 5°/s and 30°/s ($p = 0.0001$), 10°/s and 20°/s ($p = 0.003$), and 10°/s and 30°/s ($p = 0.0002$). The speed of the task influenced the DVA performance of athletes, VGPs, and controls. There was a common trend with DVA getting worse for all groups as the speed of the task increased (Figure 3.5). Most of these significant differences were comparisons between 5°/s and 10°/s and the other faster speeds.

Table 3.4. DVA performance of each velocity in horizontal motion

	5°/s	10°/s	20°/s	30°/s
	Mean ±SEM (LogMAR)	Mean ±SEM (LogMAR)	Mean ±SEM (LogMAR)	Mean ±SEM (LogMAR)
Athlete	-0.11±0.03	-0.06±0.02	0.07±0.03	0.09±0.03
VGP	-0.08±0.04	-0.04±0.03	0.14±0.03	0.2±0.03
Control	-0.07±0.03	0.01±0.03	0.15±0.03	0.18±0.03

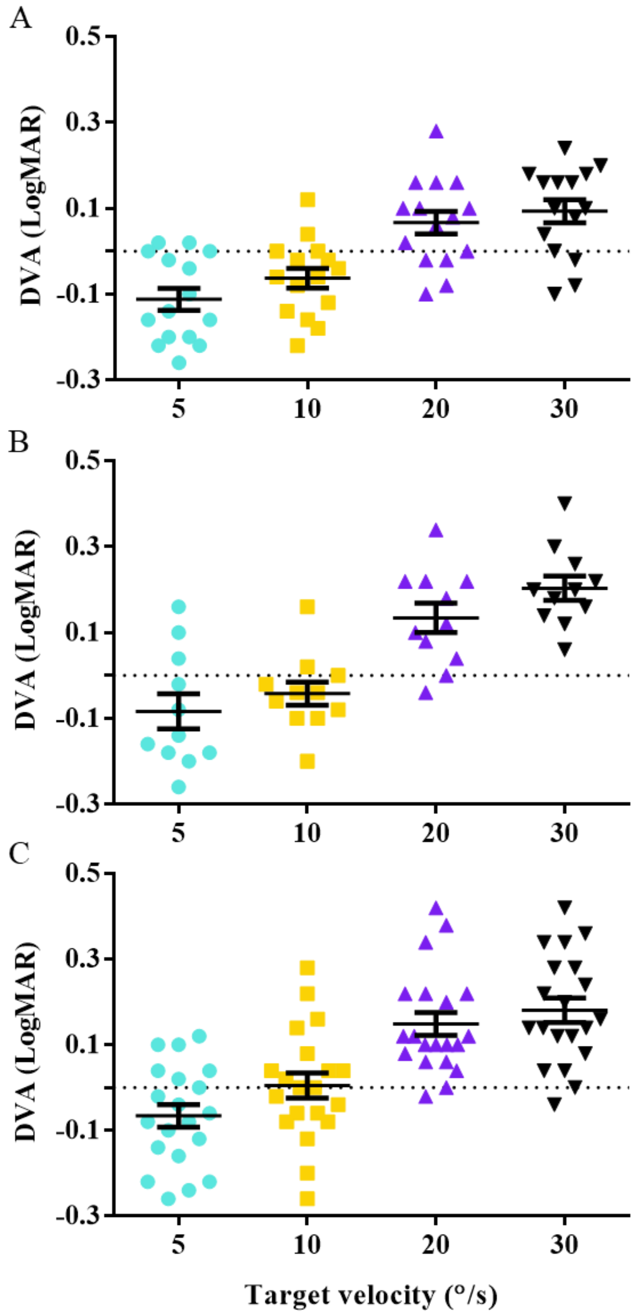


Figure 3.5 Horizontal motion DVA performance of each group and velocity. A. Athlete group. B. VGP group. C. Control group

Following the pre-registered study design, a velocity of 30°/s was again hypothesized to be significantly different between subjects. A one-way independent measures ANOVA was used to test this hypothesis. A between-subjects effect was found at 30°/s and showed a significant difference in DVA between groups ($F(2,43) = 3.78$, $p = 0.031$). Post-hoc tukey HSD revealed that athletes (mean = 0.093 ± 0.027 LogMAR) had a significantly lower DVA compared to the VGPs (mean = 0.204 ± 0.028 LogMAR, $p = 0.046$). No differences were found between athletes and controls ($p = 0.071$) or VGPs and controls (mean = 0.181 ± 0.029 LogMAR, $p = 0.855$). However, it should be noted that the post-hoc comparison between athletes and controls was nearly significant. On average, athletes' DVA was more than one line better than VGPs and almost one line better than controls with horizontal targets moving 30°/s. The results suggest that athletes were capable of discriminating the target at 30°/s better than VGPs for horizontal motion.

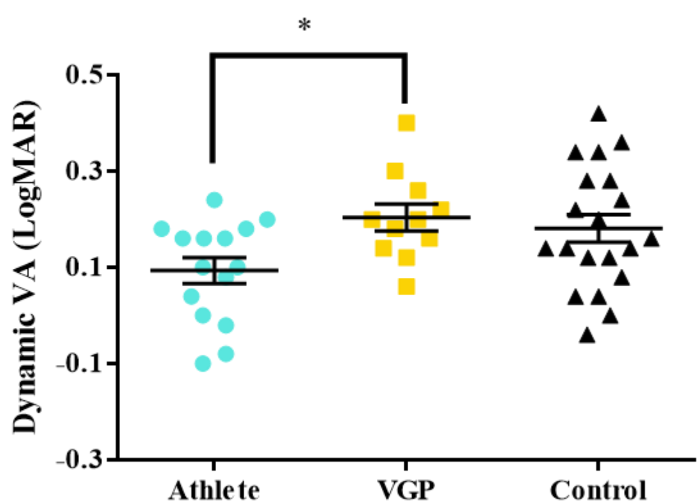


Figure 3.6 DVA performance between groups at horizontal 30°/s

3.5 Dynamic Visual Acuity - Task Response Time Per Letter

3.5.1 Horizontal Motion 30°/s

The task response time per letter for each group may have influenced DVA performance at 30°/s for each group. The DVA task recorded the response time of each letter in seconds. The response times per letter for each individual were averaged and then a group average was calculated. A one-way ANOVA was used to determine if there were any differences between the groups DVA response time per letter. At horizontal 30°/s, the athletes (mean = 1.412 ± 0.106 s), VGPs (mean = 1.553 ± 0.139 s), and controls (mean = 1.469 ± 0.093 s) response times per letter were not significantly different ($F(2,43) = 0.349$), $p=0.707$) (Figure 3.7). The results suggest that each group took approximately the same amount of time to respond to each letter. The relatively fast response time of approximately 1.5s may be due to the fact that the letter only passed across the screen once even though participants were given 20 s to respond.

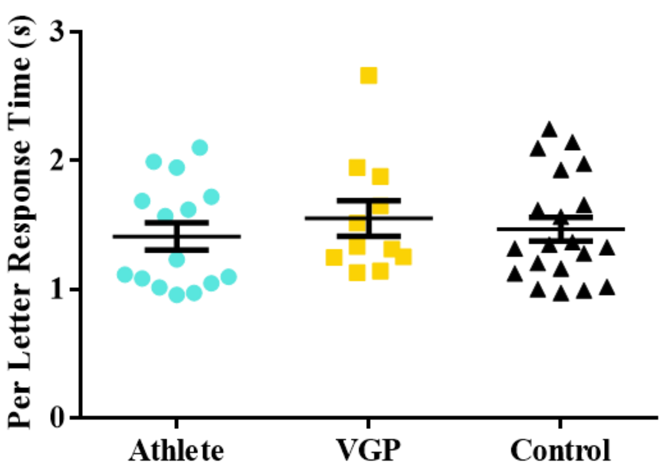


Figure 3.7 Average task response time per letter at horizontal 30°/s

3.5.2 Random Motion 30°/s

Similar to horizontal motion 30°/s, the average task response time per letter of each group were analyzed. A one-way ANOVA was used to determine if there were any differences between the groups DVA response time per letter. The task response time of athletes (mean = 3.376 ± 0.256 s), VGPs (mean = 3.532 ± 0.419 s), and controls (mean = 3.839 ± 0.419 s) were not statistically significantly different ($F(2,43) = 0.326$, $p = 0.723$) (Figure 3.8). The one outlier in the control group was included. The outlier had a few short and long responses throughout the condition. The results suggest that all groups take approximately the same amount of time to respond to each letter. Comparing both horizontal 30°/s and random 30°/s, all groups on average spent twice the amount of time in random motion. This can be expected for random motion since the target stayed on the screen for 20 seconds. In horizontal motion, the target passes once across the screen, which may have led to faster response times.

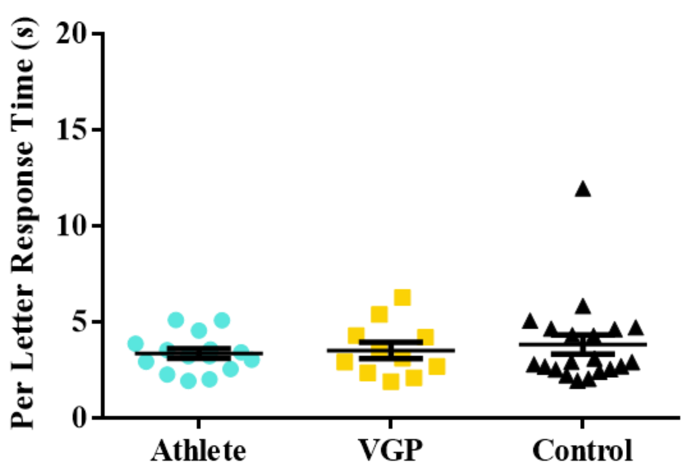


Figure 3.8 Average task response time per letter at random 30°/s

3.6 Smooth Pursuit Step-Ramp task

Smooth pursuit gains were measured using the El-Mar eye tracker. Smooth pursuit gains are unit free values that range from 0 to 1. A gain of 1 suggests the eyes and the target were in the same position at all times. The study recorded smooth pursuit gains from 5°/s, 10°/s, 20°/s, and 30°/s. Since DVA at velocity 30°/s was significant between subjects, the 30°/s results are presented here.

The smooth pursuit gains of athletes (mean = 0.534 ± 0.044) were similar to those of the VGPs (mean = 0.412 ± 0.056) and controls (mean = 0.417 ± 0.037), and a one-way ANOVA revealed no significant differences between athletes, VGPs, and controls for a target speed of 30°/s ($F(2,43) = 2.43$, $p = 0.100$) (Figure 3.9). The results suggest that athletes, VGPs, and controls were capable of performing similar smooth pursuit eye movements.

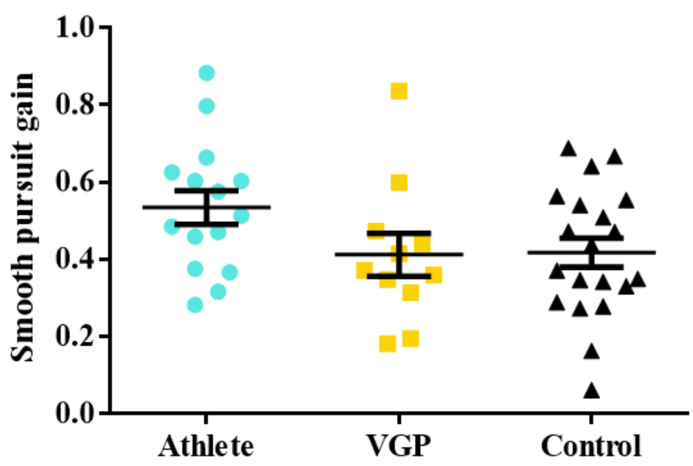


Figure 3.9 Smooth pursuit gain at velocity 30°/s compared across groups

3.7 Gaze Behaviours – First and Last Five Letters

Gaze behaviours were compared between the first five letters and the last five letters of the DVA task. The first five letters of the DVA task were well above threshold and were the easiest letters for participants to see, whereas the last five letters should be the most challenging to see since they were near DVA threshold. It was possible that participants' vision strategies may be different when examining the first and last five letters during a DVA task. A two-way repeated measures ANOVA was used to compare the first five letters and the last five letters of the DVA task. The percent duration of first and last five letters were analyzed for each type of gaze behavior (fixations, pursuits and saccades). The within subjects factor was time (first five and last five letters) and between subjects factor was group (athlete, VGPs, and controls).

3.7.1 Horizontal 30°/s - Fixation

There was a within subjects main effect of time (first five and last five letters) (F (1,43) = 7.82, p = 0.008). The fixational eye movements of the between time and groups were not significantly different (F (2,43) = 0.08, p = 0.922) (Figure 3.10, Table 3.5). Similarly, there were no significant differences between groups (F (2,43) = 0.598, p = 0.598). The results suggest that all groups spent a similar relative duration fixating in the first five letters and last five letters. Within each subject, their relative duration was different between the first and last five letters. Slightly more time was spent fixating in the last five letters for the respective subjects.

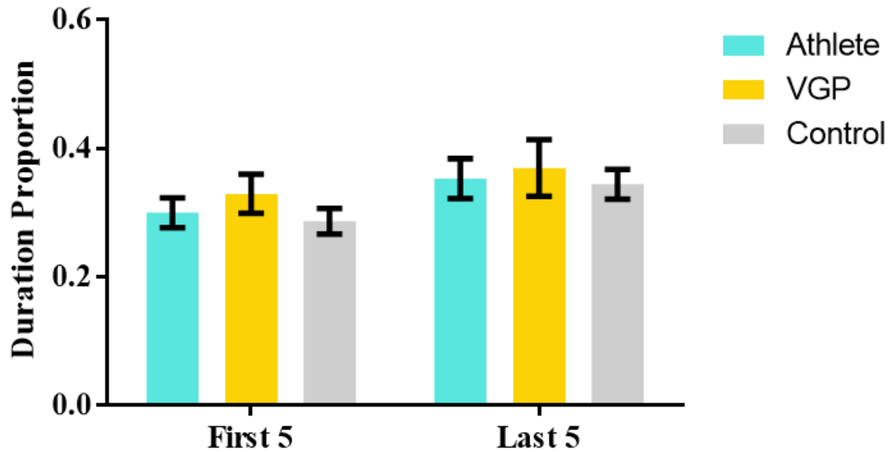


Figure 3.10 Proportional duration (from 0 to 1) of fixations for the first and last 5 letters for Horizontal 30°/s

Table 3.5 Proportional duration (from 0 to 1)of fixations during the first and last 5 letters for Horizontal 30°/s

	First 5	Last 5
	Mean ± SEM	Mean ± SEM
Athlete	0.300 ± 0.023	0.353 ± 0.031
VGP	0.329 ± 0.031	0.369 ± 0.044
Control	0.286 ± 0.020	0.344 ± 0.023

3.7.2 Horizontal 30°/s – Smooth Pursuit

The relative duration of smooth pursuit eye movements between groups were not significantly different (F (2,43) = 1.54, p = 0.226, Figure 3.11). A within subjects test (time) revealed no significant differences between the first five and last five (F (1,43) = 1.72, p = 0.197) either, and there was no interaction between time and group (F (2,43) p = 0.452). However, athletes spent approximately 40-45% of time using smooth pursuits on the first and last five letters while the VGPs spent 30-35% and controls spent 38% (Table 3.6). In comparison to fixations, athletes spent the most time using smooth pursuits followed by controls then VGPs.

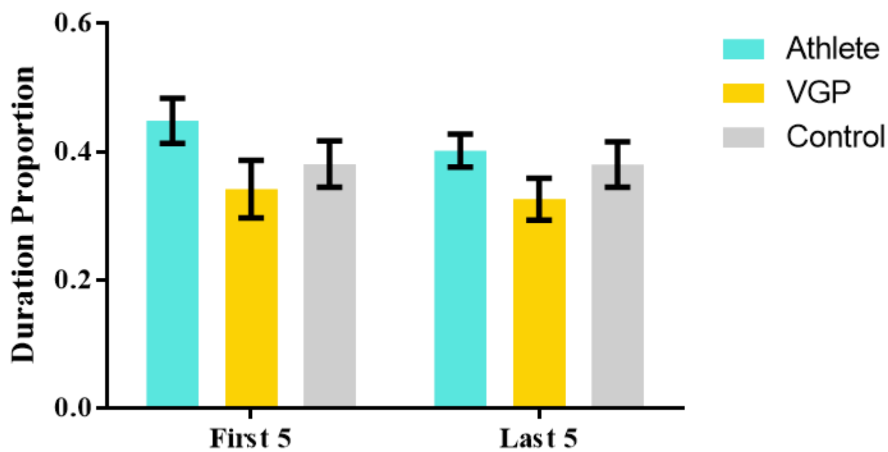


Figure 3.11 Proportional duration (from 0 to 1) of smooth pursuits for the first and last 5 letters for Horizontal 30°/s

Table 3.6 Proportional duration (from 0 to 1) of smooth pursuits for the first and last 5 letters for Horizontal 30°/s

	First 5	Last 5
	Mean ± SEM	Mean ± SEM
Athlete	0.448 ± 0.035	0.401 ± 0.026
VGP	0.341 ± 0.045	0.326 ± 0.033
Control	0.380 ± 0.036	0.380 ± 0.035

3.7.3 Horizontal 30°/s – Saccade

Proportions of saccadic eye movements were not significantly different between time and group thus there was no interaction (F (2,43) = 0.84, p = 0.441) (Figure 3.12). Similar to the other two eye movements, no post-hoc analysis could be conducted. The within subject effect also revealed no significant differences of time (F (1,43) = 2.81, p = 0.101). There was no between subjects effect of group (F (2,43) = 0.657, p = 0.523). The within subject effect suggest that there were no differences among groups in the first 5 letters or the last 5 letters, although athletes spent the least amount of time on saccades for the first five and last five letters using 5-10% less time making saccades than VGPs and controls (Table 3.7). Overall, the results suggest that saccadic eye movements at horizontal 30°/s were similar across the groups.

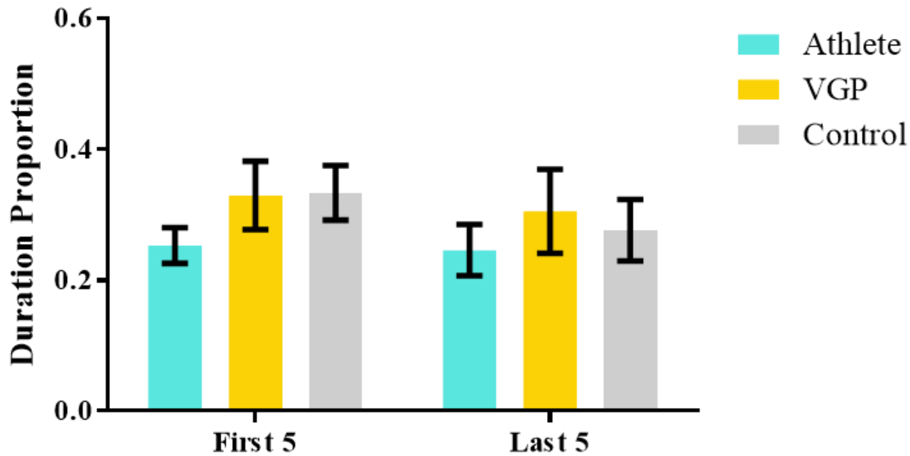


Figure 3.12 Proportional duration (from 0 to 1) of saccades for the first and last 5 letters for Horizontal 30°/s

Table 3.7 Proportional duration (from 0 to 1) of saccades for the first and last 5 letters for Horizontal 30°/s

	First 5	Last 5
	Mean ± SEM	Mean ± SEM
Athlete	0.253 ± 0.027	0.246 ± 0.039
VGP	0.330 ± 0.052	0.305 ± 0.064
Control	0.333 ± 0.042	0.276 ± 0.047

3.7.4 Random 30°/s – Fixation

Fixations were not significantly different between groups (F (2,43) = 0.70, p = 0.503). There was no interaction between time and group (F (2,43) = 1.99, p = 0.148). In other words, within the first five letters and within the last five letters, athletes, VGPs, and controls were not different among each group. However, there was a within subject effect of time (F (1,43) = 54.15, p = 0.0001) (Figure 3.13, Table 3.8). Post-hoc analysis was not conducted due to no significance between groups. The results suggest that overall athletes, VGPs, and controls spent more time fixating for the last five letters than the first five letters.

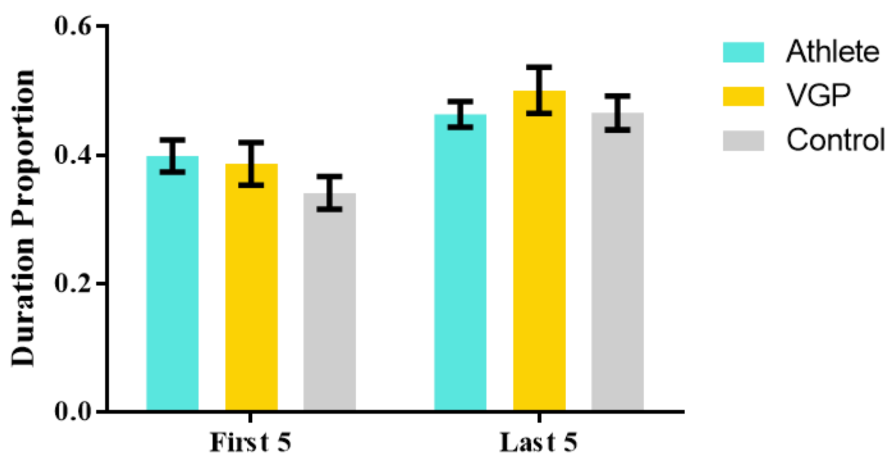


Figure 3.13 Proportional duration (from 0 to 1) of fixations for the first and last 5 letters for Random 30°/s

Table 3.8 Proportional duration (from 0 to 1) of fixations for the first and last 5 letters for Random 30°/s

	First 5	Last 5
	Mean ± SEM	Mean ± SEM
Athlete	0.398 ± 0.025	0.463 ± 0.020
VGP	0.386 ± 0.033	0.500 ± 0.036
Control	0.341 ± 0.025	0.465 ± 0.026

3.7.5 Random 30°/s – Smooth Pursuit

Smooth pursuits were not significantly different between groups (F (2,43) = 0.744, p = 0.481) (Figure 3.14). There was no interaction between time and group (F (2,43) = 0.33, p = 0.723). However, there was a main effect of time (F (1,43) = 9.63, p = 0.003). The results suggest that overall athletes, VGPs, and controls were significantly different between the first five and last five letters while using smooth pursuits.

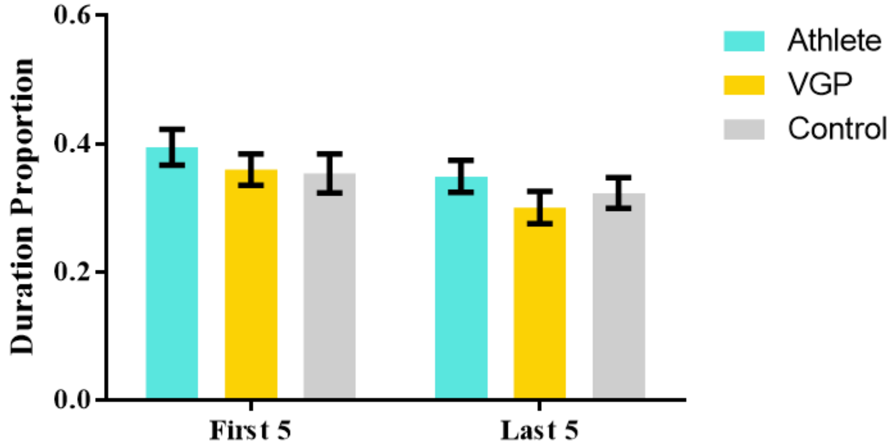


Figure 3.14 Proportional duration (from 0 to 1) of smooth purusits for the first and last 5 letters for Random 30°/s

Table 3.9 Proportional duration (from 0 to 1) of smooth pursuits for the first and last 5 letters for Random 30°/s

	First 5	Last 5
	Mean ± SEM	Mean ± SEM
Athlete	0.394 ± 0.028	0.349 ± 0.025
VGP	0.359 ± 0.025	0.300 ± 0.025
Control	0.353 ± 0.030	0.323 ± 0.024

3.7.6 Random 30°/s – Saccade

A within subject effect of time was found between the first and last five letters (F (1,43) = 11.91, p = 0.001). There was no interaction between time and group (F (2,43) = 2.11, p = 0.133). Saccade durations were not significantly different between subjects (F (2,43) = 0.69, p = 0.507) (Figure 3.15). Interestingly, there was approximately a 10% difference in percent duration between athletes (0.208 ± 0.031) and controls (0.306 ± 0.045) on the first five letters (Table 3.10). Overall, athletes appeared to use less time making saccades than either VGPs or controls. This was more pronounced for the first five letters compared to the last five letters. The trend continues into the last five letters but the average saccade duration was significantly shorter approximately 20% for all groups in these letters. The within subject effect of time indicates a difference between the first five and last five letters irrespective of group.

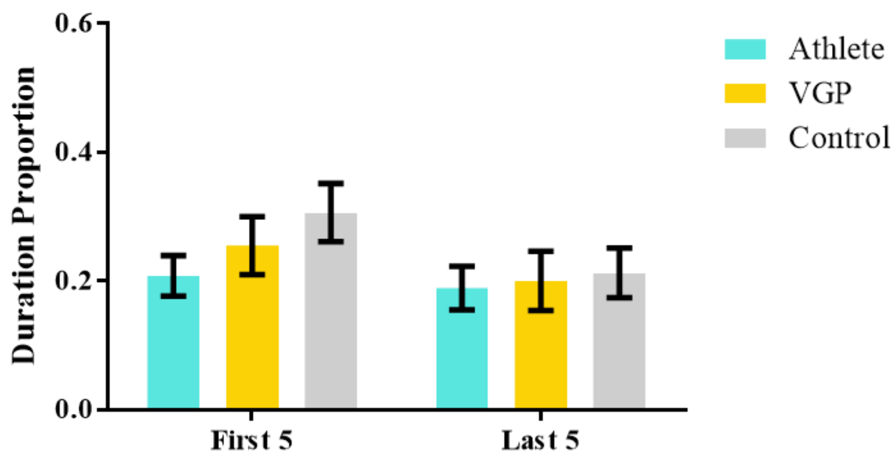


Figure 3.15 Proportional duration (from 0 to 1) of saccades for the first and last 5 letters for Random 30°/s

Table 3.10 Proportional duration (from 0 to 1) of saccades for the first and last 5 letters for Random 30°/s

	First 5	Last 5
	Mean ± SEM	Mean ± SEM
Athlete	0.208 ± 0.031	0.189 ± 0.034
VGP	0.258 ± 0.045	0.200 ± 0.046
Control	0.306 ± 0.045	0.212 ± 0.039

3.8 Post-hoc Power Analysis

Due to the limited number of VGPs in the study, a post-hoc power analysis was done using G*Power.[64,65] A post-hoc analysis was used to determine the effect size of the DVA for random motion 30°/s and horizontal motion 30°/s between each group (Appendix B). Based on the post-hoc analysis, a study design with more participants was needed to ensure sufficient power to detect effects of this size.

Chapter 4. Discussion

Dynamic visual acuity plays an important role in not only sports but in any task that requires the interpretation and discrimination of motion such as driving a car. DVA has been studied in the laboratory setting using optotypes, which were thought to have reflected gold-standard SVA charts. However, the validity and reliability of these DVA tests were not consistent.[16,66]

Very few studies have quantified and discerned the role of different types of eye movements, namely fixations, smooth pursuits, and saccades in DVA performance in athletes and non-athletes, and no studies have examined VGPs eye movement and gaze behaviours. In the present study, DVA performance on the random motion task was significantly better for athletes than controls at a target velocity of 30°/s. Similarly, DVA performance on the horizontal motion task was significantly better for athletes than VGPs at a velocity of 30°/s. However, there were no differences in DVA performance between VGPs and controls at random and horizontal 30°/s. Athletes, VGPs and controls had similar smooth pursuit gains at 30°/s speed, and the gaze behaviour results suggest that athletes, VGPs and controls use relatively the same eye movement strategies to complete the task.

High-level athletes playing sports that require object tracking were considered suitable subjects for studying their visual function on how it may affect performance since they are trained in a dynamic environment.[19] Similar to athletes, VGPs also provide valuable information about the visual system since they interact with a dynamic environment and it has been hypothesized that the visual system may be enhanced from high level video-game experiences.[20]

4.1 Static Visual Acuity

In order to have good DVA, one should have good SVA.[3] Laby et al. (1996) demonstrated that close to 80% of the Major League Baseball players had SVAs of -0.13 LogMAR or better. This is consistent with the recommendations of Coffey and Reichow (1990), that regardless of the sports situation, the recommended SVA should be a minimum of -0.13 LogMAR for both eyes.[67] In this study, the SVAs of participants in all three groups were binocularly similar which was important since this was a binocular study. Also, there were no significant differences between the left and right eye of each group. The criteria for SVA and refractive error were important. It was important to control the physiological optics of all participants so that they were as equal as possible and that no magnification or minimization effects from spectacles or contact lenses would influence DVA.

4.2 Dynamic Visual Acuity – DVA Threshold

A common problem among previous DVA studies was the wide range of testing methods, and the lack of validated instrumentation. moV& (V&mp Vision Suite), used here has recently been validated and demonstrated good test-retest repeatability for the measurement of both static and dynamic visual acuities.[16] For this study, moV& only has tumbling E or

Snellen letter targets available for use, and the tumbling E, a four-way forced choice target, was felt to be a more appropriate target than the Snellen letters (10-way forced choice).

Previous research has indicated that there was a high correlation between static visual acuity and dynamic visual acuity.[17] Interestingly, the results of this study demonstrated that even though SVA of both eyes were similar in all three groups, there were significant differences between athletes, VGPs and controls DVA. Specifically, athletes have superior DVA than VGPs or controls for horizontal motion at 30°/s and random motion 30°/s.

Our validated DVA tasks findings were consistent with previous research. Athletes completed the DVA tasks at higher speeds than controls.[14,24] For this study, the four velocities were chosen because it allowed for a comparison between the DVA task and the physiological smooth pursuit gains. The progressive decline in acuity with increasing target speed that we measured is also in alignment with previous research,[17] which found that at lower speeds, DVA performance would become more similar to SVA.

It is interesting to note, that DVA has been found to be significantly better in varsity level baseball players than non-athletes when testing DVA speed thresholds.[24] DVA speed thresholds were not examined in this particular study, but refer to the maximum speed at which the DVA task can be done when target size is constant. The baseball players speed threshold were 404°/s compared to non-athletes of 315°/s in the free eye movement condition with a 42 min of arc letter size.[24] Given that varsity level athletes were capable of completing a DVA task at these high velocities, it would be interesting to test them at speeds greater than 30°/s using moV& if the monitor's refresh rate and display size were not a limiting factor.

On average, VGPs DVA performance was not significantly different from controls on either the random or horizontal motion. Perhaps the requirements for VGPs needed to be stricter. The visual skills required for action video games can differ based on the types of games people play (i.e. first person shooters, strategy, role-playing games) yet they have all been defined as action video games.[20] The four games preferred by the participants in this particular study have been classified as first person shooters. A more highly skilled group with more hours of video game play may be required in order to determine if any differences in DVA performance exist. Another limiting factor in this analysis may be the small sample size of the VGP group. The pre-registered studies aim was to have 20 participants in each group, however only 11 VGPs were eligible for this study. One problem with recruitment was that glasses and contact lens wearers were excluded, and it seemed that VGPs were more prone to wearing glasses and contact lenses. This may be related to the many hours they spend in front of a monitor or other environmental factors, although this has not yet been proven.[68,69]

Some studies have found a practice effect in DVA performance. Brown (1972) found that there was a practice effect with better DVA thresholds in the second part of their experiment.[11] There was an improvement in acuity thresholds at target angular velocities greater than 50°/s. Long and Rourke (1989) found that observers with poorer DVA at pre-test were able to significantly improve their DVA thresholds while already skilled observers could not bring their DVA thresholds any higher. However, moV& has been demonstrated to have good test-retest reliability for DVA tasks,[16] so it is unlikely that the differences observed in this study were related to a learning effect. Hirano et al., (2017) demonstrated that the repeatability of the moV& measures was similar to the gold standard ETDRS charts. Furthermore, participants were randomly assigned the order of which motion type and speed were given in order to account for a learning effect, which again makes it unlikely that the differences in performance on the DVA task were related to differences in task learning.

The horizontal and random motion were different motion types and had different maximum durations. Horizontal motion had the stimulus passing from the left side of the screen to the right side of the screen once. Since horizontal motion had the stimulus appear from left to right, there may have been a potential cue in discriminating the target. If the cue or knowledge of the target location were a factor in DVA performance, one might expect individuals to perform better on the horizontal motion task than the random motion. Interestingly, the data shows that for all groups DVA performances were better on the random 30°/s compared to horizontal 30°/s, and that as the velocity decreased, the trend seemed less noticeable, suggesting that a difference existed between the random and horizontal DVA tasks at higher speeds. It is important to note that the presentation and response times were longer for random motion because the stimulus remained on the screen for 20 seconds.

This difference in DVA between horizontal and random motion was likely due to the fact that the horizontal motion target only passed once from the left side to right side of the screen, while the random motion target was visible for longer as it stayed on the screen for a maximum of 20 seconds until a response was given. Comparing task response time per letter at 30°/s showed that horizontal motion was approximately 1.5 seconds faster than random motion for each group. The difference in the display time between the two targets was most pronounced at the highest velocities because at high speeds the horizontal motion targets had the shortest display times.

4.3 Dynamic Visual Acuity - Task Response Time Per Letter

Although not part of the original, pre-registered analysis plan, task response time was examined because the output response may give a reason as to why athletes have a significantly better DVA. Perhaps athletes require more time in assessing the information or that they require a shorter amount of time for their motor response. If athletes did exhibit a longer response time, that may indicate the information was processed for a longer amount of time. Another reason is that athletes have a tendency to be more competitive and thus spending more time on the DVA task may help their performance. However, the results demonstrated that the athletes' task response times per letter were not significantly different compared to the other groups in any of the motion types. This suggests all groups spent the same amount of time per letter despite the fact that the DVA performance of athletes was better.

Similar to athletes, VGPs did not exhibit any differences in their response time per letter compared to other groups. Previous research has found that highly skilled VGPs were able to react to task specific targets faster than non-VGPs, which may be due to the amount of time spent playing video games.[20,58,59] If VGPs DVAs were significantly different between groups, then perhaps the response times of VGPs would be reflected as well. A faster response time may indicate a better visuomotor reaction time while a slower response time may indicate a longer time required to collect information from the scene. However, the data does not reflect VGPs response time to the task as there were no significant differences between VGPs and the other groups regardless of motion type.

The differences in DVA performance between athletes, VGPs and controls does not appear to be associated with task response time, therefore it may have been due to differences in the oculomotor control or perceptual abilities. Thus, the next step was to compare the smooth pursuit gains and gaze behaviours (vision strategies) between athletes, VGPs and controls.

4.4 Smooth Pursuit Gains

Smooth pursuit gains were recorded with the El-Mar eye tracker to measure the physiological tracking abilities of each individual's oculomotor system without testing visual acuity. Smooth pursuit gains were hypothesized to be similar between groups at a velocity of 30°/s. As expected, the smooth pursuit gains were not significantly different between groups ($p=0.100$). However, the mean gains of athletes were higher than the other groups and this near significant trend may be due to small sample size since the study was powered for DVA performance and not smooth pursuit gains. That being said, previous research has demonstrated that mean gains for racquet sport athletes and non-athletes were similar,[33] so more research is needed to understand whether or not differences in smooth pursuit gains contribute to differences in DVA performance.

4.5 Gaze Behaviours

Gaze behaviours are the combination of eye movements used to complete a task, and include fixations, smooth pursuits and saccades. The gaze behavior analysis of experts compared to novices during the DVA task was the exploratory focus of this study. Previous sports study paradigms of DVA have typically observed 1) the number of fixations made during a task in order to determine the amount of visual information assessed by the observer and 2) the differences in the duration of fixations made during the task to determine the amount of time spent collecting visual information.[1,50,51,70] Following previous research, the gaze behaviors this study assessed were the total duration of fixations (relative to the task duration). Additionally, relative durations of smooth pursuit and saccade eye movements were also assessed in this study, as has been done before in many DVA studies.[11,24,71,72] In particular, this study examined the gaze behaviours of the first five and last five letters because the vision strategies may be different for the last five letters since they were more difficult as they were closer to threshold. Since the total task duration for each person was different, the relative duration of the individual gaze behaviours were used to normalize the data so one could directly compare between individuals.

Between the first and last five letters, the relative duration of eye movements from start to finish of horizontal 30°/s had all three groups spending approximately 30% of their time using fixations. Horizontal motion smooth pursuits durations were on average 3-5% higher for athletes compared to VGP or controls but this difference was not statistically significant. The results showed smooth pursuit durations spent in the first and last five letters to be relatively similar between athletes and controls. For horizontal motion, athletes seemed to use fewer saccades than the other groups, however these differences were also not statistically significant. Despite there were no differences between the subject groups, all groups spent proportionally more time on fixation and less on saccades for the near threshold (last 5) letters compared with the first 5 letters for both types of motion.

Random motion had not been tested in previous literature. In random motion, all groups had typically exhibited longer fixations for the last five letters compared to the first five (Figure 3.13). The proportion of smooth pursuit duration between the first and last five letters were not significant between groups but show a similar trend of athletes spending more time than the other groups using smooth pursuits. Though not significant, optimizing smooth pursuit and saccade strategies to the last five letters may have increased the duration spent on foveation.[41] One way to optimize smooth pursuit strategies may be to reduce the smooth pursuit gain in order to minimize the positional error, much like the cost benefit of tracking any object.[26] The saccade duration between the first and last five letters were not significantly different between groups. However, it was interesting to see that both VGPs and controls lowered the percentage of time using saccades by 5-10% for the last five letters.

Even though VGPs and controls minimized their time spent using saccades, it does not explain the superior DVA performance from athletes.

Uchida et al. (2012) compared DVA performance and saccades at velocities of 200-900°/s for free eye movement conditions and 50-400°/s in a fixation condition. The stimulus speeds of this study were faster than the eyes capability for tracking and some studies have mentioned it is difficult to track targets at speeds greater than 700°/s.[41,73] The study found DVA had improved when participants had tracked the target with their eyes compared to fixating at a point on the screen and having the image pass by. Athletes were significantly better at the task when asked to track the target but not different to non-athletes when fixating at a point. Their results suggested that athletes superior DVA were due to the ability to track a target and not image processing.[26,73]

The current study showed no eye movement differences of each group.[24] At 200°/s, the eye would lag behind and thus catch-up saccades were often used in conjunction with smooth pursuits in order for the eyes to foveate. This lack of difference may be due to the fact that the target velocity of the current DVA study was a maximum of 30°/s; perhaps a higher velocity is required in order to detect any differences in fixation and smooth pursuit eye movements. However, the speeds in the Uchida et al. (2012) study were very fast and above the criteria of human smooth pursuit eye movements. It was unlikely that this study design actually measured smooth pursuits given their target speed velocities. Athletes could have used saccades to help reduce positional error and improve target accuracy, but this was not examined in either the Uchida et al. (2012) study or the current study, and more research is needed.

In the alternative, the results of the current study may indicate that visual perception was responsible for the superior DVA performance of athletes, particularly at higher speeds. If athletes' visual perception abilities are better than non-athletes at high speeds, this would be consistent with the findings of both the current study and Uchida et al.'s study.

A limitation of the gaze behavior analysis was the Arrington eye tracker sampling rate of 60 Hz, and this may be one factor to consider as to why data acquisition were not as accurate as they could have been if higher sampling rate eye trackers was used. The majority of eye tracking research on DVA were typically measured with a 120-500 Hz eye tracker and required a chin rest,[24,26,33] however research became possible in the 1980s to use head-mounted eye trackers.[50,52,53] A lower sampling rate of 60 Hz means 1 data point was sampled every 16.67ms while a 120 Hz sampled 1 data point every 8.3ms. Data acquisition of eye movements was more difficult with a lower sampling rate tracker because more noise could be introduced. The noise may be fixations being misclassified as smooth pursuits or saccades. Subsequently, misclassification of fixations as smooth pursuits or saccades may have been possible. A higher sampling frequency would allow for better accuracy of fixations.

Another limitation of the gaze behavior analysis in the current study was that a free-head eye tracker was used rather than a head-fixed eye tracker that requires a chin rest. Calibration of the scene camera was noisier in the current study since any sudden movements of the head would affect the cameras. A free-head eye tracker was chosen because it would potentially be more representative of gaze behaviour strategies. The eye tracker was also beneficial because it showed real time information as to what the participants were viewing. Since participants were not in a chin rest, the gaze position of participants would variable since body and head movements could occur which required the use of the Arrington eye tracker. In future studies it would be beneficial to use an additional head tracker, to ensure optimum accuracy in measuring gaze behaviours with the free-head eye tracker.

4.6 Summary

The results of this study have shown that though SVA were similar between all groups, the DVA differed between athletes and the other groups. Even though the refractive error range of all participants and SVA were similar, the DVA performance of athletes were better than the other groups suggesting their performance was not due to physiological differences. The output measurement of task response time for each letter were similar between groups at 30°/s. The smooth pursuit gains were not statistically different yet there may be a trend towards significance because of the lower number of VGPs. The findings also showed no significant differences in gaze behaviours between any groups. Based on the overall findings, there may be some visual processing differences between athletes and the other groups since the input to the eyes and response output were similar, and more investigation is needed to understand the underlying cause of the difference in DVA between athletes, VGPs and controls.

Chapter 5. Conclusion

A number of studies have examined the importance of visual and perceptual abilities of athlete performance.[26,46,50,56,74] Abernethy (1986) suggested that the superior abilities of athletes were the result of their perceptual and decision-making strategies rather than physiological differences in visual functions.[74] The current research available would argue that sports performance was less likely due to visual skills and more likely due to improving cognitive abilities which may indicate a learned behaviour.[75]

Based on the current study, DVA was markedly different at 30°/s for both motion types yet smooth pursuit gains and gaze behaviour patterns revealed no significant differences. The question still remains as to whether the differences are due to changes in the oculomotor system or perhaps perceptual learning. Differences in DVA exist between athletes, VGPs, and controls, yet eye movements were similar between the groups, which suggests that other factors may influence visual performance.

The tumbling E test like other DVA tasks is still a laboratory experiment and not an actual representation of real-world situations. In real-world sports situations, other environmental factors such as ball trajectories or field positions come into play which may influence eye movements. While these findings might not have a direct conclusion as to how the visual and motor system influences performance, they are significant in understanding the importance of gaze behaviours on visual acuity performance.

5.1 Future Work

The highest velocity (30°/s) was analyzed since DVA between groups were significant. Future work would be to analyze gaze behaviours of the other speeds and compare it to speeds in the current literature. The accuracy of smooth pursuit eye movements and positional errors may play an important role in discriminating targets. Examining fixations accurately would require a higher sampling rate eye tracker but fixation stability has been a potential avenue for research. Perhaps a heat map analysis or analysis of eye movements in a certain region may indicate differences between novices and expert's distribution of fixations.

Bibliography

1. Erickson, G. B. *Sports Vision*. *Sports Vision* (Elsevier, 2007). doi:10.1016/B978-0-7506-7577-2.50004-6

2. Kohmura, Y., Aoki, K., Honda, K., Yoshigi, H. & Sakuraba, K. The relationship between dynamic visual acuity and saccadic eye movement. *Hum. Perform. Meas.* **5,** 23–30 (2008).

3. Laby, D., Davidson, J., Rosenbaum, L., Strasser, C., Mellman, M., Rosenbaum, A., & Kirschen, D. The Visual Function of Professional Baseball Players. *Am. J. Ophthalmol.* **122,** 476–485 (1996).

4. Elliott, D. B., Yang, K. C. H. & Whitaker, D. Visual acuity changes throughout adulthood in normal, healthy eyes: seeing beyond 6/6. *Optometry and vision science* **72,** 186–191 (1995).

5. Green, C. S. & Bavelier, D. Action-video-game experience alters the spatial resolution of vision: Research article. *Psychol. Sci.* **18,** 88–94 (2007).

6. Christenson, G. Visual skills of athletes vs nonathletes. 666–675 (1988).

7. Hoshina, K., Tagami, Y., Mimura, O., Edagawa, H., Matsubara, M., & Nakayama, T. A study of static, kinetic, and dynamic visual acuity in 102 Japanese professional baseball players. *Clin. Ophthalmol.* **7,** 627–632 (2013).

8. Ludvigh, E. & Miller, J. W. Study of visual acuity during the ocular pursuit of moving test objects. I. Introduction. *J. Opt. Soc. Am.* **48,** 799–802 (1958).

9. Ludvigh, E. & Miller, J. W. A study of dynamic visual acuity. *Usn Aviat. Med. Jt. Proj. Rep.* (1953).

10. Brown, B. Resolution thresholds for moving targets at the fovea and in the peripheral retina. *Vision Res.* **12,** 293–304 (1971).

11. Brown, B. Dynamic visual acuity, eye movements and peripheral acuity for moving targets. *Vision Res.* **12,** 305–321 (1972).

12. Rouse, M. W., DeLand, P., Christian, R. & Hawley, J. A comparison study of dynamic visual acuity between athletes and nonathletes. 946–950 (1988).

13. Long, G. M. & Riggs, C. A. Training effects on dynamic visual acuity with free-head viewing. *Perception* **20,** 363–371 (1991).

14. Ishigaki, Hisao. Miyao, M. Differences in dynamic visual acuity between athletes and nonathletes. *Percept. Mot. Skills* **77,** 835–839 (1993).

15. Vital, D., Hegemann, S.C.A., Straumann, D., Bergamin, O., Bockisch, C.J., Angehrn, D., Schmitt, K., & Probst, R. A new dynamic visual acuity test to assess peripheral vestibular function. *Arch. Otolaryngol. Head. Neck Surg.* **136,** 686–691 (2010).

16. Hirano, M., Hutchings, N., Simpson, T. & Dalton, K. Validity and Repeatability of a Novel. **94,** 616–625 (2017).

17. Burg, A. Visual acuity as measured by dynamic and static tests: a comparative evaluation. *J. Appl. Psychol.* **50,** 460–466 (1966).

18. *Committee on Vision of the National Research Council - Emergent Techniques for the*

Assessment of Visual Performance. (1985).

19. Winograd, S. The relationship of timing and vision to baseball performance. *Res. Q.* **13,** 481–493 (1942).

20. Latham, A. J., Patston, L. L. M. & Tippett, L. J. The virtual brain: 30 years of video-game play and cognitive abilities. *Front. Psychol.* **4,** 1–10 (2013).

21. Morris, G. S. Dynamic visual acuity of varsity women volleyball and basketball players. *Res. Quart.* **48**, 480-483 (1977).

22. Schneiders, A. G., John Sullivan, S., Rathbone, E.J., Louise T.A., Wallis, L.M., & Wilson, A.E.. Visual acuity in young elite motorsport athletes: A preliminary report. *Phys. Ther. Sport* **11,** 47–49 (2010).

23. Sanderson, F. . & Whitling, H. . Dynamic visual acuity and performance in a catching task. *J. Mot. Behav.* **6,** 87–94 (1974).

24. Uchida, Y., Kudoh, D., Murakami, A., Honda, M. & Kitazawa, S. Origins of Superior Dynamic Visual Acuity in Baseball Players: Superior Eye Movements or Superior Image Processing. *PLoS One* **7,** e31530 (2012).

25. Barmack, N. H. & Barmack, N. H. Dynamic visual acuity as an index of eye movement control. *Vision Res.* **10,** 1377–91 (1970).

26. Palidis, D. J., Wyder-Hodge, P. A., Fooken, J. & Spering, M. Distinct eye movement patterns enhance dynamic visual acuity. *PLoS One* **12,** 1–14 (2017).

27. Long, G. M. & Rourke, D. A. Training effects on the resolution of moving targets--

dynamic visual acuity. *Hum. Factors* **31,** 443–451 (1989).

28. Bahill, A. T. & Stark, L. The trajectories of saccadic eye movements. *Sci. Am.* **Jan,** 108–117 (1979).

29. Bahill, A. T. & Laritz, T. Why Can't Batters Keep Their Eyes on the Ball? *Am. Sci.* 249–253 (1984).

30. Komogortsev, O. V. & Karpov, A. Automated classification and scoring of smooth pursuit eye movements in the presence of fixations and saccades. *Behav. Res. Methods* **45,** 203–215 (2013).

31. Yarbus, A. L. Eye movements and vision. *Neuropsychologia* **6,** 222 (1967).

32. Martinez-conde, S., Macknik, S. L. & Hubel, D. H. The role of fixation eye movements in visual perception. **5,** (2004).

33. Babu, R. J., Lillakas, L. & Irving, E. L. Dynamics of saccadic adaptation: differences between athletes and nonathletes. *Optom. Vis. Sci.* **82,** 1060–1065 (2005).

34. Rashbass, C. The relationship between saccadic and smooth tracking eye movements. *J. Physiol.* 326–338 (1961).

35. Luebke, A. E. & Robinson, D. A. Transition dynamics between pursuit and fixation suggest different systems. *Vision Res.* **28,** 941–946 (1988).

36. Leigh, R. J. & Zee, D. S. *Neurology of eye movements*. (Oxford University Press 3rd edition, 1999).

37. Kowler, E. Eye movements : The past 25 years. **51,** 1457–1483 (2012).

38. Rashbass, C. Mechanisms of visual fixation. *Nature* **183,** 55–56 (1959).

39. Ciuffreda, K. J. & Tannen, B. *Eye movement basics for the clinician*. (Mosby, 1995).

40. Duchowski, A. *Eye tracking methodology: Theory and practice*. *Eye Tracking Methodology: Theory and Practice* (2007). doi:10.1007/978-1-84628-609-4

41. Orban de Xivry, J.-J. & Lefèvre, P. Saccades and pursuit: two outcomes of a single sensorimotor process. *J. Physiol.* **584,** 11–23 (2007).

42. Spering, M., Schütz, A. C., Braun, D. I. & Gegenfurtner, K. R. Keep your eyes on the ball: smooth pursuit eye movements enhance prediction of visual motion. *J. Neurophysiol.* **105,** 1756–1767 (2011).

43. Land, M. F. & McLeod, P. From eye movements to actions: how batsmen hit the ball. *Nat. Neurosci.* **3,** 1340–5 (2000).

44. Irving, E. L., Steinbach, M. J., Lillakas, L., Babu, R. J. & Hutchings, N. Horizontal saccade dynamics across the human life span. *Investig. Ophthalmol. Vis. Sci.* **47,** 2478–2484 (2006).

45. Bahill, A. T., Clark, M. R. & Stark, L. The main sequence, a tool for studying human eye movements. *Math. Biosci.* **24,** 191–204 (1975).

46. Ripoll, H., Bard, C. & Paillard, J. Stabilization of head and eyes on target as a factor in successful basketball shooting. *Hum. Mov. Sci.* **5,** 47–58 (1986).

47. McKinney, T., Chajka, K. & Hayhoe, M. Pro-active gaze control in squash [Abstract]. *J. Vision.* **8,** (2008).

48. Lenoir, M., Crevits, L., Goethals, M., Wildenbeest, J. & Musch, E. Are better eye movements an advantage in ball games? A study of prosaccadic and antisaccadic eye movements. *Percept. Mot. Skills* 546–552 (2000).

49. Mack, D. J. & Ilg, U. J. The effects of video game play on the characteristics of saccadic eye movements. *Vision Res.* **102,** 26–32 (2014).

50. Vickers, J. N. Visual control when aiming at a far target. *J. Exp. Psychol. Hum. Percept. Perform.* **22,** 342–54 (1996).

51. Vickers, J. N. Gaze control in putting. *Perception* **21,** 117–132 (1992).

52. Vickers, J. N. Perception, cognition, and decision training: The quiet eye in action. *Perception, cognition, and decision training: The quiet eye in action.* (2007).

53. Land, M. F. Eye movements and the control of actions in everyday life. *Prog. Retin. Eye Res.* **25,** 296–324 (2006).

54. Ripoll, H. & Fleurance, P. What does keeping one's eye on the ball mean? *Ergonomics* **31,** 1647–1654 (1988).

55. Williams, A. M., Ward, P., Knowles, J. M. & Smeeton, N. J. Anticipation skill in a real-world task: Measurement, training, and transfer in tennis. *J. Exp. Psychol. Appl.* **8,** 259–270 (2002).

56. Vickers, J. N. *Advances in coupling perception and action: the quiet eye as a bidirectional link between gaze, attention, and action*. *Progress in Brain Research* **174,** (Elsevier, 2009).

57. Posner, M. I. & Cohen, Y. Components of visual orienting. *Atten. Perform. Control Lang. Process.* 531–556 (1984). doi:10.1162/jocn.1991.3.4.335

58. Castel, A. D., Pratt, J. & Drummond, E. The effects of action video game experience on the time course of inhibition of return and the efficiency of visual search. *Acta Psychol. (Amst).* **119,** 217–230 (2005).

59. Bialystok, E. Effect of Bilingualism and Computer Video Game Experience on the Simon Task. **60,** 68–79 (2006).

60. Green, C. S., Pouget, A. & Bavelier, D. Improved probabilistic inference as a general learning mechanism with action video games. *Curr. Biol.* **20,** 1573–1579 (2010).

61. ViewPoint EyeTracker Software Users Guide. Scottsdale, Arizona: Arrington Research Ltd. 1–19 (2010).

62. Willms, A. & Dalton, K. Eye Tracker Software Document. *Technology* (2016).

63. Komogortsev, O. V., Gobert, D. V., Jayarathna, S., Koh, D. H. & Gowda, S. M. Standardization of automated analyses of oculomotor fixation and saccadic behaviors. *IEEE Trans. Biomed. Eng.* **57,** 2635–2645 (2010).

64. Faul, F., Erdfelder, E., Lang, A.-G. & Buchner, A. G*Power: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* **39,** 175–191 (2007).

65. Faul, F., Erdfelder, E., Buchner, A. & Lang, A.-G. Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behav. Res. Methods* **41,**

1149–1160 (2009).

66. Hitzeman, S. & Beckerman, S. What the literature says about sports vision. *Optometry Clinics* **3**, 145–169 (1993).

67. Coffey, B. & Reichow, A. Optometric evaluation of the elite athlete. *Probl Optom* **2,** (1990).

68. Jones-Jordan, L. A., Lynn M.G., Cotter, S.A., Kleinstein, R.N., Manny, R.E., Mutti, D.O., Daniel T.J., Sims, J.R., & Zadnik, K.. Visual activity before and after the onset of juvenile myopia. *Investig. Ophthalmol. Vis. Sci.* **52,** 1841–1850 (2011).

69. Saxena, R., Vashist, P., Tandon, R., Pandey, R.M., Bhardawaj, A., Menon, V., & Mani, K. Prevalence of Myopia and Its Risk Factors in Urban School Children in Delhi: The North India Myopia Study (NIM Study). *PLoS One* **10,** (2015).

70. Abernethy, B. & Wood, J. *An Assessment of the Effectiveness of Selected VIsual Training Programs in Enhancing Sports Performance*. (National Sports Research Centre, 1992).

71. Uchida, Y., Kudoh, D., Higuchi, T., Honda, M. & Kanosue, A. K. Dynamic visual acuity in baseball players is due to superior tracking abilities. *Med. Sci. Sports Exerc.* **45,** 319–325 (2013).

72. Kato, T. & Fukuda, T. Visual Search Strategies of Baseball Batters: Eye Movements During the Preparatory Phase of Batting. *Percept. Mot. Skills* **94,** 380–386 (2002).

73. Ilg, U. J. Slow eye movements. *Prog. Neurobiol.* **53,** 293–329 (1997).

74. Abernethy, B. Enhancing sports performance through clinical and experimental optometry. *Clin. Exp. Optom.* **69,** 189–196 (1986).

75. Quevedo-Junyent, L., Aznar-Casanova, J. A., Merindano-Encina, D., Cardona, G. & Solé-Fortó, J. Comparison of Dynamic Visual Acuity Between Water Polo Players and Sedentary Students. *Res. Q. Exerc. Sport* **82,** 37–41 (2011).

Appendix A - Pre-registered Study

Investigation of dynamic visual acuity in athletes, video game players, and controls.
Contributors: Alan Yee, Benjamin Thompson, Kristine Dalton

Study Information

1. Title
   1.1. Investigation of dynamic visual acuity task in athletes, video game players, and controls.

2. Authorship
   2.1 Alan Yee. Benjamin Thompson. Kristine Dalton.

3. Research Questions
   3.1. Do athletes and video game players (VGPs) have better dynamic visual acuity (DVA) than non-athlete/non-VGPs (control group) when the optotype moves randomly at 30 deg/sec?
   3.2. Do athletes and VGPs have better DVA than the control group when the optotype moves horizontally at 30 deg/sec?
   3.3. Do any DVA differences between groups depend on the motion type or speed of the optotype?
   3.4. Do athletes and VGPs have better smooth pursuit gains than controls at 30 deg/sec?
   3.5. Does performance on a smooth pursuit step-ramp task predict dynamic visual acuity?
   3.6. Do vision strategies (i.e. longer fixations, and smooth pursuits) differ between athletes, VGPs, and controls while performing the DVA task?
   3.7. Does vision strategy predict performance on DVA independent of smooth pursuit gain?

4. Hypotheses
   4.1. DVA is significantly better in athletes and VGPs when the optotype moves randomly at 30 deg/sec compared to the control group. Non-directional hypotheses.
   4.2. DVA is significantly better in athletes and VGPs when the optotype moves horizontally at 30 deg/sec compared to the control group. Non-directional hypotheses.

4.3. DVA differences between groups will be related to motion type and/or speed of the optotype. Non-directional hypotheses.
4.4. Athletes and VGPs smooth pursuit gains will be similar to controls at 30 deg/sec. Non-directional hypotheses.
4.5. Performance on a smooth pursuit step-ramp task will not predict DVA. Non-directional hypotheses.
4.6. The vision strategies that athletes and VGPs use include significantly longer fixations and smooth pursuits while performing the DVA task than the vision strategies used by controls. Slower average eye movement velocities per trial will demonstrate this. Non-directional hypotheses.
4.7. Differences in vision strategy predict differences in performance on DVA, independent of smooth pursuit gain. Non-directional hypotheses.

Sampling Plan

In this section we will ask you to describe how you plan to collect samples, as well as the number of samples you plan to collect and your rationale for this decision. Please keep in mind that the data described in this section should be the actual data used for analysis, so if you are using a subset of a larger dataset, please describe the subset that will actually be used in your study.

5. Existing data
   5.1. Registration prior to creation of data: As of the date of submission of this research plan for preregistration, the data have not yet been collected, created, or realized.

6. Explanation of existing data
   6.1. Pilot data has been collected as a way to test the study protocol. The study protocol is a walkthrough of the test procedures. The pilot data have not been analyzed.

7. Data collection procedures.
   7.1. Human subjects will be used in this study. The population will consist of young healthy adults (18-26 year old). The participants will either be athletes, VGPs or controls. The athlete group inclusion criteria: athletes must play a dynamic sport (such as hockey, soccer, baseball etc.) at a varsity level or equivalent. The participants need to have played the sport for a minimum of 5 years and been members of the varsity team or equivalent for more than 1 year

with a current participation of more than 6 hours per week. The VGPs inclusion criteria: VGPs must play video games a) at least 4 times a week for a minimum of 1 hour per day, and b) must have done so for the previous 6 months. The controls will be selected on the criteria that they are not athletes or VGPs. The control group inclusion criteria: controls participate in recreational sports less than 3 hours per week and play video games for less than 1 hour per month. The exclusion criteria for all participants (regardless of group) are 1) nil stereopsis or amblyopia, 2) significant refractive error 3) self-reported ocular health anomaly that could impact visual acuity.

7.2. Recruitment of individuals will be from the University of Waterloo Games Institute, the University of Waterloo Warrior Athletics program, and the University of Waterloo Optometry Program mailing lists (graduate and undergraduate), participant databases, posters accessible to the general public, and word of mouth. Participants will be compensated $20 ($10/hour) for the study. The study will commence data collection in July 2016 and project is expected to end August 2017.

8. Sample size

8.1. There are 3 groups in this study. The athlete group (n=20), video game players (n=20), controls (n=20). The total sample size of the study will be n=60.

9. Sample size rationale

9.1. A power analysis using G*Power helped to determine the sample size for each group. However, time constraint may play a factor if participant recruitment is slow. Based on data by Uchida et al., 2012 (Fig.1), the mean of group 1 (athletes) was 404 deg/sec, the mean of group 2 (non-athletes) was 315 deg/sec, the standard deviation of group 1 was 74, and the standard deviation of group 2 was 69 that lead to an effect size of 1.243. Two-tailed with an alpha value of 0.05 thus 0.95 power. This led to a sample size of 18 in each group. Thus, a sample size of 20 in each group will be used for this study, to protect against participant dropout. The rationale for choosing the Uchida et al., 2012 to power the experiment was that the study design of the paper is as similar as possible to the current proposed study design.

10. Stopping rule

10.1. Data collection will cease April 2017 even if recruitment targets have not been met.

Variables

In this section you can describe all variables (both manipulated and measured variables) that will later be used in your confirmatory analysis plan. In your analysis plan, you will have the opportunity to describe how each variable will be used. If you have variables that you are measuring for exploratory analyses, you are not required to list them, though you are permitted to do so.

11. Manipulated variables
    - 11.1. On the DVA task, the manipulated variables will be the motion type and the optotype speed.
    - 11.2. On the smooth pursuit step-ramp task, the manipulated variables will be the target speed and with, or without fixation.

12. Measured variables
    - 12.1. On the DVA task, the dependent variable measured will be DVA.
    - 12.2. On the step-ramp task, the dependent variable measured will be the smooth pursuit gains.
    - 12.3. On the vision strategy assessment, the dependent variable measured will be the average velocity of eye movements per trial.

13. Indices

Design Plan

In this section, you will be asked to describe the overall design of your study. Remember that this research plan is designed to register a single study, so if you have multiple experimental designs, please complete a separate preregistration.

14. Study type
    - 14.1. Experiment
        - 14.1.1. Participants are assigned to one of the three groups (athletes, VGPs, controls); DVA, smooth pursuits, and vision strategy will be measured for all participants in each group.

15. Blinding
    - 15.1. Personnel who interact directly with the study participants will be aware of which group they are assigned.

15.1.1. No blinding is involved in this study.

16. Study design

16.1. This study is a three-group independent measures design.

17. Randomization

17.1. Dynamic visual acuity parameters and smooth pursuit trials will be randomized for each participant. A random number generator will be used to create balanced random permutations for each task.

Analysis Plan

You may describe one or more confirmatory analysis in this preregistration. Please remember that all analyses specified below must be reported in the final article, and any additional analyses must be noted as exploratory or hypothesis generating.

A confirmatory analysis plan must state up front which variables are predictors (independent) and which are the outcomes (dependent), otherwise it is an exploratory analysis. You are allowed to describe any exploratory work here, but a clear confirmatory analysis is required.

18. Statistical models

18.1. Hypothesis 4.1 will be tested with a one-way independent measures ANOVA. The factor will be group (athletes, VGPs, or controls). A significant effect of group will be explored using independent samples t-tests.

18.2. Hypothesis 4.2 will be tested with a one-way independent measures ANOVA. The factor will be group (athletes, VGPs, or controls). A significant effect of group will be explored using independent samples t-tests.

18.3. Hypothesis 4.3 will be tested with a mixed ANOVA with factors of group (independent measures: athletes, VGPs, controls), motion type (repeated measure: random, horizontal), and speed (repeated measures: 5, 10, 20, 30 deg/sec). Significant interactions will be followed up with a two-way ANOVA analyses and/or t-tests.

18.4. Hypothesis 4.4 will be tested with a one-way independent measures ANOVA. The factor will be group (athletes, VGPs, or controls). A significant effect of group will be explored using independent samples t-tests.

18.5. Hypothesis 4.6 will be tested with a regression analysis using DVA as a dependent variable; predictor variables will be group (categorically coded), smooth pursuit gain and their interaction. Regression analyses will be run independently for each task speed.

18.6. Hypothesis 4.7 will be tested with a one-way independent measures ANOVA. The factor will be group (athletes, VGPs, or controls). A significant effect of group will be explored using independent samples t-tests.

18.7. Hypothesis 4.8 will be tested with a regression analysis using average eye movement velocity as a dependent variable; predictor variables will be group (categorically coded), DVA, smooth pursuit gain and their interaction. Regression analyses will be run independently for each DVA motion type.

19. Transformations

20. Follow-up analyses

21. Inference criteria

21.1. The p-values used will be 0.05 and two tailed tests. This applies to all hypothesis tested.

22. Data exclusion

22.1. Eye movement data will be excluded if recordings are of poor quality, if there is equipment failure, or if there is non-compliance with study protocols.

22.2. Primary analysis will be conducted including all samples. A sensitivity analysis will be conducted with outliers excluded to assess the impact of outliers on the primary analysis.

23. Missing data

23.1. All available data will be included in the analysis.

24. Exploratory analysis (optional)

Script (Optional)

The purpose of a fully commented analysis script is to unambiguously provide the responses to all of the questions raised in the analysis section. This step is not common, but we encourage you to try to create an analysis script, refine it using a modeled dataset, and use it in place of your written analysis plan.

25. Analysis scripts (Optional)

Other

26. A planned sample size using G*Power has been attached (Figure 1). The planned sample size for each group is 20.

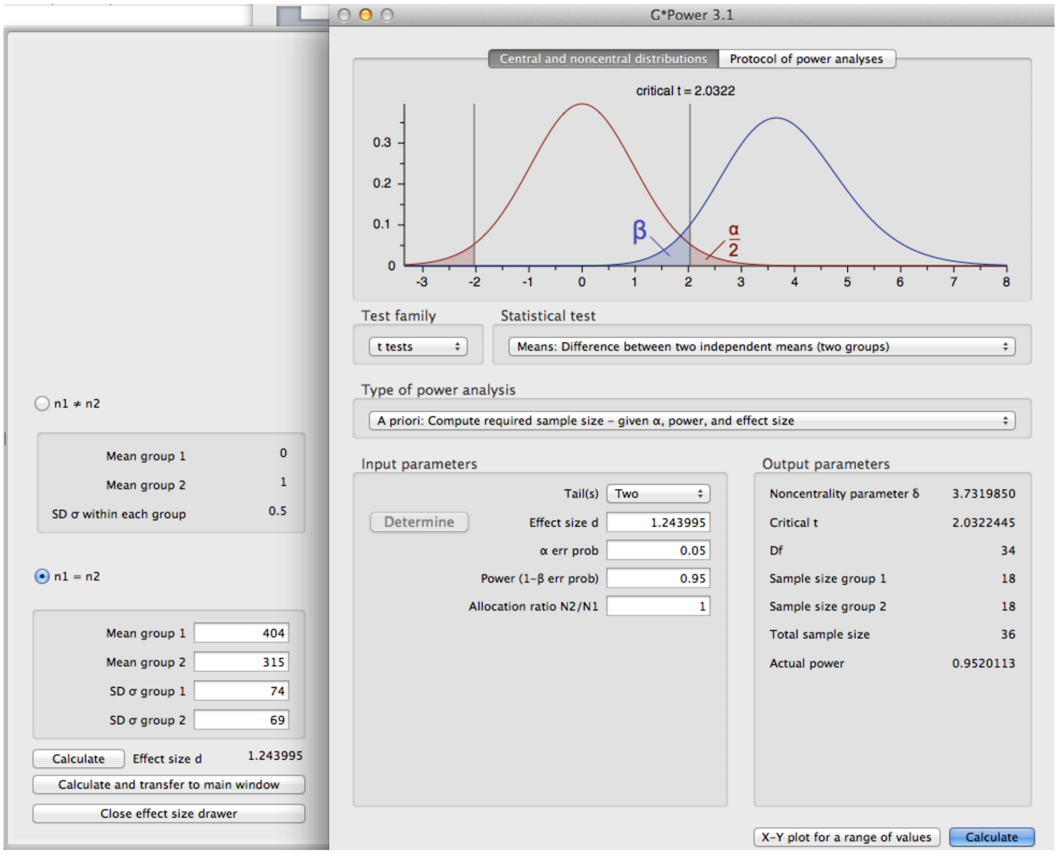


Figure 1: Power analysis from Uchida et al., 2012 paper.

References:

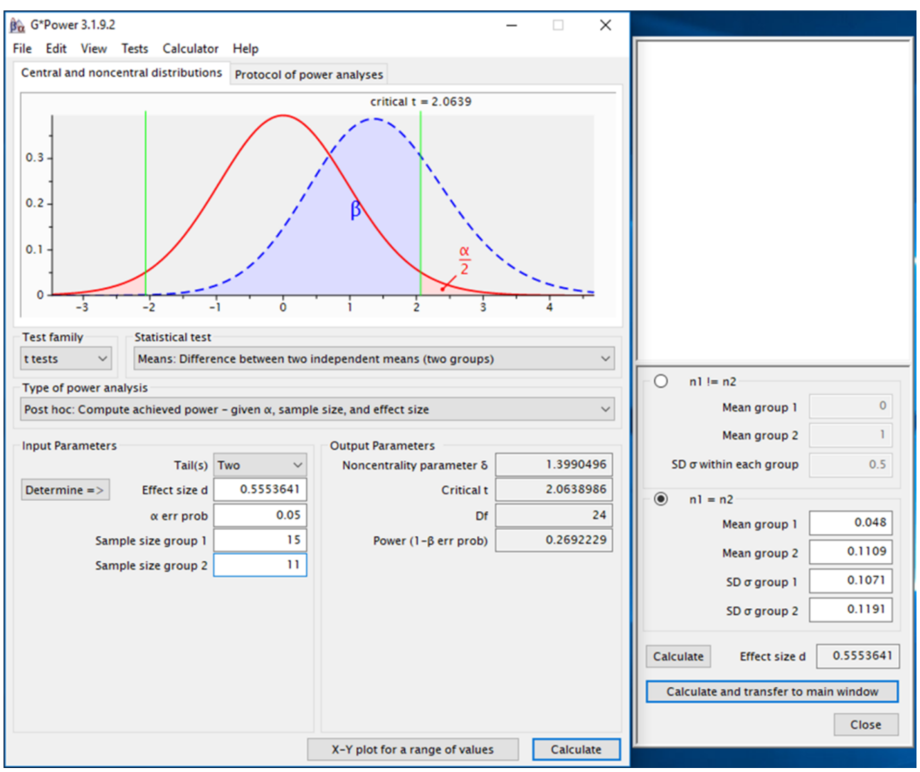
Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods,39*, 175-191.

Uchida, Y., Kudoh, D., Murakami, A., Honda, M., & Kitazawa, S. (2012). Origins of Superior Dynamic Visual Acuity in Baseball Players: Superior Eye Movements or Superior Image Processing. *PLoS ONE*, *7*(2), e31530.

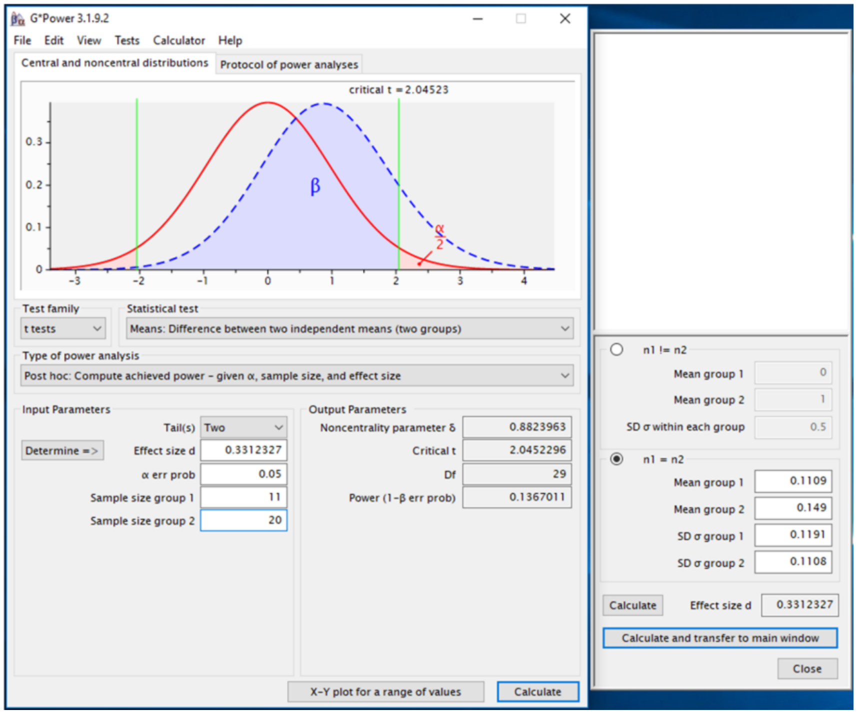
Appendix B - Post-hoc Analysis

Post-hoc analysis of dynamic visual acuity for random motion 30°/s (Figure 5.1Figure 5.1 Post-hoc analysis of DVA for random 30°/s. A. Athletes and VGPs. B.) and horizontal motion 30°/s (Figure 5.2) are presented since the intended sample size criteria were not met. Post-hoc analysis of random 30°/s between athletes and controls revealed a power of 0.749 (Figure 5.1C). The power between athletes and VGPs were 0.269 and VGPs and controls were 0.136. The post-hoc analysis of horizontal 30°/s between athletes and VGPs had a power of 0.770 (Figure 5.2A). The power between athletes and controls were 0.570 and VGPs and controls were 0.136. The means and standard deviation used in the calculation were DVA scores for the respective speeds.

A.



B.



C.

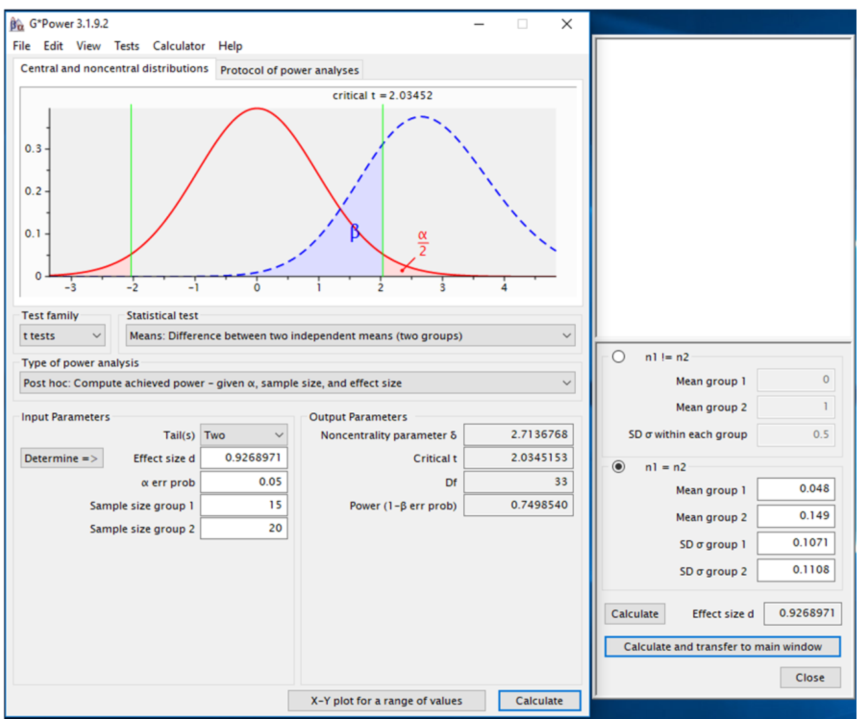
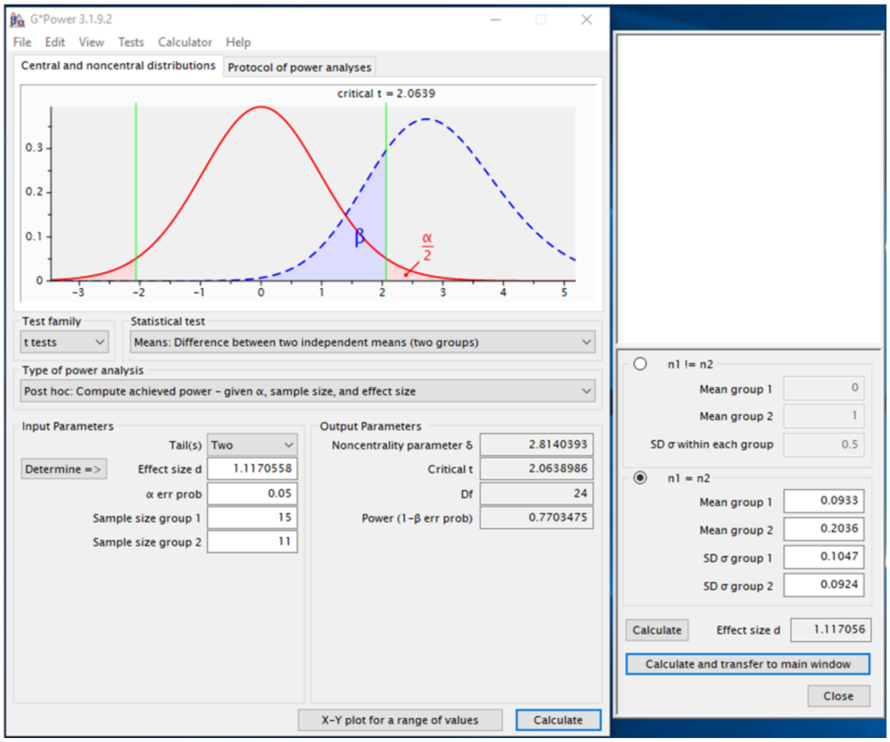
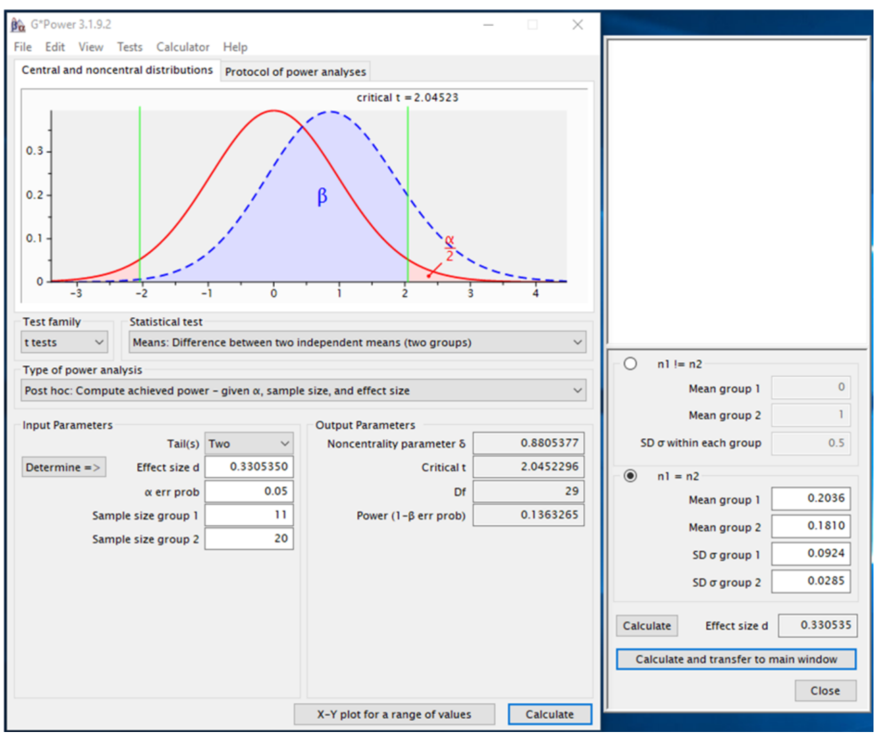


Figure 5.1 Post-hoc analysis of DVA for random 30°/s. A. Athletes and VGPs. B. VGPs and controls. C. Athletes and controls

A.


G*Power 3.1.9.2
File Edit View Tests Calculator Help
Central and noncentral distributions
Protocol of power analyses
critical t = 2.0639
0.3
0.2
0.1
0
-3
-2
-1
0
1
2
3
4
5
β
α/2
Test family
t tests
Statistical test
Means: Difference between two independent means (two groups)
Type of power analysis
Post hoc: Compute achieved power – given α, sample size, and effect size
Input Parameters
Tail(s) Two
Determine =>
Effect size d 1.1170558
α err prob 0.05
Sample size group 1 15
Sample size group 2 11
Output Parameters
Noncentrality parameter δ 2.8140393
Critical t 2.0638986
Df 24
Power (1-β err prob) 0.7703475
X-Y plot for a range of values
Calculate
n1 != n2
Mean group 1 0
Mean group 2 1
SD σ within each group 0.5
n1 = n2
Mean group 1 0.0933
Mean group 2 0.2036
SD σ group 1 0.1047
SD σ group 2 0.0924
Calculate
Effect size d 1.117056
Calculate and transfer to main window
Close

B.


G*Power 3.1.9.2
File Edit View Tests Calculator Help
Central and noncentral distributions
Protocol of power analyses
critical t = 2.04523
0.3
0.2
0.1
0
-3
-2
-1
0
1
2
3
4
β
α/2
Test family
t tests
Statistical test
Means: Difference between two independent means (two groups)
Type of power analysis
Post hoc: Compute achieved power – given α, sample size, and effect size
Input Parameters
Tail(s) Two
Determine =>
Effect size d 0.3305350
α err prob 0.05
Sample size group 1 11
Sample size group 2 20
Output Parameters
Noncentrality parameter δ 0.8805377
Critical t 2.0452296
Df 29
Power (1-β err prob) 0.1363265
X-Y plot for a range of values
Calculate
n1 != n2
Mean group 1 0
Mean group 2 1
SD σ within each group 0.5
n1 = n2
Mean group 1 0.2036
Mean group 2 0.1810
SD σ group 1 0.0924
SD σ group 2 0.0285
Calculate
Effect size d 0.330535
Calculate and transfer to main window
Close

C.

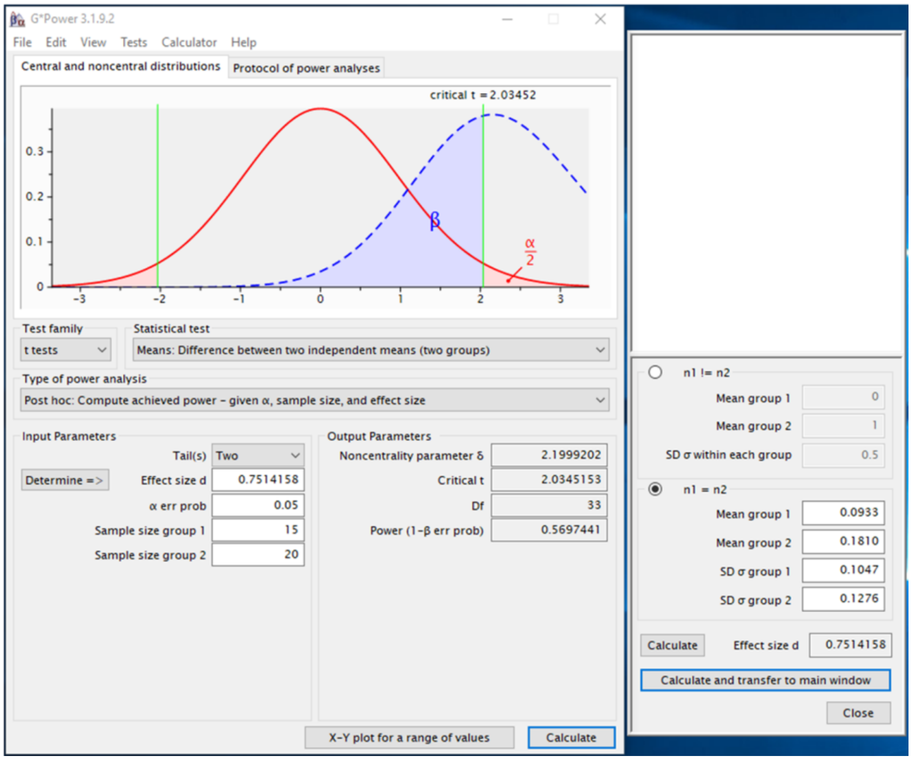


Figure 5.2 Post-hoc analysis of horizontal 30°/s. A. Athletes and VGPs. B. VGPs and controls. C. Athletes and controls