DYNAMIC COMPONENTS OF HORIZONTAL AND VERTICAL SACCADIES DURING VISUAL SEARCH TASKS

Submitted by
Robert Chapman
BA BAppSc(Hon)

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Faculty of Life and Social Sciences
Swinburne University of Technology
Hawthorn, Victoria 3122
Australia

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Abstract

Dynamic components of saccadic eye movements were investigated following visual search in a multi-saccade paradigm. Previous research by Morgan (1999) identified faster, longer and more frequent saccades were indicative of successful performance in normal participants and that there was no perceptual disadvantage to performing saccades during the task as one might expect due to saccadic suppression. Additionally, elite players from visually demanding sports such as football, netball and soccer generally produced faster, longer and more frequent saccades than non-elite players from the same sports as well as elite athletes from non-visually demanding sports such as swimming and cycling. A group of experiments were conducted which replicated and extended Morgan’s findings and addressed a number of key methodological issues. A non-sport specific visual search strategy task (VSST) was employed which involved looking for target letters amongst distracters on a display board subtending 56° of visual angle at six limited exposure times. Saccadic eye movements were recorded by electrooculography (EOG) during the VSST. A conservative saccade detection algorithm was employed involving velocity, amplitude and duration thresholds. The limitations of this algorithm identified that small underestimates of saccade amplitude, duration and rate were apparent. The experiments were conducted in a dimly lit environment that produced a high degree of contrast between the target display luminance and the ambient illuminance level. This light level was chosen because it produced the least variation in signal amplitude over the recording period and specifically addressed concerns that amplitude variation is often greatest when participants are pre-adapted to a bright environment and are then recorded in a dark environment. Thirty-three normal participants performed the VSST in both the horizontal and vertical domain. Horizontal and vertical saccades were predominantly calibrated using a linear regression trendline however, some calibrations were improved using non-linear trendlines. Eyelid artefact was removed objectively by differentiating it from saccades using a novel method involving the low velocity periods of eye movements. From the data collected, horizontal VSST results were similar to Morgan (1999) in some variables and dissimilar in others. Higher saccade rate and greater combined amplitude and velocity were characteristics associated with successful responses at 650, 800 and 1000 ms exposure times. Saccade latency was only significant at 1000 ms exposure time with correct trials having a shorter latency as
expected. The saccadic search behaviour for correct and incorrect responses during vertical VSST trials was completely unrelated to horizontal VSST trials at all exposure times. The only observable trend was that correct trials had a higher saccade rate than incorrect trials, but this was only significant to the 0.05 level for the 350 and 800 ms exposure times. One possible explanation for why the same trends were not observed may be that humans scan horizontally more than vertically during everyday tasks such as reading and this trained ability has lead to a more efficient visual search strategy. The same VSST was also performed by seven elite Australian Rules footballers and eleven non-elite footballers. Elite footballers did not exhibit any differences in dynamic components of horizontal saccades from non-elite footballers, challenging Morgan’s (1999) prior research. Remarkably, elite footballers generated smaller and slower vertical saccades at almost all stimulus exposure times. There were two major findings relating to the acquisition of visual information during visual search tasks. Firstly, at no point in time did the generation of saccades display any perceptual disadvantage during any VSST. Secondly, elite and non-elite footballers surprisingly did not reveal any horizontal search strategy differences. However, elite footballers made smaller and slower saccades on the more demanding vertical VSST, but this was not at any perceptual disadvantage.
Acknowledgements

The completion of this thesis has involved contributions and a great deal of support from many people. All have assisted in keeping me on track until final submission.

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I would also like to thank Dr. Stuart Morgan who wrote his thesis (Morgan, 1999), and the preliminary work, on which my own thesis was based. The use of his experimental equipment and software were invaluable for the replication of his results.

Next, I would like to thank the members of the Sensory Neuroscience Laboratory who provided a springboard for my many experimental problems and hypothesising. A notable mention here must go to Martin Dubaj whom I pestered many times throughout my studies. His help provided much needed mathematical and electronic expertise, as well as essential software debugging tuition.

Although my university colleagues helped contribute directly to my thesis, it was the indirect support from family and friends to whom can be equally credited with keeping me committed. Special thanks must go to my wife Sarah, and my parents Ron and Kathleen Chapman for their unwavering support. Without their continual encouragement, I would not now be submitting this thesis.

Lastly, I would like to thank the volunteers who gave up there time willingly to participate in these studies. The Hawthorn Football Club should in particular be acknowledged for allowing access to some of their AFL players, given their highly demanding training schedules. However, all volunteers must be equally thanked for their participation and the interest they showed during testing because it was often the driving force of my own motivation to finally submit.
Dedication

Over the course of writing this thesis, I experienced many high and lows. Many of these experiences have been life altering, affecting me socially and emotionally just as much as the studying helped me professionally. These experiences have also given me direction.

I would like to dedicate this thesis to two people who would have appreciated the scientific endeavour that went into its completion, but were unable to see its final submission. One a grandfather and researcher, the other a best mate.

Patrick O’Loughlin  
20 November 1913 - 12 August 2002

Gerard Hurley  
31 December 1977 - 5 September 2003

May they both rest in peace.
Statement of Authorship

“I declare that this report does not incorporate without acknowledgment any material previously submitted for a degree in any University, College or Advanced Education, or other educational institution; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person where due reference is made in the text.

I further declare that the ethical principles and procedures specified in the Psychology Discipline’s document on human research and experimentation have been adhered to in the preparation of this thesis.”

Robert Chapman
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<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>AFL</td>
<td>Australian Football League</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
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<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DVA</td>
<td>Dynamic Visual Acuity</td>
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<td>EEG</td>
<td>Electroencephalograph</td>
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<tr>
<td>EOG</td>
<td>Electro-Oculogram</td>
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<tr>
<td>ISI</td>
<td>Inter-saccadic intervals</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
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<tr>
<td>ISCEV</td>
<td>International Society for Clinical Electrophysiology of Vision</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LGN</td>
<td>Lateral Geniculate Nuclei</td>
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<tr>
<td>LogMAR</td>
<td>Logarithm of the minimum angle of resolution</td>
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<tr>
<td>OKN</td>
<td>Optokinetic Nystagmus</td>
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<tr>
<td>RMS</td>
<td>Root Mean Squares</td>
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<td>VSST</td>
<td>Visual Search Strategy Task</td>
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Chapter 1   A Review of Saccadic Eye Movement Literature

The following chapter provides an overview of the visual system and the visual pathways. The chapter then introduces the oculomotor system and various types of ocular movements. Special emphasis is placed on saccadic eye movements and the various detection technologies capable of recording these movements. Visual search strategies of the general population are then reviewed as well as the more specific visual search behaviour of sports-related expert-novice studies. In many cases, special reference is made to the findings of Morgan (1999), which this thesis attempts to replicate and extend.

1.1 Neurophysiology of the Ocular Motor System

We rely on vision more than any other sense in the body (Martini, 2004). The visual receptors contained within the eye not only detect light but also allow us to create detailed images of our environment.

1.1.1 Anatomy and Physiology of the Eye

The human eye is approximately 24 mm in diameter and set in a protective cone-shaped socket along with extrinsic eye muscles and cranial nerves (Martini, 2004). The wall of the eye contains three distinct layers: an outer layer, intermediate layer and inner layer.

The outer layer of the eye primarily consists of elastic connective tissue called the sclera, which is identified by the white portions of the eye. The outer layer also comprises the transparent cornea, which allows light to enter the eye. The cornea provides 2/3 of the eye’s refractive power. The border between the cornea and sclera is known as the limbus.

The intermediate layer of the eye contains two portions: the anterior portion containing the iris and ciliary body, and the posterior portion containing the choroid. The iris can be seen through the transparent cornea, recognised by its pigmented membrane, as the coloured part of the eye. At the centre of the iris is the round opening called the pupil. The pupil appears black because cells at the back of the retina in the pigment epithelium are packed with the black pigment melanin, which absorbs light to prevent reflection.
back to the retina (Tessier-Lavigne, 1991). The size of the pupil can change via constrictor or dilator muscles to regulate the amount of light that enters the eye. The ciliary body, also part of the intermediate layer, encircles the iris and is connected by ligaments to the crystalline lens. The muscles of the ciliary body hold the lens in place and either relaxes to flatten the lens or contracts to make the lens more rounded for focusing images onto the retina. This process is called accommodation (Martini, 2004). The choroid is the largest portion of the intermediate layer primarily supplying oxygen and nutrients to the retina.

The innermost layer of the eye contains the photoreceptive cells of the retina. These photoreceptive cells, called rods and cones, convert light into electrical and chemical signals. The rods number approximately 125 million throughout the periphery of the retina and are light sensitive but do not discriminate colour. Cones on the other hand provide us with colour vision but require more intense light than rods. Cones are heavily concentrated at an area called the macula lutea numbering around 6 million. Rods are not found in this area. The fovea is the central portion of the macula lutea and is the site of sharpest vision. When focusing on an object, the image falls on this part of the retina (Martini, 2004).

The visual process begins by allowing light to pass through the clear cornea at the front of the eyeball and pass through to the retina at the back of the eye. This is illustrated in Figure 1.1.1.

![Figure 1.1.1: Anatomical sites of the eye.](image)

The transverse section of the right eye shows light entering the eye at the cornea and passing through the lens to strike photoreceptors at the fovea. The three layers of the eyeball can be seen; the cornea and sclera comprising the outermost layer, the choroid and lens the middle layer, and the retina as the innermost layer (extracted from Tessier-Lavigne, 1991, p.401).
1.1.2 Visual Neurophysiology

Following stimulation of the photoreceptors, the signal is transmitted through approximately 6 million bipolar cells and converges further to 1 million ganglion cells. The ganglion cells that monitor rods are called magno cells (Martini, 2004). As many as one thousand rods may pass information to a single magno cell. Magno cells provide information on shape, motion and shadows during dim light (Tessier-Lavigne, 1991; Fitzgerald, 1992; Martini, 2004). Activation of magno cells indicate light has been received in a general area rather than a specific location due to the considerable convergence. The ganglion cells that monitor cones are called parvo cells and undergo little or no convergence (Martini, 2004). The fovea contains an almost 1:1 ratio of cones to parvo cells. Parvo cells are active in bright light and provide information on fine detail and colour (Tessier-Lavigne, 1991; Fitzgerald, 1992; Martini, 2004).

The optic disc is a circular region just lateral to the fovea at the back of the eyeball (Martini, 2004). The axons of the retinal ganglion cells converge on the optic disc to form the optic nerve (Fitzgerald, 1992). The optic nerve of both eyes travels about 5 cm to converge at the optic chiasm where the fibres from the nasal half of each retina cross to the opposite side of the brain (Howard & Rogers, 1995; Martini, 2004). These reorganised retinal axons form the optic tract that terminates at the lateral geniculate nuclei (LGN) of the thalamus displayed in Figure 1.1.2 (Tessier-Lavigne, 1991).

![Figure 1.1.2: The visual pathway. The retinal fibres of the eye form the optic nerve. The optic nerve converges at the optic chiasm where fibres are reorganised before terminating in the thalamus. Fibres then project to the visual cortex of the occipital lobe (extracted from Martini, 2004, p.495).](image-url)
The LGN process and relay visual information to the visual cortex as well as reflex centres of the brain stem (Martini, 2004). The LGN have six layers of cell bodies. The two most ventral layers of the LGN are responsible for magno cells and the four dorsal layers for parvo cells (Mason & Kandel, 1991; Fitzgerald, 1992). The superior colliculus in the brain stem issues motor commands controlling involuntary, reflexive eye movements (Martini, 2004; Fitzgerald, 1992). Conversely, voluntary saccades are initiated in the frontal eye fields directly in front of the pre-motor cortex (Fitzgerald, 1992).

1.2 Ocular Motor System

The Ocular Motor System controls the position of the eyes (Goldberg, Eggers & Gouras, 1991). Each eye has six extrinsic muscles attached to the sclera, which are responsible for five types of ocular movements. The five ocular movements are responsible for two major functions: (1) bringing targets onto the fovea and (2) keeping them there (Goldberg et al., 1991).

1.2.1 Types of Eye Movement

The five ocular movements can be classified by whether the movements are disjunctive (eyes rotate in opposite direction) or conjugate (eyes rotate in the same direction). Alternatively, they can be functionally classified by whether the movements stabilise the eye when the head moves, or whether the movements keep the fovea on the visual target. However, the basic role of eye movements is still the same; they are an attempt to orient stimuli of interest onto the fovea for closer examination (Cohen, 1981).

1.2.1i Vestibulo-ocular Reflex

This type of eye movement uses vestibular input to hold images stable during rapid head rotation (Goldberg et al., 1991). It is a conjugate movement that stabilises the eye when the head moves and occurs even in complete darkness when there are no visual cues. During head movements, the semicircular canals within the inner ear are stimulated signalling how fast the head is rotating (Stern, Ray & Quigley, 2001). The oculomotor system responds to this by rotating the eyes in the opposite direction at an equal velocity to the head rotation (Goldberg et al., 1991). This stabilises the eyes relative to the
external world and keeps visual images fixed on the retina allowing us to see clearly even when moving (Goldberg et al., 1991).

During sustained rotation, the eyes do not rotate to the end of the eye socket and remain there as the head moves in the opposite direction. Instead, as the eyes approach the edge of the sockets, they rapidly reverse direction moving back across the centre of gaze. This rapid reversal is known as the quick phase (Goldberg et al., 1991). A typical example of a vestibulo-ocular reflex (VOR) recording is displayed in Figure 1.2.1.i.

![Figure 1.2.1i: The vestibulo-ocular reflex. An example of a human participant’s horizontal eye position as they were rotated rightward in total darkness (extracted from Goldberg, Eggers & Gouras, 1991, p.662). The quick phase is the rightward (upward deflection) eye movement followed by a slower drift leftwards (downward deflection).]

### 1.2.1ii Optokinetic Nystagmus

Optokinetic nystagmus (OKN) uses visual input to hold images stable during sustained or slow head rotation (Leigh & Zee, 2006). OKN is a conjugate movement that stabilises the eye when the head moves. The eyes fixate on an object that continuously moves past the observer (Stern et al., 2001). Figure 1.2.1.ii illustrates the type of eye movement recorded during OKN.

![Figure 1.2.1ii: The optokinetic reflex. An example of a human participant’s horizontal eye position as they sit still inside a vertically striped drum rotating slowly to his right (extracted from Goldberg, Eggers & Gouras, 1991, p.662).]
1.2.iii Smooth Pursuit Movements

Smooth pursuit eye movements are slow, conjugate movements that hold an image of a moving target on the fovea (Goldberg et al., 1991). Smooth pursuit eye movements are involuntary movements because they are induced by a moving object in the visual field (Stern et al., 2001) and it is the target which defines the speed of the eye movement. Smooth pursuit is voluntary in a sense that the observer chooses whether to follow the moving target and can cease pursuit of that target at any time. Smooth pursuit can be continuously modified if the moving target alters its trajectory or velocity (Barmack, 1970).

1.2.iv Saccades

Saccades are quick, conjugate jumps from one fixation point to another (Stern et al., 2001). Saccades bring new objects of interest from the periphery onto the fovea (Goldberg et al., 1991). Saccades can be differentiated by the nature of the task and the degree of conscious control we have over their occurrence i.e. whether they are goal directed or whether they are reorienting (Becker, 1989). Goal directed saccades are voluntary and attempt to position the fovea onto a specific point in our visual field. They include; (a) refixation saccades which often alternate gaze between two permanently visible fixation points (b) scanning saccades which explore the visual environment to objects of interest (c) tracking or reaction saccades which are evoked by the sudden change of a stimulus and instructions to follow it to the new position, and (d) catch-up saccades occur when the smooth pursuit system fails to retain the object of interest on the fovea due to the speed of the object (Becker, 1989). Conversely, reorienting saccades are involuntary and are often accompanied by a head movement to bring invisible parts of the world into the central visual field. These are the quick phases of the VOR and OKN (Becker, 1989).

1.2.iv Vergence Movements

Vergence movements are the mechanism by which binocular fixation is maintained (Stern et al., 2001). They are disjunctive eye movements that adjust the eyes for images of different viewing depths allowing the observer to fixate on targets nearer or farther away (Goldberg et al., 1991; Stern et al., 2001). Voluntary attentional factors can adjust vergence movements by influencing which components of our visual scene are selected.
to provide the stimulus for depth (Leigh & Zee, 2006). However, vergence movements are generally performed without our being aware of them (Leigh & Zee, 2006).

1.2.2 Extrinsic Muscles of the Eye

Six extrinsic eye muscles originate outside the eyeball and insert onto the sclera (see Figure 1.2.2). The extrinsic eyes muscles are controlled by the third (oculomotor), fourth (trochlear) and sixth (abducens) cranial nerves (Martini, 2004; Stern et al., 2001; Leigh & Zee, 2006). The six muscles work in antagonistic pairs causing the eye to move horizontally, vertically and torsionally. The pairs are the lateral rectus and medial rectus, the superior rectus and inferior rectus, and the superior oblique and inferior oblique.

![Figure 1.2.2: Extrinsic muscles of the eyeball.](image)

The superior rectus muscle is responsible for rolling the eyeball upwards and the inferior rectus muscle responsible for rolling the eyeball downwards. The lateral rectus rolls the eyeball laterally (away from the nose), while the medial rectus rolls the eyeball medially (towards the nose). The oblique muscles are primarily responsible for rotating the eyeball on its axis but also act as synergists for abduction as well as vertical antagonists (Roth & Speeg-Schatz, 2001; Martini, 2004). Through binocular coordination, the muscles of both eyes work together to scan the visual field for objects of interest.
1.2.3 Human Visual Field Limits

The human visual field is often separated into two regions; the central visual field and peripheral visual field. The central visual field is the portion of the visual field within the 30° radius of fixation and our peripheral visual field is everything outside of this (Harrington, 1976). When we fixate on an object, it falls upon the fovea, the 2-3° region of the central visual field where the most detailed processing of our visual field takes place (Cohen, 1981). Due to the small region of high visual acuity, our peripheral vision becomes very important especially in sport. Information in our periphery is processed quickly to facilitate detection of movement and redirect focus to other events. Awareness of motion to the side or above allows the eyes and the athlete to react to more game specific situations (Knudson & Kluka, 1997).

The extreme limit of the human visual field is restricted anatomically by the nose, brows and cheekbones. In terms of the horizontal visual field, each eye is capable of detecting light up to 95-110° laterally and only 56-60° medially due to the nose (Harrington, 1976; Howard & Rogers, 1995). The extreme limit of the horizontal visual field extends between 200° (Harrington, 1976; Cohen, 1981; Goldberg et al., 1991) and 208° (Hartridge, 1919). The overlapping region of the visual field detected by both eyes simultaneously is known as the binocular visual field and extends horizontally 114-120° (Harrington, 1976; Howard & Rogers, 1995). The vertical visual field of both eyes is restricted downwards by the cheekbone and upwards by the brow. In terms of visual angle it covers 50-60° upwards and 70-75° downwards depending on how prominent the cheekbone and brow are (Howard & Rogers, 1995; Harrington, 1976). Therefore, the total vertical visual field is in the range of 120-135° (Harrington, 1976; Cohen, 1981).

1.3 Eye Movement Registration Techniques

Eye movement registration techniques provide information regarding foveal orientation (Williams & Davids, 1998). There are many techniques capable of accurately recording eye movements during visual field scanning of which there is no overall optimum method. Depending on the nature of the tests and the environment being tested in, some
techniques are arguably better than other are. The following are just some of the more tried and proven methods developed and improved over the past 50 years.

1.3.1 Magnetic Scleral Coil Technique

The scleral coil technique, designed by Robinson (1963) and modified by Collewijn, Van der Mark and Jansen (1975), is arguably the gold standard for measuring both eye and eyelid movements in the horizontal and vertical field. It involves placing detection coils made up of fine wires embedded in soft plastic contact lens annulus and placed on the participant’s eye after local anaesthetic had been topically applied (Chioran & Yee, 1991). The participant’s head then sits inside pairs of horizontal and vertical induction coils to create an alternating current (AC) magnetic field. The linear range of the system is $\pm 20^\circ$ both horizontally and vertically (Collewijn et al., 1975; Chioran & Yee, 1991). It has an extremely high spatial resolution better than 1 minute of arc (Collewijn et al., 1975) and the sampling speed has improved considerably over time from 200 samples per second (Chioran & Yee, 1991) to 500 samples per second (van der Geest & Frens, 2002).

Although potentially the most accurate system in terms of eye movement recordings, the disadvantages are that the system is expensive, requires more cooperation from the participant, the participant generally experiences some discomfort from its application and the system is extremely bulky due to having to sit within a magnetic field (Yee, Schiller, Lim, Baloh, Baloh & Honrubia, 1985).

1.3.2 Electrooculogram

The electrooculogram (EOG) records the potential difference between the front and back of the eyeball by electrodes applied externally around the eye. The potential difference, or corneo-retinal potential as it is more commonly known, is based on the principle that the cornea always remains 0.4 to 1.0 mV positive with respect to the retina (Stern et al., 2001). As the eyeball rotates, the positive charge of the cornea will move towards a surface electrode, and a shift in direct current (DC) output is recorded.

To record horizontal eye movements, electrodes are placed at the outer canthus of either eye (see Figure 1.3.2). As the eyeball rotates left or right, the electrode potential
becomes more positive or negative. This is recorded as an upwards or downwards deflection. Similar deflections are recorded when electrodes are placed above and below a single eye to detect vertical eye movements.

EOG can record eye movements up to $\pm 70^\circ$ (Stern et al., 2001) although $5^\circ$ is the suggested lower limit to perform accurate analysis of saccades (Inchingolo & Spanio, 1985). The major concern with EOG is the slow drift of the baseline observed over time. Modern amplifiers and electrodes reduce this problem considerably (Stern et al., 2001). A second concern is movement of the head. The head can alter the direction of gaze without the need for a change in eye position. If there is no change in eye position, there will not be a change in signal. This concern is overcome by using a bite board or chin rest to ensure the head remains stable. A third concern is the detection of muscle artefact, especially during vertical EOG (Chioran & Yee, 1991). Other factors also influence the EOG signal and these include light adaptation, diurnal variation, alertness and gender (Stern et al., 2001).

### 1.3.3 Corneal Reflection and Purkinje Image Tracker

Both corneal reflection and Purkinje image detection methods are based on the principle of reflecting light off the eyeball. In corneal reflection, the surface of the cornea acts as
a convex mirror reflecting light as a bright white dot. Eye position determines the location of the reflected white dot. In Purkinje imaging, light is reflected from both the front surface of the cornea and the rear surface of the crystalline lens. In both cases, the reflected light is imaged onto film, camera or a photosensitive cell (Stern et al., 2001). For images recorded onto film or camera, the spatial resolution is high but the trade-off is low temporal resolution of between 100 Hz (Barnes et al., 1997) and 250 Hz (Accardo et al., 1995). However, even with high spatial resolution, the linear relationship is restricted to the range of ±20º horizontally (Accardo, Pensiero, Da Pozzo & Perissutti, 1995; Barnes, Grealy & Collins, 1997). Additionally, as with EOG, the disadvantage of these techniques is that the head is required to be stable, or that head position be calculated for each measurement to ensure accuracy.

1.3.4 Infrared Oculography

Infrared (IR) oculography involves the emission of IR light from a fixed source aimed at the eye and eyelid and generally mounted on spectacle frames (Tucker & Johns, 2005; Schmidt, Abel, Dell’Osso & Daroff, 1979). The amount of IR light reflected back to the sensor determines the eyes position. A phototransistor detects the reflected IR light with temporal resolution as high as 1090 Hz (Garbutt, Harwood & Harris, 2001) and linear range of ±20º (Schmidt et al., 1979; Abel, Troost & Dell’Osso, 1983). The use of IR light is practical as it is invisible to the eye. Unfortunately, other sources of IR light can interfere with the signal including but not limited to sunlight or fluorescent lights.

1.3.5 Video-based Systems

A simple method is to record eye movements with a camera by noting the change in position of the pupil. However, the amount of data that needs to be analysed is very large and is almost prohibitive (Collewijn et al., 1975; Stern et al., 2001). A similar method is the recording of the position between the iris and sclera (the limbus) and again using IR light (Stern et al., 2001) to infer position.

Video-oculography is another video-based eye tracking method capable of measuring at sampling rates as high as 250 Hz (van der Geest & Fens, 2002). Correlations between this and magnetic scleral search coil have observed extremely closely related output for saccadic parameters to ±40º.
The most accurate technique is undoubtedly magnetic scleral coil but due to expense, eye irritation and greater participant cooperation requirements it is used less readily (Yee et al., 1985). IR oculography is an easy technique to administer, but is generally inaccurate for vertical eye movements beyond 10° upwards and 20° downwards (Yee et al., 1985). Inexpensive video systems and non-infrared reflection systems have their benefits but both systems are unable to record during low-light conditions.

Of the five methods mentioned, only one is generally not beyond the means of most psychophysiological laboratories in terms of expense, ease of use, and not interfering with vision; that is EOG (Stern et al., 2001). As long as EOG is capable of recording the desired parameters with high resolution and stability, then EOG is more than suitable to use in this study.

1.4 Saccadic Eye Movements

1.4.1 Saccadic Eye Movements and Visual Attention

When saccades are recorded during visual search for targets displayed at consistent locations, the saccades are not random and when quantified give researchers insight into the study of visual attention (Leigh & Zee, 2006). However, the detection of saccades by the devices mentioned earlier does not necessarily infer that attention has shifted to the point of gaze, nor which items in a display been attended to during fixations (Zelinsky, Rao, Hayhoe, & Ballard, 1997; Williams & Davids, 1998). Fixations are defined as a condition in which the eye remains stationary for a given period of time generally preceding and following the saccade (Williams & Davids, 1998).

It is now widely accepted that attention can shift from one location to another in the visual field without any concomitant movement of the eyes (Zelinsky et al., 1997; Egeth & Yantis, 1997). However, the literature is less conclusive and often task specific when it comes to whether the eye can move without a concomitant attentional shift. Evidence suggests that saccades generated in the absence of a peripheral cue do not require shifts of attention during simple detection tasks such as a brief change in luminance (Remington, 1980; McPeek, Maljkovic & Nakayama, 1999). Alternatively, during more
complex discrimination tasks such as letter identification, saccades require shifts of attention (Kowler, Anderson, Dosher, & Blaser, 1995; McPeek et al., 1999; Zelinsky et al., 1997).

Therefore, recording saccadic eye movements does provide a general indication of the spatial and temporal attentional allocation given to items in a search display. Analysing the dynamic components of these saccades is a way of objectively assessing the efficiency of visual search.

### 1.4.2 Saccadic Eye Movement Properties

#### 1.4.2i Saccade Rate

*Saccade Rate* is defined as the number of saccades performed in a given period of time, generally standardised as saccades per second (Morgan, 1999). We make on average 3-4 saccades per second (McPeek et al., 1999; Goldberg et al., 1991). The number of saccades per second is affected by the period of fixation between saccades and the duration of the saccade itself. During common reading tasks fixations can last anywhere from 100-500 ms (Reichle, Pollatsek, Fisher, & Rayner, 1998), but are generally about 200-250 ms (Tole & Young, 1981; Reichle et al., 1998). Studies involving masking of the stimulus have observed that information is extracted in the first 45-75 ms of the fixation before attention is reallocated, thus instigating a new saccade (Unema, Pannasch, Joos & Velichkovsky, 2005). During reading tasks, the target of the next saccade is programmed between 25 and 100 ms after the fixation begins (Reichle et al., 1998). However, older studies that used the term inter-saccadic interval (ISI) to describe the period of fixation between saccades reported even shorter pauses of between 0 ms to 200 ms (Levy-Schoen & Blanc-Garin, 1974; Barmack, 1970; Bahill, A., Bahill, K., Clark, & Stark, 1975).

#### 1.4.2ii Saccade Amplitude

*Saccade Amplitude* is the magnitude of the angular distance that the eye travels between successive fixation points. However, a more accurate definition is the change in angle from the point of zero velocity at the start of the saccade to the point of zero velocity at the end of the saccade because this definition accounts for the overshoot commonly seen in eye movement recordings (Bahill, Brockenbrough, & Troost, 1981). *Saccade*
Amplitude is generally reported in degrees of visual angle and ranges from small micro-
saccades of 0.05° up to 90° of visual angle which is the physical limit of the orbits (Tole
& Young, 1981; Becker, 1989). Amplitudes less than 5° are considered small saccades
(Becker, 1989), although others have suggested 5-15° more clearly defines small
saccades (Balogh, Kumley & Honrubia, 1976). Large saccades are considered those
which measure 25° or greater (Balogh et al., 1976) generally because saccades of this
size are made in conjunction with a head movement. Most naturally occurring saccades
are less than 20° (Bahill, Clark & Stark, 1975a; Bahill, Adler & Stark, 1975;
Duchowski, Medlin, Cournia, Murphy, Gramopadhye, Nair, Vorah, & Melloy, 2002).
More precisely, as many as 86% of naturally occurring saccades in an outdoor
environment are less than 15° in magnitude (Bahill, Adler & Stark, 1975).

1.4.2iii Peak Saccade Velocity

Peak Saccade Velocity is perhaps the most commonly reported saccade dynamic (Leigh
& Zee, 2006; Becker, 1989). For any given saccade, peak velocity is determined by the
fastest rate of change in degrees of visual angle per unit of time. It is generally recorded
as degrees of visual angle per second (°/s). The extensive literature on Peak Saccade
Velocity suggests maximum velocities saturate near 1000°/s (Clark & Stark, 1975;
Goldberg et al., 1991; Hitzeman & Beckerman, 1993) for Saccade Amplitudes between
40° and 80° (Clark & Stark, 1975; Collewijn, Erkelens & Steinman, 1988a). However
even smaller saccades of 20° have generated peak velocities as high as 900°/s (Bahill et
al., 1981). Peak velocity is reduced when saccades are made in the dark (Becker &
Fuchs, 1969; Riggs, Merton & Morton, 1974), when participants are drowsy (Riggs et
al., 1974) and when sleep deprived (Minzhong, Russo, Johnson, Kamimori, 2004).

Saccade Average Velocity is also a common measure of saccade performance. It is
calculated as the change in position over duration in time. The typical range for average
velocity is from 350 to 500°/s (Becker, 1989). Saccade velocities can be differentiated
further for analysis of the acceleration and deceleration phases of a saccade. Saccade
peak acceleration has been reported to average about 30,000°/s² in saccades of 10° and
saturates at about 35,000°/s² for amplitudes greater than 15° (Becker, 1989). Other
reports have claimed much higher accelerations approaching 80,000°/s² (Tole & Young,
1.4.2iv Saccade Duration

*Saccade Duration* is generally defined as the period of time which the eye velocity exceeds a certain threshold (Becker, 1989). More accurately, and similar to the *Saccade Amplitude* definition, *Saccade Duration* is the time elapsed from the point of zero velocity at the beginning of the saccade to the point when it reaches zero velocity at the end of the saccade (Bahill *et al.*, 1975a). Most *Saccade Durations* generally do not exceed 100 ms (Leigh & Zee, 2006).

1.4.2v Saccade Latency

Another heavily researched saccade characteristic is *Saccade Latency*. *Saccade Latency* is the difference in time between the presentation of the stimulus and the onset of the primary saccade. It varies greatly depending on the nature of the task. The conditions which produce this variation include whether the appearance of the stimulus is random, whether the stimuli always occurs in the same location, the size of the saccade, target luminance and whether there is incentive to perform the task quickly i.e. when the new target needs to be discriminated in a short period of time before being extinguished. Stimuli that appear at random times and locations, and tasks that have no incentive, have regular *Saccade Latencies* in the vicinity of 180 to 250 ms (Wheeless, Cohen & Boynton, 1967; Becker, 1989; Jüttner & Wolf, 1992; Kalesnykas & Hallett, 1994), but this can be as low as 150-160 ms (Jüttner & Wolf, 1992). However, *Saccade Latency* is shorter when there is prior knowledge of both target location and the frequency at which the target appears at that location (Jüttner & Wolf, 1992). The *Saccade Latency* of these *express* saccades is closer to 100 ms (Fischer & Ramsperger, 1984) yet only occur when there is a sufficiently long temporal gap between the offset of the fixation point and onset of the target stimulus (Wright & Ward, 1994). When targets appear at the same location 100% of the time, *Saccade Latency* can drop to as low as 80 ms (Jüttner & Wolf, 1992). It is important to note that there is no difference between horizontal and vertical *Saccade Latency* (Kalesnykas & Hallett, 1994).

1.4.3 Saccadic Eye Movement Relationships

The ballistic nature of saccades means that many saccadic variables are interrelated. In fact *Saccadic Duration*, *Average Velocity* and *Peak Velocity* all increase as *Saccade
Amplitude increases (Bahill et al., 1975a). Plots of Peak Saccade Velocity or duration as a function of amplitude are referred to as Main Sequence relationships (Bahill et al., 1975a; Leigh & Zee, 2006). The Main Sequence relationships are consistent enough that they can be used as an indicator of normal saccade ranges (Leigh & Zee, 2006).

Saccade Duration increases linearly with Saccade Amplitude between approximately 5° and 50° (Bahill et al., 1975a; Becker, 1989; Garbutt et al., 2001; Leigh & Zee, 2006). Beyond approximately 50°, the relationship becomes non-linear, although some studies have observed linearity between 6-90° (Baloh, Sills, Kumley & Honrubia, 1975b). Using the more restricted range of 5-50°, the duration has an almost constant rate of increase in the vicinity of 1.5-3 ms/deg and an intercept between 20-30 ms (Becker, 1989; Garbutt et al., 2001).

Peak Saccade Velocity increases linearly with Saccade Amplitude up to 20° but reaches saturation at progressively higher amplitudes believed to be around 500°/s (Bahill et al., 1975a; Baloh et al., 1975b; Garbutt et al., 2001; Leigh & Zee, 2006). Furthermore, the ratio of peak velocity to average velocity is relatively consistent. Normal values for this ratio range from 1.38 to 1.90 but are centred near 1.6 (Becker, 1989; Leigh & Zee, 2006). Additionally, a relationship has been shown to exist between Peak Saccade Velocity and Saccade Rate, although literature on this topic is hardly comprehensive. One study showed that Peak Saccade Velocity increased with Saccade Rate (Lueck, Crawford, Hansen, Kennard, 1991) although another study suggested that no relationship existed (Morgan, 1999). Although both tasks had limited time in which to perform the task, they both differed significantly in methodology; one was a voluntary visual search task and the other a monotonous tracking task.

1.4.4 Saccadic Suppression

Visual suppression is a term used to describe the neural events that act to decrease vision during oculomotor behaviours (Volkmann, 1986). Visual suppression is observed during saccades, eyelid blinks, vergence movements and the fast phase of nystagmus (Volkmann, 1986). Of these oculomotor behaviours, undoubtedly the majority of research has focused on suppression during saccades. For this reason, visual search
experiments have focused on the duration and frequency of ocular fixations and relatively ignored saccade parameters (Williams, Davids, Burwitz & Williams, 1993a).

Saccadic suppression is believed to occur so that the perceiver can maintain a stable world and blunt the effect that rapid visual motion would otherwise induce (Burr, Morgan & Morrone, 1999; Thiele, Henning, Kubischik & Hoffman, 2002). The time-course of saccadic suppression begins around 35-85 ms before (Remington, 1980) and up to 100 ms after the onset of the saccade (Burr et al., 1999). Consequently, visual suppression could extend beyond the duration of the saccade itself (Latour, 1962). Some explanations of saccadic suppression concerned mechanical factors such as retinal blur and retinal shear, but these were discounted when it was realised suppression preceded saccade onset. Others proposed vision was simply insensitive to high velocities (Matin, 1974; Ross, Burr & Morrone, 1996). This is true for small objects, but the visual system can process motion of large objects during saccades as fast as 300° to 800° (Burr, Morrone & Ross, 1994; Ross et al., 1996).

A great deal of evidence now suggests that saccades may selectively suppress the magnocellular pathway (transient and high-velocity stimuli of low spatial frequency) whilst sparing or enhancing the parvocellular pathway (colour) (Burr et al., 1994). By suppressing the magnocellular pathway during saccades, the disturbing sense of motion is curtailed (Ross et al., 1996). The underlying neuronal mechanisms of saccadic suppression remain elusive (Thiele et al., 2002).

### 1.5 Visual Search Strategies

During visual search of our environment, the fovea must be pointed at objects of interest (Leigh & Zee, 2006). To achieve this saccades are generated to point the fovea at these objects followed by periods of fixation where we acquire sensitive information about the stimulus that we attend to. Saccades have to be fast in order to minimise the time that perception of our environment is suppressed as well as bring important information into the area of high visual resolution for processing (Becker, 1989). Saccades also have to be accurate otherwise corrective movements will ensue causing considerable delays in identifying the objects. Perfect accuracy would involve real-time feedback during the saccade to monitor and correct the saccade trajectory. This ability would be time
CHAPTER 1 A REVIEW OF SACCADIC EYE MOVEMENT LITERATURE

consuming because of the delays associated with visual processing (Becker, 1989). Therefore, speed and accuracy are conflicting.

We already know information provided in our periphery is relatively indistinct because visual acuity is less effective outside the fovea. The peripheral retina is also sensitive to low levels of illumination and movement (Cohen, 1981). Peripheral cues are likely to provide an important basis to direct our focused attention and visual scanning (Cohen, 1981). The mechanism responsible for the redirection of gaze is not yet understood; however, global or local stimulus control and internal or cognitive control of eye fixation patterns have been proposed. It is likely that the nature of the task dictates the visual search strategy (Cohen, 1981). If searchers gain prior knowledge of the relevance of stimulus information, they can selectively allocate attention critical to resolving the task (Cohen, 1981).

A model proposed by Cohen (1981) was used to better understand age differences in visual search following the sequential nature of searching for a target. Four processes were identified: parsing, comparing, testing and confirming. Parsing involved the searcher having to identify where relevant visual information in the display field was located. Comparing involves determining which stimuli of interest are most relevant for task solution. Testing formulates a plan of action that verifies prior hypotheses. Confirming asks the participant to decide whether they have sufficient information to confirm the hypothesis. If there is insufficient information, the entire process begins again. It is possible to bypass some stages i.e. testing may be unnecessary if the comparison process allows a decision to be made. The major difference between adults and children was at the testing phase where the generation of the search strategy utilised peripheral information in conjunction with foveal information to guide visual search.

Very little is known about how visual search develops (Cohen, 1981). However, adults are characterised as more efficient scanners compared to children (Cohen, 1981). Children do have various scanning strategies available yet do not always use the most appropriate or efficient strategy. Efficient search strategies are a function of task demand. Using exhaustive scanning for stimulus recognition and discrimination may not be the most efficient visual search strategy (Cohen, 1981). However, successful
scanning depends upon good pre-established programmes and the adaptability of those programmes when change occurs (Levy-Schoen, 1981).

Traditionally, most visual search studies focus on experiments that control fixation and use brief displays that minimise eye movements. Additionally, most visual search experiments may involve multiple stimuli but only a single target (Palmer, Verghese & Pavel, 2000).

However, one study in particular has defied this trend by asking participants to identify multiple targets amongst multiple, brief stimuli (Morgan, 1999). This study required participants to search a horizontal display spanning 56° for five stimuli placed at constant positions 14° apart. The aim was to identify multiple target letters amongst distracters. The identification of a target letter required a high degree of visual acuity and therefore peripheral vision alone would not resolve the target. Between zero and three targets were presented per trial at six exposure times ranging from 200 ms to 1000 ms. During trials in which the stimuli were presented for 350 ms or less, response accuracy was not related to saccadic eye movement behaviour, as was the case at the 1000 ms exposure time. In trials where the stimuli were presented for between 500 and 800 ms, participants were more accurate when they made larger, faster and more frequent saccades. However, shorter saccade latencies were not a feature of successful performance as one may expect. These findings were unexpected because it meant successful visual search in this task entailed greater periods where visual information was suppressed due to more frequent and larger saccades. However, at no time was there any evidence to suggest that making faster, longer and more frequent saccades resulted in any perceptual deficit.

Morgan (1999) explained this apparent paradox by a cost-benefit analysis. The benefit of making a saccade is that it brings items of interest from the periphery, where acuity is low, to the fovea, where acuity is higher, enough to discriminate stimuli more accurately. The cost, however, is that with each saccade generated, visual information is suppressed prior to and during each eye movement (Remington, 1980; Burr et al., 1999). Therefore, the cost-benefit approach is a speed-accuracy trade-off. The most successful visual search strategy for any given task is one that finds the most appropriate balance (Morgan, 1999). Therefore, at the 200 ms exposure time, the most
appropriate strategy may be to minimise or eliminate eye movements and use peripheral vision to resolve targets because speed is the primary concern. This strategy may be more likely to yield a successful outcome than to generate many saccades that cannot be executed in the available time to make use of the accuracy they afford.

Conversely, at exposure times between 500 to 800 ms, making more frequent saccades resulted in greater accuracy. Therefore, given the requirements of this visual search task, 500 ms may have been sufficient time to make several saccades gaining the accuracy of the fovea whilst sacrificing speed. However, this does not explain why larger saccades were not counterproductive to visual search considering saccadic suppression increases as a function of Saccade Amplitude (Bridgeman, Hendry & Stark, 1975). Morgan (1999) believed the frequency distribution of Saccade Amplitude was evenly spread across a larger spectrum for accurate trials. This suggested that generating a broad range of saccade amplitudes might permit an accurate response, but within that range, smaller saccades were specifically a less efficient search strategy to use.

The visual search characteristic that was easiest to relate to successful performance was Peak Saccade Velocity. It intrinsically makes sense that the faster the saccade, the quicker the environment is scanned, and hence more time is spent fixated on or near the stimuli to successfully discriminate them. However, the Main Sequence stipulates that Peak Saccade Velocity is a function of Saccade Amplitude, so it is more likely velocity is a less significant factor than Saccade Amplitude. Therefore, if longer saccades were more indicative of successful scanning, and longer saccades were naturally faster because of their logarithmic relationship, then faster saccades would likely be significant too.

Although the findings were remarkable, the study could be criticised for a number of key reasons. Firstly, EOG recordings were made in complete darkness after pre-adaptation to ambient lighting in the room. This has a considerable effect on the EOG output as the voltage, and hence amplitude, would diminish over time. Using this method would cause an underestimate of amplitudes in trials towards the end of the same testing session. Secondly, individual amplitude calibrations were not performed. Instead, a group calibration was derived based in many cases, on participants not involved in the same study. There could be considerable variation in EOG signal from
one person to the next due to position of the electrode (Shackel & Davis, 1960: van Lith & Balik, 1970) bone structure (Arden, Barrada & Kelsey, 1962; Krogh, 1976) and electrical resistance of the skin amongst others. In many cases this would have resulted in underestimates or overestimates of the amplitude, but to what extent is uncertain. The only way to avoid these variations is to perform an amplitude calibration on each participant. Thirdly, learning or fatigue effects may have been present because the exposure time was always presented in the same order. To avoid this criticism the presentation sequence should be counterbalanced. Finally, the fixed pre-stimulus period of 1500 ms may have provided a reliable anticipatory cue for the impending stimulus. This could have been avoided by providing a variable pre-stimulus period.

1.6 Sport-Related Eye Movement Literature

Suppression of visual information during saccades and blinks can severely affect the awareness of individuals who are required to scan quickly and frequently, especially in dynamic sporting situations (Knudson & Kluka, 1997). For this reason saccadic suppression can thus be expected to impact negatively in sport where constant scanning is required. The question then arises of how saccades are integrated into a visual search strategy such that they improve rather than hinder our visual awareness.

1.6.1 Expert-Novice Studies

The most common method of studying skilled performance is to draw comparisons between the behaviour of experts and novices. More specific to sports performance is the comparisons made between elite and non-elite players of the same sport. It is argued that the ability to quickly and accurately perceive stimuli in a complex sports environment is an essential requirement of skilled performance (Williams et al., 1993a). The environment consists of rapidly changing motion of the ball, teammates, opponents and field of play requiring constant visual scanning.

Search rate is highly dependent on the nature of the task. In ‘closed skills’ such as the basketball free throw (Vickers, 1996), putting in golf (Vickers, 1992) or a tennis serve (Goulet, Bard & Fleury, 1989) the focus is primarily on the ball or target (Vickers, 1992). In these tasks, experts have more efficient search pattern involving lower saccade rate with fixations of longer duration (Goulet et al., 1989). In dynamic ‘open’ play
simulations such as soccer where participants view emerging offensive or defensive patterns of play, the inexperienced players fixate primarily on the ball or ball handler whilst experienced players exhibit higher search rates of shorter duration on movements off the ball (Williams et al., 1993b). Any differences in search rate are assumed to be due to the experts more refined visual search strategy (Williams & Davids, 1998). Experts use prior knowledge from a more extensive task specific knowledge base to interpret events, furthermore knowledge structures direct expert’s search strategies towards more relevant areas based on expectations and more effective processing (Williams & Davids, 1998).

However, there is no stereotypical search strategy that is employed during all ‘open’ skilled tasks. For example, experienced soccer players used more fixations of shorter duration when observing 11-on-11 (Williams et al., 1994) and 1-on-1 dynamic film sequences (Williams & Davids, 1998) but not 3-on-3 film sequences (Williams & Davids, 1998). This contradicted previous research into the same sport, when expert soccer players used fewer fixations of longer duration during dynamic set plays involving either 2-on-2 or 3-on-3 players (Helsen & Pauwels, 1993). This suggested that different search strategies may emerge during more complex open-play situations and emphasised the point that the nature of the task dictates the visual search strategy. It was apparent that experienced players used a more exhaustive search of the visual field when observing an open play involving multiple players. In time constrained situations, a search pattern with lower saccade rate may be more efficient due to inactive periods of information processing. This places more emphasis on the role of peripheral vision because it is faster to switch attention than make saccades (Posner & Raichle, 1994).

However, the use of a non-sports specific static display has recently revealed visual search based differences between elite and non-elite Australian Rules football players and soccer players (Morgan, 1999). This is surprising given the existing body of literature that suggests skilled-based differences only become apparent when the task is devised around a valid sporting context (Williams et al., 1993a; Abernethy, Neal & Koning, 1994). For example, Morgan (1999) used his letter, discrimination task (described in detail earlier in chapter 1) to expose footballers and soccer players to stimuli at predictable times and locations, which contrasts the unpredictable environment in which they play their sport. Furthermore, the static display did not
reveal any motion cues by which the sportsmen could associate with developing offensive or defensive plays. Given these points it was surprising that elite footballers and soccer players demonstrated a tendency to make faster and longer saccades, but not more frequent saccades over their non-elite counterparts. This translated in significantly more successful performance for elite footballers but not elite soccer players.

In addition to visual search strategy differences observed between elite and non-elite footballers and soccer players, Morgan (1999) also observed cross-sport differences between elite netballers, elite cyclists and elite swimmers using the same letter, discrimination task. Elite netballers performed significantly faster, larger and more frequent saccades than elite cyclists and swimmers although this search strategy did not translate into more successful task performance, nor did the more frequent generation of saccades cause any perceptual deficit.

The obvious trend was that elite sportspeople in dynamic visual sports (football, soccer and netball) consistently made faster and larger saccades, but not always more frequent saccades than sportspeople from non-visually demanding sports (cycling and swimming). These findings suggest that an overall relationship exists between oculomotor behaviour and skill level, and to some extent that expertise may be attributable to superior eye movement capacity. An important limitation of these results is that just because the non-elite sportsmen and elite swimmers and cyclists did not produce saccades of the same speed, size and frequency, there is no evidence to suggest that they cannot.

1.6.2 Hardware vs. Software (i.e. Physiological vs. Psychological)

Much of the early work on skilled perception in sport focussed on the structurally-fixed components or “hardware” of the visual system such as static and dynamic visual acuity (DVA), depth perception, colour vision, and peripheral visual range (Williams et al., 1993a). DVA for example is the ability to discriminate the fine part of a moving object (Ishigaki & Miyao, 1993) and is considered to be related to performance in fast-ball sports (Sanderson & Whiting, 1974) such as baseball, tennis and badminton. DVA was found to be superior in athletes than non-athletes when the target to resolve was fast moving (Ishigaki & Miyao, 1993). When the target was larger or when the speeds were slower, performance by both groups were the same. However, other studies examining
skilled and unskilled soccer players (Helsen & Starkes, 1999) and gridiron players (Deshaies & Pargman, 1976) did not identify hardware differences. The inconsistent results proved inconclusive leading researchers to believe that skilled based differences did not emerge on these structurally fixed components suggesting once again that testing needed to be sports specific (Deshaies & Pargman, 1976; Williams et al., 1993a; Williams, 2000).

The lack of evidence for expertise differences in physical or optical characteristics of the visual system led researchers to study their “software” or knowledge acquired through experience. Elite athletes selectively attend to, recognise, analyse and interpret visual information more effectively than their non-elite counterparts (Abernethy et al., 1994). Elite athletes have more elaborate task-specific knowledge bases which allow them to respond to events similar to those previously experienced (Williams, 2000). The knowledge bases direct their visual search to areas in the environment based on their expectations and more effective processing of context specific information (Williams, 2000).

1.6.3 Sports Vision Training

There is little research relating to the effectiveness of various vision training exercises that have been developed and as yet there is no convincing evidence to show that such programmes work (Wood & Abernethy, 1997). The question of whether sports performance can be enhanced by visual training programmes involves three related issues; 1) what role does vision, and especially visual skill play in sports performance 2) to what extent are the critical visual-perceptual attributes of the athlete trainable and 3) to what extent do improved visual skills transfer to improved sports performance (Hitzeman & Beckerman, 1993; Wood & Abernethy, 1997).

One example of the inconsistent results from completing visual training programmes involved soccer players performing “eyerobics”. McLeod (1991) found female university soccer players who completed the four-week training programme significantly improved three out of the four facets in which they were tested i.e. foot-eye co-ordination and balance. The same programme was used to train elite soccer players over a four-week period (Cohn & Chaplik, 1991) and the results found there was no evidence to suggest that “eyerobics” benefits soccer-related skills. Generally, and as
was the case in these two studies, the period of training is quite small which makes it quite difficult to demonstrate a substantial benefit (Knudson & Kluka, 1997).

The balance of opinion regarding the efficacy of sports training programmes remains divided with sports scientists saying that performance is not significantly improved by enhancing hardware components of vision (Wood & Abernethy, 1997) whilst sports optometrists say that it is. This argument is consistent with the overall view that expertise in sport is a function of superior cognitive and decision-making skills and not the hardware components that acquire information (Morgan, 1999).

1.7 Aims and Objectives

The primary aim of this thesis was to replicate the exploratory efforts of Morgan (1999) in understanding the relationship between saccadic eye movement parameters and acquisition of visual information. Morgan’s preliminary effort provided evidence that generating larger, faster and more frequent saccadic eye movements actually enhanced performance rather than creating a perceptual liability. The visual search task Morgan used was designed to expose differences in oculomotor behaviour that were not associated to sport-specific knowledge or skill.

The secondary aim of this thesis was to extend this exploratory effort and identify whether visual search characteristics identified by Morgan (1999) in the horizontal visual field could be extended to the vertical visual field. Participants will be recruited from the general population to assess the overall success of search strategies and a smaller group from elite and non-elite Australian Rules football players to assess skilled-based differences. The Australian Rules footballers were chosen primarily because they participate in a perceptually demanding and unpredictable sport, and secondly because it can be directly compared to Morgan’s results.

Finally, some methodological limitations were identified in the Morgan (1999) study and will be addressed throughout the thesis. Alterations were only made to the methodology if it was deemed to improve the accuracy or precision of the data. However, limitations relating to the visual search task were not addressed if it contradicted this theses’ primary aim.
Chapter 2  General Materials and Methods

The data acquisition system, experimental display and visual search tasks described in Chapter 2 are based largely on the experimental methodology of Morgan (1999). Care was taken to accurately replicate his experimental design but to enhance it in three key areas: 1) apply individual calibrations rather than group calibrations 2) ensure the limitations of the saccade detection algorithm were known (covered in Chapter 3) and 3) ensure the ambient illumination level had no effect on the acquired signal (covered in Chapter 4).

2.1  Data Acquisition Apparatus

The corneo-retinal potential recorded by the EOG electrodes was differentially amplified and transmitted directly to a serial acquisition device. The data were serially processed and sent to the central processing unit (CPU). The CPU synchronised the recording of eye movement data, the acquisition of a manual response of the participant, and the delivery of the stimuli via a specially designed light emitting diode (LED) display (Morgan, 1999).

2.1.1  Differential Amplifier

Differential amplifiers amplify the difference between non-inverting and inverting inputs and reject signals that are common to both inputs (Brigell, Bach, Barber, Moskowitz & Robson, 2003). The differential amplifier used in these experiments was designed to decrease the amount of EEG, muscle artefact and 50 Hz noise present in the signal.

The differential amplifier was powered by two 9 volt batteries. The variable gain of the amplifier was set at 385. The frequency response for this differential amplifier showed that signals within the range of 0.05 Hz to 40 kHz were reproduced to at least the –3 db level (see Figure 2.1.1).
Figure 2.1.1: Differential amplifier frequency response. Signal amplitude was 100% replicable for frequencies greater than 1 Hz and less than 10 kHz. The bandwidth frequency shown above is approximately 0.5 Hz to 40 kHz.

2.1.2 Serial Acquisition Device and CPU

A dual-channel serial acquisition device was used to transmit eye movement data from the differential amplifier to the recording CPU. The device featured an on-board analogue to digital converter (ADC), with a sampling rate of 19,200 bits per second. The output from the serial device was connected to a standard serial port installed in a Pentium 233 MHz PC. Data were acquired at 4 bytes per sample at a sampling frequency of 480 Hz. The spatial resolution was 10 Bits, outputting serial values ranging from +1024 to -1024.

The same Pentium 233 MHz PC was used for all tests. The operating system of the CPU was Windows 98 2nd Edition with 96 Mb RAM. The PC had 32-bit virtual memory and ran “easx2” (Morgan, 1999), an EOG recording and analysis software program compiled in Microsoft Visual Basic 3.0TM.

2.1.3 Standard Electrode Arrangement for EOG Recordings

The International Society for Clinical Electrophysiology of Vision (ISCEV), set standards for EOG testing in 1993 and 1998 (ISCEV, Marmor & Zrenner, 1993; ISCEV, Marmor, 1998), including horizontal electrode placement. Conforming to these standards, a ground electrode was attached to the glabella [smooth area between the eyebrows just above the nose, formed by part of the frontal bone (Wilson, Glue, Ball, &
two signal electrodes were attached as close to the outer canthi of both eyes as possible (see Figure 2.1.3).

ISCEV does not set standards for electrode placement in vertical EOG recordings, possibly due to the limitations of performing vertical EOG tests. Investigation into the most appropriate electrode sites identified that directly above the supraorbital ridge and below the infraorbital ridge (Bauer, Strock, Goldstein, Stern & Walrath, 1985) of the same eye produced the highest amplitude signal (Hakkinen, Hirvonen, Hasan, Kataja, Varri, Loula, & Eskola, 1993), also seen in Figure 2.1.3. The horizontal EOG ground electrode attached at the glabella remained unchanged and was used as the vertical EOG ground electrode. However, these three vertical EOG electrode sites were more susceptible to blink artefact (Hakkinen et al., 1993).

A Kendall Excel Blue™ (Chicopee, USA) diaphoretic electrode, with foam and blue adhesive hydrogel, was used for the ground electrode. The active electrodes were 6 mm pure tin cup electrodes (Electro-Cap International, Inc., Eaton, USA) applied using a conductive gel. According to ISCEV standards (Marmor & Zrenner, 1993), silver-silver chloride skin electrodes should have been applied. However, the aforementioned combination was the least intrusive, most resilient to movement and perspiration and consistently produced the clearest signal. Additionally, ISCEV standards expect the
resistance of the electrodes to be less than 10 kΩ, but the electrode combination allowed the current studies to achieve higher recording fidelity of no more than 5 KΩ. Skin was prepared using methylated spirits with care taken at all sites around the eyes.

2.2 Stimulus Display

A 100 cm × 100 cm experimental display board (Figure 2.2a) contained two arrays of five alphanumeric LED displays. Each array was arranged such that five LED displays appeared horizontally and five more vertically. The middle LED display appeared in both arrays, so that only nine LED displays were required for the display board. The midpoints of each LED display were spaced 20 cm apart. Each array spanned 80 cm from the mid-point of the furthest two LED displays (either horizontally or vertically). The 7-segment alphanumeric LED displays were 25 mm in height and 13 mm in width mounted in a unit that was 33 mm high and 22 mm wide.
Figure 2.2a: Horizontal and vertical experimental display board: The display above shows the nine LED displays arranged in a horizontal and vertical array. Each array spans 80 cm from the mid-point of the furthest two LED displays (either horizontally or vertically). The distance between two LED displays is 20 cm. Each LED display is 25 mm high and 13 mm wide.

Participants were seated a distance of 75 cm in front of the most central LED display. A head support chin rest was used to stabilise the head during the testing session and to keep the LED display distance constant. The experimental display board was flat with respect to the participant, designed specifically to replicate the experimental display of Morgan (1999). A flat display board, rather than a concavely curved display board, has the capacity to introduce small accommodative eye movement errors due to small variations in display depth. However, replication of Morgan’s (1999) experimental
display was considered essential whilst the accommodative errors introduced were considered negligible.

Figure 2.2b demonstrates the visual angle of the LEDs (measured in degrees) when the participant views the display from 75 cm. Each 20 cm gap between the midpoints of any two LED displays subtends 14° of visual angle, totalling 56° of visual angle for the entire array. The visual angle was identical for both the horizontal and vertical array.

2.3 Procedure

Ethical approval was granted by the Swinburne Human Research Experimental Committee (Appendix A). Before participation in one of the three studies, all participants read the supplied information sheet and signed the relevant consent form (see Appendices B, C and D). All participants were required not to consume any
caffeine or nicotine related products at least 2 hours before the testing session. Participants were asked if they had any prior visual impairment that may preclude them from completing the study. Corrective lenses were allowed at all times.

2.3.1 Standard Visual Pre-Test Battery

Three tests were used to obtain knowledge about the participant’s general visual ability. The tests were the dominant eye, colour-blindness, and visual acuity test.

2.3.1i Dominant Eye Test

The dominant eye test was used to determine which eye was used for vertical EOG electrode placement. This was important for two reasons. Firstly, the dominant eye processes and transmits information to the brain a few milliseconds faster than the non-dominant eye (Knudson & Kluka, 1997). This has no impact on horizontal saccades because the EOG recording is from both eyes however, vertical EOG recordings are conducted on a single eye so vertical Saccade Latency could potentially be slower in the non-dominant eye. This would affect between-subject comparisons if the dominant eye were not consistently chosen. Secondly, and of more practical importance, in the unlikely circumstance that a participant is unaware of an existing visual impairment, it identified which eye to use by means of an independent determination.

The dominant eye test requires participants to extend both hands in front of their face (similar to Parson’s Monoptoscope test described by Kommerell, Schmitt, Kromeier & Bach, 2003). The hands are placed together, overlapping to form a small triangle between the crossed over thumbs and forefingers (see Figure 2.3.1i). The gap should not be too wide (approximately 2 cm per side), just wide enough for the researcher to be able to see the participant’s eye. The participant then looks through the triangular gap at the researchers face. The researcher sits approximately two meters away from the participant and looks through the triangular gap created by the participant and records which eye is visible. This eye is deemed the dominant eye.
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Figure 2.3.1i: Hand placements used in the dominant eye test. The hands overlap to create a small triangular gap between the crossed over thumbs and forefingers. The participant looks at the examiner's face through the gap. The examiner then sights a single eye, which is classified as the dominant eye.

2.3.1ii Ishihara Colour-Blindness Test

The Ishihara Colour-Blindness test was used to exclude participants who suffered colour vision deficiency (Ishihara, 1970). Participants were asked to view a coloured plate (see Figure 2.3.1ii for an example) and consider whether a number, a line or nothing was observed. Depending on their answer, numbers were read aloud and the lines were traced respectively. The participant’s answers were compared against the answers for normal vision, red-green deficiencies and total colour blindness.

Figure 2.3.1ii: Example of the Ishihara colour blindness test. The above pictures represent plate 2 (left) and plate 14 (right) from the 24-plate Ishihara (1970) test. Participants with normal vision are expected to see the number 8 when viewing the left image. If participants have red-green colour vision deficiencies, they should identify the number 3. Completely colour-blind participants should not be able to identify any numeral. Participants with normal colour vision or total colour blindness, when viewing the right hand image, should not be able to identify any number. Participants with red-green deficiencies should see the number 5.
2.3.1iii Visual Acuity Test

The Visual Acuity test determined the ability to discriminate fine detail (Johnstone, 1999) using a LogMAR eye chart (see Figure 2.3.1.3). LogMAR is defined as the logarithm of the minimum angle of resolution (Johnstone, 1999). The chart contained 14 rows of five letters with proportional spacing between letters and rows. A logarithmic progression of letter size was used (Johnston, 1999). Only 10 letters were used on the LogMAR chart, chosen because they are near equal in terms of legibility (Bailey & Lovie, 1976). The letters were D E F H N P R U V Z. Scores from the LogMAR chart range from 1 to -0.3. A score of one represents 6/60 vision (i.e. what most people can see from 60 m, the participant can only see from 6m), and a score of zero represents 6/6 vision or normal vision. Scores less than zero suggest better than normal vision. Participants who were unable to see the 0.5 line were excluded as this line was the approximate equivalent to identifying alphanumeric characters 75 cm from the display.

The participant was positioned 3 meters in front of the LogMAR eye chart. The participant covered one eye with the palm of their hand (not fingers) and was asked to read progressively smaller rows of letters until they could read no further. The smallest line that the participant could read was recorded. The first eye was uncovered and the process repeated with the other eye, but this time the participant read the chart in the opposite direction (i.e. reading right to left subsequently changes to reading left to right). Participants were allowed to use glasses or contact lenses, as the best-corrected vision was required.

Figure 2.3.1iii: Example of a Bailey and Lovie (1976) LogMAR eye chart. The chart contains 14 rows of 5 alphabetical letters with proportional spacing between letters and rows. The 10 letters depicted above were different to those actually used: D E F H N P R U V Z. Participants were excluded if they were unable to read the 0.5 line as this was the equivalent to viewing the LED displays at a distance of 75 cm.
2.3.2 Horizontal EOG Amplitude Calibration Routine

A calibration routine was devised to accurately convert the raw digitised serial values into degrees of visual angle. Participants underwent standard EOG set-up and were positioned 75 cm from the earlier described stimulus display. Care was taken to ensure that the participant’s head was perfectly in-line with the central LED (therefore maintaining a constant visual angle of 14º between displays) and that the head remained motionless during the entire routine (by using the head support chin rest). This ensured the calibration routine would return a linear function.

There were six trials in the calibration routine with each performed in the following manner. Participants were instructed to begin by fixating on the central LED display. The illumination of this display indicated both the beginning of a single calibration trial and the pre-stimulus for participants to focus upon. After 1500 ms exposure (to determine a baseline), the pre-stimulus on the horizontal array changed to the numbers ‘1’, ‘2’, ‘3’, ‘4’, ‘5’ (reading left to right). The participant was asked to look from the central LED display to the far left (number ‘1’) and fixate on this display for approximately 500 ms. The participant’s gaze then shifted right, fixating for 500 ms each on LED display ‘2’ through ‘5’ respectively. All numbers in the horizontal array remained lit for the remainder of the trial. After each 3-second presentation, a visual mask appeared which illuminated all displays in that array. The mask remained illuminated until the participant responded by pressing any number on a hand-held response pad. The responded value held no significance but allowed the task to remain self-paced. The pre-stimulus for the next trial began immediately after a response was registered.

Participants were asked to avoid coughing, sneezing and blinking during trials as best they could to avoid any potential artefact effecting the EOG signal. If they needed to cough, sneeze or blink, then they were asked to wait until the visual mask was illuminated because the EOG signal was not recorded during that part of the sequence.

Participants were given a minimum of six trials as practice prior to an actual recording. This allowed the participants to become comfortable with the routine and practice the
sequence timing. If more practice was required then it was provided. An account of the verbal instructions is supplied in Appendix E.

Figure 2.3.2 demonstrates both the time-course of this calibration routine and an example of the stimuli as seen by the participant during a single trial.

**Figure 2.3.2: Time-course and stimuli of the horizontal calibration routine.** The above figure represents the stimulus presentation sequence on the horizontal array. The pre-stimulus, which lasts for 1500 ms, only illuminates the middle segment of the central LED display. After the pre-stimulus, the numbers ‘1’, ‘2’, ‘3’, ‘4’, and ‘5’ appear from left to right for 3000 ms. Following this stimulus, a visual mask appears illuminating all remaining segments. These segments remain illuminated until the participant presses a button signalling the beginning of the next trial.

### 2.3.3 Horizontal Visual Search Strategy Task

Following the EOG amplitude calibration routine, participants performed the 72-trial visual search task. The visual search strategy task (VSST) involved participants scanning the horizontal array to identify a target letter amongst non-target distracters. The target letter was the letter ‘E’ and the non-target distracters were ‘F’, ‘S’, ‘L’, and ‘B’. Participants were asked to use their own visual search strategy to scan the horizontal array whilst keeping their head still. Examples were given to illustrate the different types of strategies possible i.e. scan from farthest left LED display to farthest right LED display, or scan from farthest right LED display to farthest left LED display (see Appendix E for more examples and an actual account of the verbal instructions supplied to the participants). It was up to the participant to determine which visual search strategy was most effective for them.
As opposed to the calibration routine, there was no pre-stimulus for participants to fixate on. This task used a blank pre-stimulus, lasting 1500 ms, to avoid influencing the nature of the visual search strategy employed. It is important to note that a blank pre-stimulus could still act as a reliable anticipatory cue for the impending stimulus, but this was seen as negligible compared to the primary objective, which was to replicate the Morgan (1999) results. The letters were exposed for pre-defined periods beginning at 1000 ms and decreasing to 800 ms, 650 ms, 500 ms, 350 ms and 200 ms respectively. Again, it is important to note that not counterbalancing the exposure times could lead to learning or fatigue effects but this was again seen as negligible compared to the primary objective. The visual mask used in the EOG amplitude calibration routine followed the stimulus exposure time. Figure 2.3.3 shows the time-course of these events and the stimulus presented.

During each of the six exposure time blocks, 12-trials were performed totalling 72-trials per horizontal array. In any given trial, the target letter ‘E’ would appear between 0 to 3 times each trial, with non-target distracters making up the remainder. For each exposure time block, there was an even representation of the number of times a target letter appeared; zero target letters occurred 3-times, one target letter 3-times, two target letters 3-times and three target letters 3-times. Both target and non-target letters appeared in pseudo-random sequence.
The participants responded using a hand-held response pad by pressing ‘0’, ‘1’, ‘2’, or ‘3’. The participants were instructed that the task was not multiple-choice, and that they were not allowed to guess. They could only respond with the number of target letters they definitely saw. The participants were not informed that there was an equal representation of target letters per trial in each exposure time block. Participants were instructed that this was a self-paced experiment and they were allowed unlimited time to submit their response.

A number of trial runs for both the calibration and visual search test were performed before any testing session.

### 2.3.4 Repetition of Horizontal EOG Amplitude Calibration Routine

The 6-trial EOG amplitude calibration routine was repeated a second time following the 72-trial VSST. The repeated test allowed conclusions to be made regarding the effect of ambient light level and duration of task on participants. The effects of ambient light level on the corneo-retinal potential will be discussed further in Chapter 4.

### 2.3.5 Vertical EOG Amplitude Calibration and Visual Search Strategy Task

The vertical tasks were performed in the same manner as the horizontal tasks. A 6-trial vertical EOG amplitude calibration routine was performed followed by a 72-trial vertical VSST and concluded with a final 6-trial vertical EOG amplitude calibration routine. During the vertical tasks the eyes had to be level with the central LED display to ensure no bias towards the upper or lower LED displays in an attempt to return a linear calibration function again. The vertical calibration routine used the same pre-stimulus, but the numbers 1-5 appeared from the top LED display to the bottom LED display as opposed to left to right. The target letters and non-target distracters during the vertical VSST also appeared from top LED display to bottom LED display as opposed to left to right.
2.4 Data Analysis Software

The initial data analysis software, ‘EOG5’ was created by Morgan (1999) and compiled in Microsoft Visual Basic 5.0™. This software program was used to transform the digitised EOG data from a binary file to a modified output file.

2.4.1 Data Transformation

The EOG data, digitised at a rate of 480 samples per second, was passed through an automated Fast Fourier Transform and converted into the frequency domain. The frequency bins greater than or equal to 20 Hz were set to zero, providing an effective high-cut filter. The combination of the DC-restoration amplifier, acting as a low-cut filter by removing the very slow drift, and the transformation method results in a bandpass filter between 0.01 Hz and 20 Hz. This bandwidth conforms to ISCEV recommendations (ISCEV, Marmor & Zrenner, 1993). An Inverse Fast Fourier Transform function then returned all data to the time domain.

2.4.2 Amplitude Calibration

The digitised data were then plotted on a serial value versus time graph. An example of this graph is shown in Figure 2.4.2a. As displayed, the pre-stimulus has an initial stable baseline with virtually no offset lasting 1500 ms. When the pre-stimulus changed to the numbers ‘1’, ‘2’, ‘3’, ‘4’ and ‘5’, the trace deflects upwards from the baseline as a result of a voluntary leftwards saccade until the eyes fixate on LED ‘1’ corresponding to the maximum positive serial value. The trace then deflects downwards in a steplike manner as a result of voluntary rightward saccades interspersed with fixations on LED ‘2’ through ‘5’. Additionally, Figure 2.4.2a shows the participant returning their gaze to the central LED display to fixate there ready for the next calibration trial.
Figure 2.4.2a: Example of an EOG recording from the horizontal EOG amplitude calibration routine. The green line in the above graph denotes the raw EOG signal of the participant. The red line denotes an averaged stable fixation that when differentiated does not exceed a certain threshold. As shown, the participant’s initial focus on the middle alphanumeric display for the designated 1500 ms pre-stimulus time to observe a stable baseline. The amplitude of the signal then rises and remains stable close to 280 (fixation on LED ‘1’). The amplitude then decreases where the participant is fixating on display ‘2’ (~140). Fixation at LED ‘3’ (~ -10), ‘4’ (~ -150), and ‘5’ (~ -265) follows before the participant returns their attention to the middle segment ready for the next calibration trial.

Each calibration trial was then differentiated to ascertain whether the change in amplitude was higher than a pre-determined threshold. If the differentiated serial value was not above this threshold, then the signal was considered stable and it was determined that a fixation took place. Figure 2.4.2a demonstrates these fixations via the red lines overlapping the green raw EOG signal. The predetermined threshold was initially set at five, but for some participants there was a need to reduce this due to variation in the amplitude of the EOG signal.

Each fixation was then plotted as a single data point of averaged serial value versus degree of visual angle. The initial baseline (averaged serial value during the pre-stimulus period) was used as an offset to adjust all averaged fixation serial values for LEDs ‘1’ through ‘5’. Therefore, five valid data points could be obtained per trial and 30 for each calibration routine. When performed before and after a 72-trial VSST, 60 valid data points were obtained. A linear regression line was plotted to determine the calibration equation and a coefficient of determination ($r^2$ value) demonstrates the variance of the data points from this regression line. An example of this is shown in Figure 2.4.2b.
Figure 2.4.2b: Determining the calibration equation from the EOG amplitude calibration routine. The graph shows the averaged fixation raw serial values plotted against the corresponding degree of visual angle subtended from the display for participant 23. The equation for the linear regression trendline is shown in the top right corner. The coefficient of determination is 0.9905 which conveys that there was very little variance in the data points for each degree of visual angle.

The regression line equation was then used to convert all serial values into amplitude measured in degrees of visual angle. The resulting graph would be expected to look similar to that shown in Figure 2.4.2c. The example shown in Figure 2.4.2c is the same as that in Figure 2.4.2a but with serial values calibrated to amplitude measured in degrees of visual angle. As expected the amplitude range covers 56° of visual angle with each fixation for each LED display very close to 14° apart.

Figure 2.4.2c: Example of the final calibrated EOG recording. The calibrated values for participant 23 are now shown graphically as amplitude (degrees of visual arc) over time (seconds).
2.4.3 Saccade Detection and Derivation of Saccade Variables

The detection of individual saccades per trial was carried out to assess the visual search strategy of each participant. The actual saccade detection algorithm will be outlined in greater detail in Chapter 3.

The saccade variables of interest which directly replicate the dependent variables of Morgan (1999) were Saccade Rate, Mean Saccade Amplitude and Mean Peak Saccade Velocity. Saccade Rate was operationally defined as the number of completed saccades generated within the given exposure time for each trial. For the purposes of comparing Saccade Rate across all exposure times, it was standardised to 1 second i.e. 3 saccades performed during the 500 ms exposure time would result in a value of 6 saccades per second. Mean Saccade Amplitude calculates the average size of all completed saccades (in degrees of visual angle) generated within a given trial. Mean Peak Saccade Velocity identifies the peak velocity of each saccade per trial and combines these values to produce an overall mean per trial. In the event that no saccades were detected, the Mean Saccade Amplitude and Mean Peak Saccade Velocity were disregarded.

Three more variables were calculated to expand the investigation into visual search strategies begun by Morgan (1999). These include Saccade Latency, Cumulative Saccade Amplitude and Cumulative Peak Saccade Velocity. Saccade Latency was operationally defined as the time elapsed between stimulus onset and the generation of the first saccade. Cumulative Saccade Amplitude combined the magnitude of each saccade per trial whilst Cumulative Peak Saccade Velocity combined the peak velocity values of all saccades executed per trial.

During the horizontal and vertical VSST, it was possible to anticipate the beginning of the exposure time due to the constant 1500 ms pre-stimulus. Any saccades which began prior to and concluded after the onset of the stimulus exposure time were deemed anticipatory in nature and considered invalid; firstly because there was no advantage in making saccades prior to the onset of the exposure time and secondly because the algorithm employed only began calculations at the first sample after the exposure time, not before. For these reasons, anticipatory saccades were excluded from all Saccade Rate, Amplitude and Velocity calculations. Failure to exclude anticipatory saccades
would cause outliers to the *Main Sequence* relationships i.e. the generation of a 30° saccade takes place with 15° occurring prior to exposure time onset and 15° occurring after exposure time onset. Only the 15° which occurs after the exposure time onset would register, however the full peak velocity would register (peak velocity is likely to occur at the point of stimulus exposure time onset) which relates to a 30° saccade. The *Main Sequence* would suggest that the saccade was abnormally fast for that sized amplitude. Therefore, any saccade begun prior to the exposure time, even by as little as one sample, was excluded.

The same exclusion criteria applied to saccades generated just prior to and completed after the exposure time. Any saccades not completed by the end of the exposure time would be deemed incomplete and therefore excluded for the same reasons that anticipation saccades were excluded. However, extra leniency (5 samples or 10.4 ms) was given at the end of a trial because it became apparent that some participants were able to respond correctly to targets that were fixated upon after the exposure time concluded. This suggests either a slight inaccuracy in the execution of the exposure times by the CPU or an ability to perceive during the deceleration phase of a saccade.
Chapter 3  Saccade Detection and Evaluation

An objective assessment of the EOG recordings was required to establish that the detection and evaluation of each saccade during the VSST was correct. The detection algorithm must clearly identify saccadic eye movements within the EOG data. The evaluation sub-routine must then extract values that measure the most important saccade variables such as velocity, amplitude and duration for further analysis. To write an adequate software algorithm, it was essential to understand the key components of the saccade first.

3.1 Saccade Detection Characteristics

Repeated identification of saccades requires classification of their common features. These common features need to be distinct from nystagmus, smooth pursuit eye movements and blinks.

Saccades were defined in Chapter 1 as voluntary, rapid shifts of visual attention that bring a target from the periphery to the fovea in the shortest possible time (Baloh, Langhofer, Honrubia, & Yee, 1980; Goldberg et al., 1991). Conversely, smooth pursuit eye movements are slow, involuntary eye movements and OKN (uses involuntary saccades) involve eye movements whilst the head moves (Baloh et al., 1980).

3.1.1 Saccade Characteristics

Every saccade has two distinct characteristics: (1) onset of a saccade, and (2) termination of a saccade (Juhola, Jäntti, Pyykkö, Schalén, Akesson, & Magnusson, 1987; Wyatt, 1998). Locating these two characteristics is essential when trying to distinguish when a saccade occurs. Fixation on an object or point of interest often follows the termination of a saccade. However, fixation is not a third characteristic because if the primary saccade overshoots or undershoots, then a secondary saccade immediately follows rather than a fixation. Therefore, a fixation does not occur after every saccade.
A stereotypical saccade comprises an amplitude of $20^\circ$, a duration of 60 ms, a maximum velocity of about $600^\circ$/s, and a mean velocity of $300^\circ$/s (Juhola, Jäntii, Pyykkö, Magnusson, Schalén, & Åkesson, 1985).

Stereotypical saccade behaviour includes:

1. **Saccade Latency** typically ranges from 120-300 ms (Tole and Young, 1981; Wells & Barnes, 1999), but generally between 180-250 ms (Jüttner & Wolf, 1992).

2. An extremely high initial acceleration (up to $30,000^\circ$/s$^2$) producing an abrupt onset of movement (Becker, 1989) to a relatively constant high velocity (Clark & Stark, 1975).

3. A peak velocity between 400-600$^\circ$/s (Becker, 1989) but as high as 900$^\circ$/s (Bahill et al., 1975a) rising in proportion to the magnitude of the saccade.

4. The peak of this velocity is approximately to $\frac{1}{2}$ way along the saccade trajectory (Bahill et al., 1975a).

5. A smaller, less rapid deceleration, which is still large enough to terminate the eye movement almost instantaneously (Hyde, 1959; Clark & Stark, 1975; Becker, 1989).

6. **Saccade Amplitudes** can range from small micro-saccades of 0.05$^\circ$ up to 90$^\circ$ of visual angle (Tole & Young, 1981).

It also helps to know that saccade trajectory and saccade velocity cannot be voluntarily altered. Practice and motivational factors cannot influence saccade velocity and duration (Balah, Kumley & Honrubia, 1976a).

### 3.1.2 Smooth Pursuit Characteristics

The function of smooth pursuit eye movements is to stabilize a moving target on the fovea (Balah, Kumley, Sills, Honrubia & Konrad, 1976b). In an everyday environment, smooth pursuit eye movements are not under voluntary control during the movement, but can be voluntarily initiated and abandoned.

A number of studies have questioned whether a moving target is required for making smooth pursuit eye movements (Westheimer & Conover, 1954; Westheimer, 1954a; Heywood, 1972; Kowler & Steinman, 1979; Barnes et al., 1997). If a moving target
were required, then it is possible to assume that smooth pursuit does not take place because the targets in the VSST are stationary. However, if this assumption proved false and a moving target was not required to generate smooth pursuit movements then it is important to define other characteristics that differentiate smooth pursuit from saccades.

An examination of the literature suggests that all voluntary smooth eye movements performed in the absence of a moving target are saccadic (Kowler & Steinman, 1979; Barnes et al., 1997). In the past 50 years, only two studies have reported this not to be the case although the findings were based on only two and one participant respectively (Westheimer & Conover, 1954; Heywood, 1972). However, other researchers have presented a stabilised image outside the fovea and managed to induce smooth pursuit tracking without a visually moving target (Barnes, Grealy & Collins, 1997). This is not generalisable to all cases though as Kowler and Steinman (1979) found that their participants were unable to make voluntary, directed smooth pursuit eye movement when asked to track between two stationary targets.

Although only two reported incidents of smooth pursuit tracking without any visually guided target have occurred, it would be safer not to assume that smooth pursuit does not take place and further refine the algorithm to differentiate saccades and smooth pursuit. One distinguishing difference between these two eye movements is through angular velocity.

### 3.1.2.1 Maximum Smooth Pursuit Velocities

Early studies suggested that smooth pursuit velocities begin to saturate at about 20°/s to 30°/s before the saccadic system began to take over (Westheimer, 1954b; Rashbass, 1962). A number of years later the maximum velocity for optimal smooth pursuit functioning was increased to 40°/s (Schalén, 1980; Baloh et al., 1980) or 50°/s (Baloh et al., 1976; Engelken & Wolfe, 1979). During this later research period, only Collewijn and Tamminga (1984) found that saccades occurred significantly before 21°/s moving targets.

At higher velocities, saccades were used more frequently to match target speeds. At target speeds of 60°/s, participants track using smooth pursuit only 75% of the time (Schalén, 1980). At even higher target velocities of 75°/s and 100°/s, smooth pursuit
may only account for 70% of the tracking (Engelken & Wolfe, 1979), although some participants were unable to track the stimulus at all.

Opinion has varied as to what the exact upper limit of tracking target frequencies using human smooth pursuit is before the saccadic system assumes full control. Bahill and McDonald (1983) state the human upper limit is $126^\circ/s$ whilst $128^\circ/s$ has been observed in monkeys (Barmack, 1970). An elite baseballer has been observed making smooth pursuit eye movements as fast as $130^\circ/s$ (Bahill & LaRitz, 1984). Meyer, Lasker and Robinson (1985) suggested this upper limit saturates above approximately $87^\circ/s$ if target velocities are $100^\circ/s$. It is now widely accepted that the smooth pursuit eye movement system has maximum velocities of approximately $100^\circ/s$ (Goldberg et al., 1991).

Consequently, the smooth pursuit system is principally in control up until $50^\circ/s$ and remains active in eye movements until saccades take over completely at approximately $130^\circ/s$. It is therefore quite evident that the separation of smooth pursuit from saccades is a delicate procedure because their velocity ranges overlap (Arzi & Magnin, 1989; Sauter, Martin, Di Renzo & Vomscheid, 1991).

### 3.1.3 Blinking and Interference Characteristics

EOG deflections during blinks are artefact and probably represent lid movement, not eye movement (Collewijn, van der Steen, & Steinman, 1985). Therefore, they need to be excluded from saccade calculations. There are three major types of blinks: reflexive, voluntary and spontaneous (VanderWerf, Brassinga, Reits, Aramideh, & Ongerboer de Visser, 2003; Rambold, Spenger & Helmchen, 2002). Reflexive eye blinks occur when the supraorbital nerve is electrically stimulated or a puff of air is injected into the eye. However, such movements are irrelevant to this thesis because the methods used to induce reflexive blinks are not performed during the VSST. Additionally, voluntary eye blinks can be discounted because participants were specifically asked not to blink during each VSST trial. Unfortunately, it was still possible for spontaneous blinks to occur during the trials.

The likelihood of a spontaneous blink occurring is further increased because visual search tasks involving saccadic eye movements, such as the VSST, actually induce
spontaneous blinks. These blinks are more common during vertical eye movements than horizontal eye movements and more specifically from eye movements in an upwards rather than downwards direction (Tada & Iwasaki, 1985). Eye blink frequency is even greater still during fixation tasks and following the completion of a task (Tada & Iwasaki, 1985). Due to the similar nature of the search tasks by Tada and Iwasaki (1985) and the VSST, one would expect that spontaneous blinks would infrequently occur during horizontal trials, more frequently during the vertical trials and be most common at the completion of trials.

To exclude spontaneous blinks from saccade calculations, there must first be an understanding of their dynamic components. The eyelid movements during spontaneous blinks have maximum velocities around $565 \pm 297^\circ/s$, which is a similar speed to a $20^\circ$ saccade. The duration of spontaneous blinks lasts for $334 \pm 67$ ms; the down phase (eyelid closing) of the blinks lasted $92 \pm 17$ ms and the up phase (eyelid opens) lasted $242 \pm 55$ ms (VanderWerf et al., 2003).

In addition to the artefact caused by the eyelid movement of a blink, spontaneous blinks also cause transient downward and nasalward eyeball rotations of between $1^\circ$ and $5^\circ$ during the closure (Collewijn et al., 1985; Rottach, Das, Wohlgemuth, Zivotofsky, & Leigh, 1998, Rambold et al., 2002). Collewijn and colleagues (1985) suggested that blink related eye movements are not saccadic because saccades have shorter durations and faster speeds. In comparison, a transient $2^\circ$ eyeball rotation during a blink lasts 100 ms and covers $40^\circ/s$, whilst a $2^\circ$ saccade lasts for 40 ms and covers $60^\circ/s$. An appropriate minimum velocity or amplitude threshold would potentially exclude these transient eyeball rotations.

### 3.2 Saccade Detection Methods

Most saccade detection methods rely on displacement, velocity (first derivative), acceleration (second derivative) or even jerk (third derivative) to determine saccadic activity or to exclude saccades from eye movement data (Tole & Young, 1981). These methods include:

(2) Position reset criterion (Collewijn, Curio, Grüsser, 1982).
(3) Velocity profile (Bahill et al., 1975a).
(4) Percentage of peak eye velocity (Bahill et al., 1975a; Barnes et al., 1997).
(6) Acceleration thresholds (Behrens & Weiss, 1992; Kowler et al., 1995; Behrens & Weiss, 1999; Wells & Barnes, 1999; Morgan, 1999).
(7) Velocity and acceleration thresholds (Kowler & Steinman, 1979; Collewijn & Tamminga, 1984; Zaccara, Baldini, Gangemi, Messori, Parigi, & Nencioni, 1991; Ross, Thaker, Buchanan, Kirkpatrick, Lahti, Medoff, Bartko, Goodman & Tien, 1997; Katsanis, Iacono, & Harris, 1998; Crawford, Sharma, Puri, Murray, Berridge & Lewis, 1998; McPeek & Keller, 2002; Rambold et al., 2002; Duchowski et al., 2002).
(9) Filter methods:

- Non-recursive adaptive digital filter (Tole & Young, 1981; Juhola et al., 1985).
- Kalman Filter (Sauter et al., 1991).
- Damping Ratio (Chen, Chen, Lin & Tsai, 1998).

### 3.2.1 Amplitude Variance

This method determines that a saccade has occurred when a ‘zero crossing’ was detected (Troelstra & Garcia, 1974). Whenever the recorded signal crosses the baseline at zero, the eight pre-zero crossing data points and the eight post-zero crossing data points determine Saccade Amplitude. The first data points on either side of this zero crossing were excluded. The median value of the remaining seven pre-zero data points were then deducted from the median value of the post-zero data-points. The remaining value was a good estimate of Saccade Amplitude. However, because the median value was used, this technique cannot accurately calculate saccade onset or termination and hence does not allow Saccade Duration and Peak Saccade Velocity evaluation.
A saccade was detected when the amplitude made a zero crossing. The median of the pre-zero crossing data points were deducted by the median of the post-zero crossing data points to estimate saccade amplitude (extracted from Troelstra & Garcia, 1974, p.234).

Blink detection was also possible using the ‘zero crossing’ method (Troelstra & Garcia, 1974). Blinking during the recording caused positive deflections. Each time a negative zero crossing occurred, a check determined whether the eight pre-event samples were positive. If not, a blink had probably occurred. The only other reason for the eight pre-zero samples not to be positive was because the fixation was not long enough. The nature of Troelstra and Garcia’s task dictated that fixations of 1.5 seconds were expected. For their task, the zero crossing method could distinguish between a saccade and blink. However, in other tasks involving limited exposure times, it would be an unrealistic expectation that fixations would last as long.

Dick (1978) also used amplitude to identify artefact and measure amplitude, but his method also determined saccade onset. To identify saccade onset, Dick (1978) chose an amplitude threshold after analysis commencement. This amplitude threshold was designed to identify the onset of 30° saccades. The threshold appears to be about 10° although this could vary with different Saccade Amplitudes. There is no mention on how to detect the saccade end-point. A similar technique by Duchowski and colleagues (2002) was used to identify the stationary portions of the signal. When the visual angle did not alter by 3° for 300 ms, this portion of the signal was deemed a fixation. Periods outside this were considered saccades.

Jüttner and Wolf (1992) described another saccade detection method based on amplitude. Two regression lines were passed through the eye movement record until
their angle of intersection passed through a maximum. When the two lines met, the corresponding point of intersection provided a robust method for Saccade Latency.

Brigell and colleagues (2003, ISCEV) suggested the use of an amplitude criterion would adequately exclude blinks and unwanted artefacts from signals. They suggest that the rejection threshold should be greater than the expected amplitude of the physiological signal and background physiological noise (pg.13).

### 3.2.2 Position Reset Criterion

The slow and fast phase recorded during OKN movements helps define this saccade detection method. The fast phase is a saccadic eye movement. It can easily be detected because the fast phase of the signal deflects in the opposite direction, or the ‘position resets’ itself back to the original baseline. This allows easy determination of the beginning and end of the saccade by the position signal (Collewijn et al., 1982).

### 3.2.3 Velocity Profile

The amplitude variance and position reset criterion both have difficulty determining Saccade Duration, and to a lesser extent Saccade Amplitude, because it is hard to determine the precise start and end-point of a saccade by a position versus time graph. A velocity versus time graph identifies the start and end points more accurately due to the sharper rise or fall in signal at these points.

Bahill, Clark and Stark (1975a) mention six possible methods for detecting saccades based on a velocity profile. The first is the zero-zero method. A saccade is identified when the velocity at the beginning of the saccade is zero and the velocity at the end of the saccade is zero. However, this does not account for undershoot or overshoot, which would make duration abnormally smaller or larger respectively.

The second method uses a ‘critically damped saccade’ of the same amplitude and peak velocity to trace the end over the undershooting original saccade. The new velocity trace shows where the end velocity is at zero. The zero-zero method can then be used to calculate duration. However, this same technique cannot be used for overshooting saccades (Bahill et al., 1975a).
Methods 3, 4 and 5 all use similar techniques to those above. Method 3 measures from zero velocity at the start to the second zero velocity at the ending. Method 4 measures zero velocity at the start to peak negative velocity. Method 5 traces an ideal velocity ending to estimate *Saccade Duration* (Bahill *et al.*, 1975a).

It must be stated that Bahill, Clark and Stark (1975a) preferred another method to the five mentioned here; this method is one of the few saccade detection methods that does not rely on differentiation. The ‘pulse width modulation model’ (Bahill *et al.*, 1975a), in which the width of the controller signal determines the saccadic amplitude, duration and peak velocity is but one.

Bahill, Clark and Stark (1975a) suggest that using digital differentiation easily determines peak velocity of a saccade. Duration and amplitude pose more of a problem. The above methods also do not account for noisy signals. Zero velocity readings are very precise, so any interference may cause larger amplitudes or longer durations.

### 3.2.4 Percentage of Peak Eye Velocity

Another method of saccade detection was based on the velocity profile of the recorded signal. This method used the precise figure of *Peak Saccade Velocity* and gauged where 10% of the peak velocity rise time lay. This point was defined as saccade onset. 90% of the peak velocity rise time determined saccade termination (Bahill *et al.*, 1975a). This same approach was extended by others by using a regression line to plot the next 100ms of the velocity data (Barnes *et al.*, 1997). This line was extrapolated back towards zero to determine the beginning of the saccade. This estimate of saccade onset proved to be quite precise. Other researchers have varied the percentage used to as low as 5% of *Peak Saccade Velocity* (Rambold *et al.*, 2002). The maximum saccade velocity range was approximately 150-500°/s, which equates to a velocity threshold of between 7.5-25°/s. The saccade begins and ends when the saccade velocity rises above this threshold.
3.2.5 Velocity Thresholds

Arguably, the simplest and most widely used saccade detection algorithm is the velocity threshold method (Juhola et al., 1986). There are many variations of velocity calculations but the most common method is based on a 2-point central difference algorithm that calculates the difference between two consecutive position values over time (Bahill et al., 1981; Bahill & McDonald, 1983; Inchingolo & Spanio, 1985). Quite often accompanying a velocity threshold was either an amplitude or a duration threshold depending on the algorithm requirements. An amplitude or duration threshold reduces the chance of incorrectly identifying noise as small saccades within the recording.

Baloh, Sills, Kumley and Honrubia (1975b) defined saccade onset when velocity exceeded the minimum velocity threshold of 40°/s for a period longer than 30 ms. The saccade ended when the velocity dropped back below 40°/s. The same research group revised the minimum duration threshold to 40 ms just one year later (Baloh, Kumley & Honrubia, 1976). Juhola, Jantii and Aantaa (1986) also employed the same parameters although they acknowledged that the threshold values could sometimes be inappropriate for detecting small saccades.

Baloh, Langhofer, Honrubia and Yee (1980) attempted to quantify saccades, smooth pursuit, and nystagmus eye movements using velocity thresholds. A saccade was defined as continually exceeding a minimal velocity of approximately 4°/s for at least 20 ms duration and has a minimum peak velocity of 140°/s. This was expected to also eradicate any small eye movements less than 5° amplitude. Movements conforming to the above amplitude, velocity and duration criteria but occur in the opposite direction with less than 100 ms in between movements were discarded as probable blinks. Nystagmus was identified using a minimum peak velocity of 70°/s to identify saccades as small as 1° in amplitude. Nystagmus was more difficult to define since some slow eye movements may reach velocities that place them in a fast category range. A direction criterion is used to ensure that noisy slow components (with velocities of 70°/s) are not mistaken as fast components.

Smith, Bittencourt, Lloyd and Richens (1981) used a velocity threshold to identify primary and corrective saccades. A corrective saccade was identified when the velocity
passed 100°/s for more than 30 ms. However, the corrective saccade had to appear within 300 ms of the end of the primary saccade.

Another study compared minimum velocity threshold values of 10°/s and 50°/s whilst enforcing minimum amplitudes of 5° (Inchingolo & Spanio, 1985). They made some interesting findings. Firstly, by employing high sampling rates (1000 Hz) and cut-off frequencies (75 Hz), the peak velocities were considered more accurate (which are not affected by the rounding of lower sampling/filter settings). They also noted that using the higher velocity threshold decreases the apparent Saccade Duration. This is understandable as the higher the velocity threshold, the fewer data points that will exceed the threshold, and hence reduce the Saccade Duration. They concluded that the 10°/s threshold produced the best signal processing

Gangemi, Messori, Baldini, Parigi, Massi and Zaccara (1991) were the first researchers to utilise different saccade onset and termination velocities and durations. The start of the saccade had to move more than 20°/s for at least 32 ms and then to end drop below 10°/s for at least 8 ms. This hysteresis type effect made it harder for noise to effect saccade detection because it required consistent higher than threshold velocities over a long period to register a saccade but when detected, it made it more difficult to be terminated.

Other researchers also chose different velocity thresholds for saccade onset and termination but decided not to use an amplitude or duration criterion. Radant and Hommer (1992) used a 50°/s threshold to detect saccade onset and a 40°/s threshold for saccade termination whilst Rottach et al., (1998) chose 40°/s as saccade onset and 25°/s for saccade termination.

Apart from saccade detection, velocity thresholds could also determine artefact or blinks. Generally, a high upper velocity threshold was chosen such as 800°/s (Balogh, Kumley & Honrubia, 1976), 850°/s (Radant & Hommer, 1992) or 1000°/s (Bahill & Kallman, 1983) because saccades do not exceed this maximum velocity, while blinks and electronic artefact occasionally do. However, some researchers preferred considerably smaller thresholds of 200°/s although acknowledging that some spikes
exceeded 1000°/s (Juhola et al., 1987). In this way they could distinguish between spikes and saccades because almost all spikes were higher than 200°/s whilst saccadic velocities were between 50°/s and 200°/s at the beginning of the saccade. Unfortunately, Juhola and colleagues fail to acknowledge that saccades often reach velocities higher than 200°/s, especially in their task involving consistent 20° saccades, and then fail to provide an explanation for how they differentiate the saccade from artefact during these overlaps.

Additionally, when velocity signals in one direction were followed immediately by another high velocity interval in the opposite direction, a blink was deemed to have occurred and therefore excluded (Radant & Hommer, 1992). On many occasions, a visual inspection was still employed to double-check that errors had not been made (Balloh et al., 1975b; Baloh, Kumley & Honrubia, 1976; Smith et al., 1981).

3.2.6 Acceleration Thresholds

Researchers have used acceleration as a threshold criterion because of the confusing velocity overlap between faster smooth pursuit, and slower saccades (Behrens & Weiss, 1992; Behrens & Weiss, 1999; Morgan, 1999; Wells & Barnes, 1999). An acceleration threshold of 800°/s² to 1000°/s² was expected to distinguish the two components of the eye movements because saccades began more rapidly than smooth pursuit. A rise above and drop below this threshold respectively denoted the onset and termination of the saccade. Absolute values of acceleration were used to avoid direction of the saccade and to avoid zero crossings. In some instances either a minimum Saccade Duration threshold of 12 ms (Behrens & Weiss, 1992, Behrens & Weiss, 1999; Morgan, 1999), or a maximum Saccade Duration threshold of 100 ms (Behrens & Weiss, 1992) or a Saccade Amplitude threshold of 5° (Morgan, 1999) were used in combination with the acceleration criterion. Thus, both normal and small saccades can be detected reliably.

3.2.7 Velocity and Acceleration Thresholds

Kowler and Steinman (1979) used both velocity and acceleration criteria to detect saccades. Small saccades (5-10°) were identified using acceleration criteria typically of the range 75°/s² - 100°/s² for exclusion from the data. Large saccades were detected when a 15° displacement between two successive samples (10 ms apart) and an increase
in eye velocity of at least 200°/s between two successive pairs of 10 ms samples was reached. Visual inspection confirmed the computer algorithm correctly marked the onset of saccades.

Zaccara, Baldini, Gangemi, Messori, Parigi, and Nencioni (1991) used velocity, acceleration and duration thresholds. The start of the saccade was identified after exceeding a velocity of 100°/s for 16 ms duration. The end of the saccade was then defined as a drop below 100°/s for at least 8 ms. However, more interestingly an acceleration threshold of 1500°/s² was used to identify the exact beginning and end of the saccade. Saccades as small as two degrees were accurately identified at the expense of incorrectly including some electronic noise as saccades.

Other studies have similarly made use of velocity and acceleration criteria to detect saccades. One study involving a smooth pursuit task (target speed of 23°/s) set the minimum velocity threshold of saccades at 28°/s (Katsanis et al., 1998) but failed to disclose the acceleration threshold. Another study also failed to elaborate on the acceleration threshold (Crawford et al., 1998) but mention that a velocity threshold of 30°/s was used in addition to an acceleration across three consecutive samples (sampling frequency not mentioned). Yet another study used a velocity threshold of 130°/s and an acceleration threshold of 1000°/s² (Duchowski et al., 2002) believing this would reliably detect saccades greater than 3°. The Main Sequence was used to estimate duration. They claim that velocity based analysis is easier to deal with, but more sensitive to noise resulting in more saccades being detected than were present.

Other studies have also reported the use of velocity and acceleration criteria in the detection of saccades. However, the authors failed to include either threshold (Collewijn & Tamminga, 1984; Ross, Thaker et al., 1997; McPeek & Keller, 2002). McPeek and Keller (2002) did suggest that each trial was visually inspected to verify the accurate identification of saccades.

3.2.8 Jerk and Acceleration

Wyatt (1998) used a jerk threshold of 200,000°/s³ for saccade onset detection. Criterion for termination used an acceleration (±1200°/s²) for two consecutive 6 ms samples. The
benefit of using jerk is that it is possible to pick-up smaller eye movements, which an
algorithm based on acceleration, would miss.

Wyatt (1998) suggests that going from velocity detection to acceleration detection to
jerk detection improves saccade discrimination. However, this algorithm also increases
the noise component and requires more samples to perform the calculation, thus
reducing saccade onset accuracy.

3.2.9 Filtering Methods

Numerous authors have used varying digital filtering methods to reduce the amount of
noise present in the signal and extract the essential aspects. They perform these methods
on position, velocity or acceleration.

Bahill and McDonald (1983) suggest the easiest method of calculation for computing
derivatives is the two-point central difference algorithm. This method has also been
used by others (Bahill & Kallman, 1983; Barnes et al., 1997, Ueno, Tateyama, Takase
& Minamitani, 2002). Methods such as a standard forward difference technique (Somia,
Rash, Epstein, Wachowiak, Sundine, Stremel, Barker, & Gossman, 2000) and
differentiation and median filtering (Kingma, Gullikers, de Jong, Jongen, Dolmans,
Stegeman, 1996) have also been used.

3.2.9i Non-recursive Adaptive Digital Filter

Tole and Young (1981) use a finite impulse response (non-recursive) for calculating
saccade onset. It filters acceleration with nine samples. If the filter identifies a peak that
were above acceleration threshold A (saccade begins), and then identifies a second peak
greater in magnitude than threshold B (saccade ends), and finally passes the minimum
and maximum duration thresholds, then a saccade has been deemed to have taken place.
However, Tole and Young (1981) criticise set threshold levels because artefact can
cause false identification of saccades when noise is present in the signal. Therefore, the
thresholds were made functions of Root Mean Squares (RMS), so they become adaptive
to recent acceleration history.

Juhola, Jäntii, Pyykkö, Magnusson, Schalén and Åkesson (1985) also use a non-
recursive adaptive digital filter for saccade detection. The filter produces a floating
mean, which substitutes for the velocity threshold. The threshold they use was computed at the outset of the displacement signal, which does not contain a saccade. Filtered output values are determined from the displacement values. The threshold was assigned to the mean of these output values. The filtered values also define their own amplitude and duration criteria. To successfully determine whether the detected signals are saccades or blinks and interference, the signal is passed through another criterion. The specific parameters are not mentioned, but it follows a basic velocity threshold algorithm.

### 3.2.9ii Kalman Filter

A Kalman filter is a recursive technique used for obtaining the solution to a least squares fit. It is useful for a number of reasons. You do not require \textit{a priori} knowledge of the eye dynamics or their signal, there is a high immunity to noise, and it could be used for on-line analysis (Sauter \textit{et al.}, 1993).

Sauter and colleagues (1991) used a second-order autoregressive model to predict eye movement velocity. An autoregressive model uses previous data to predict future data. Comparisons are made between the predicted velocity values and the actual velocity values. The squared difference between the predicted velocity and the actual velocity of the signal was called innovation. The squared difference was highest when a saccade occurs. After the final calculation of innovation, a Chi-square test was performed on it to determine how reliable the detection of each saccade was.

### 3.2.9iii Damping Ratio

The damping ratio also uses a Kalman filter to differentiate position profiles. The position profile was characterised by a transfer function. Using the least-mean-square (LMS) algorithm, the position profile can be fitted by a transfer function of any given order (Chen \textit{et al.}, 1998).

Chen, Chen, Lin and Tsai (1998) propose that the damping ratio could be useful parameter in analysing saccadic dynamics and it even offers an alternative method to velocity profiles. Damping ratio was expected to be a more sensitive quantification parameter than the peak velocity.
3.3 Saccade Detection Criteria

Reviewing previous saccade detection methods allowed an informed decision to be made regarding acceptable criteria that were advantageous to saccade detection and extraction. The outcome of these decisions were to ensure that the methods and thresholds chosen were capable of accurately calculating the dependent variables mentioned in chapter 2 i.e. Saccade Rate, Saccade Amplitude, Mean Peak Saccade Velocity, and Saccade Latency.

The most popular saccade detection methods utilised were minimum velocity and acceleration thresholds. Fixed minimum velocity thresholds spanned from 25°/s up until 130°/s, with the most popular thresholds ranging 40-50°/s. Acceleration thresholds varied between 800-1500°/s² with the popular choice around 1000°/s². Considering that one of the distinguishing characteristics of a saccade is their high velocities, it would be wise to consider one of these popular methods in the algorithm. A saccade would need to exceed a velocity or acceleration threshold before a saccade registers. However, because there is such a considerable overlap in velocities between saccadic and smooth pursuit movements, it requires a delicate procedure to distinguish the two components (Sauter et al., 1991).

In addition to the use of a minimum velocity threshold, a maximum velocity threshold of 800-1000°/s would exclude high frequency interference. Furthermore, to ensure muscle artefact or blinks were not mistaken for saccades, the deviation in signal should remain above the minimum velocity threshold for a given duration. Duration thresholds ranged between 12-40 ms with the majority at around 25 ms. A duration criterion was similar to having an amplitude criterion because of the close linear relationship between Saccade Amplitude and Saccade Duration (Bahill, Clark & Stark, 1975a). If the algorithm were trying to look at small micro-saccades, then duration had to be quite short to allow inclusion. However, the algorithm was not looking for micro-saccades because firstly, the spatial resolution of the EOG was unlikely to distinguish a micro-saccade from noise and secondly, the distance between targets in the VSST is 14° making their presence unlikely. Therefore, the algorithm could use both an amplitude threshold and duration threshold to facilitate this.
Unfortunately, throughout the multitude of publications on saccade detection, not one article acknowledged that saccade velocity and blink velocity overlapped. This was possibly because most algorithms relied upon the maximum velocity threshold to differentiate them. To overcome this reliance, once the algorithm processed the data the signal was visually checked to determine if any erroneous data had been incorrectly included as saccades. In the case of blinks, if a signal deflection was followed almost immediately by a second deflection in the opposite direction of similar amplitude, then a blink was likely to have occurred. In tasks involving predictable movements or movements in one direction, this combination would visibly stand out and therefore allow exclusion. However, in the VSST the scanning behaviour was unpredictable and different for each participant so such a rule may not be feasible. Surprisingly, the short pause between the two consecutive deflections (the eyelid closure period) was never compared to the minimum time required to fixate on an object.

It was apparent that one single criterion was insufficient to resolve the issue of saccade detection. If velocity were the sole criterion, and a velocity of 40°/s were chosen, then it was possible that smooth pursuit components would be confused with saccades. It was also possible that if a 130°/s threshold were chosen, which rules out smooth pursuit, then a single velocity data point could cause a saccade to register due to noise in the signal. The addition of a minimum duration threshold, such as 12.5 ms used by others (Behrens & Weiss, 1992; Morgan, 1999), avoids single erroneous data points being included as saccades. However, it was still possible that noisy components of the signal registered as small saccades. The velocity threshold and Saccade Duration threshold may not entirely eradicate these from saccade membership. However, a Saccade Amplitude threshold of 5° would reject all small saccades within the signal including corrective saccades. Finally, a maximum velocity threshold would rule out other forms of artefact such as blinks with a subjective check used for confirmation. Therefore, a combination of criteria should be used to assess the eye movement signal.

Supplied with this information, it was worth checking to see what effect setting fixed thresholds had on a number of situations designed to test the algorithm for accuracy and reliability. The fixed thresholds were a minimum Saccade Amplitude threshold of 5°
and a minimum *Saccade Duration* of 12.5 ms. The velocity threshold was the most contentious of all the thresholds. Rather than assuming smooth pursuit does not take place due to the nature of the VSST and choosing a small velocity threshold, an objective method of excluding smooth pursuit eye movements was preferable. Three velocity thresholds of 40°/s (a common saccade detection threshold based on earlier studies), 100°/s (a conservative measure) and 130°/s (the maximum smooth pursuit velocity recorded) were selected. This range of velocity thresholds reflects the overlap of smooth pursuit and saccadic eye movement velocities.

The importance of choosing a velocity threshold can not be underestimated considering it affects all saccade variables, namely *Saccade Amplitude*, *Saccade Duration*, *Saccade Rate* and *Peak Saccade Velocity*. A high velocity threshold would likely cause a delay to saccade onset and a premature saccade termination, which reduces both *Saccade Amplitude* and *Saccade Duration*. However, a smaller velocity threshold would possibly allow more saccades to register increasing *Saccade Rate*. *Peak Saccade Velocity* was expected to remain unchanged regardless of the velocity threshold chosen.

### 3.4 Method

A saccade detection algorithm was developed to accurately extract the saccades during the VSST. There were three threshold values of interest: minimum duration, minimum amplitude and minimum velocity thresholds. Minimum duration threshold was preset to 12.5 ms (6 data-points @ 2.083 ms/sample) and the minimum amplitude threshold was fixed at 5°. The minimum velocity threshold was set to one of three values: 40°/s, 100°/s and 130°/s.

All simulated and raw EOG data were differentiated using a 2-point central difference algorithm to extract saccade velocity. These values were then compared to the velocity threshold. If the differentiated value was above this threshold, then saccade membership was achieved. Saccade membership assigns an arbitrary value of either zero for non-membership or ten for membership. The algorithm then polls through the saccade membership for a minimum of six consecutive samples (12.5 ms) that vary in amplitude by greater than 5°. If the data passes all three criteria, then a saccade is registered and evaluated further.
The saccade detection algorithm was assessed using four test situations; simulated smooth pursuit scanning, real EOG amplitude calibration routine data, real VSST data and real blink data.

### 3.4.1 Simulated Smooth Pursuit Scanning

Simulated digital waveforms are a noise-free technique for checking that the data extraction algorithm was performing the task according to its threshold requirements. Baloh and colleagues (1980) used this technique to confirm the reproducibility of their saccade detection algorithm whilst others used it to simulate 50 Hz noise (Juhola, 1991).

In this first test of the algorithm, a sinusoidal waveform was created to simulate smooth pursuit scanning of the experimental display board used in the VSST. To simulate this, a 56° peak-to-peak amplitude, 0.75 Hz simulated sinusoidal waveform was used, eliciting maximum smooth pursuit scanning at 132°/s which is very close to the known maximum velocity of 130°/s (Bahill & LaRitz, 1984). The use of this waveform would show how effective each of the proposed minimum velocity thresholds were in the saccade detection algorithm. The best-performed algorithm in this test situation would detect the least number of saccades because no saccades were present.

### 3.4.2 Actual EOG Amplitude Calibration Routine Recording

The second algorithm test situation involved a single participant performing a standard EOG amplitude calibration routine. The participant, chosen at random, was a 32 year-old female with no history of eye disorders and 20/20 vision. Electrodes were connected to the participant in the manner described in Chapter 2 to record horizontal EOG. The participant then performed a 6-trial EOG amplitude calibration routine.

Correct performance of the task would entail a single saccadic eye movement to the left (spanning 28°), then four saccades to the right (spanning 14°). Fixations would separate each saccade to make them very distinct. It was possible that the participant may make a final saccade back to the central LED. With this prior knowledge, it was expected that either 5 or 6 saccades would be generated, and that their amplitude would be consistent with each visual angle step. An accurate algorithm would confirm this.
3.4.3 Actual Visual Search Strategy Task Recording

The third algorithm test situation was of a participant performing the VSST. A 24 year-old male without history of eye disorders and 20/20 vision volunteered to perform 12 trials of the horizontal VSST. Each trial had a blank pre-stimulus for 1500 ms and an exposure time of 1000 ms. EOG set-up, preparation and calibration occurred in the same manner described in Chapter 2. The calibrated signal was passed through the algorithm offline to detect and evaluate the saccades generated.

In this test situation there was no objective measure of actual saccade performance because the participant was not told to perform the task in a set way. However, the data was subjectively checked offline to determine how many saccades were present.

3.4.4 Actual Blink Test Recording

In this fourth test of the algorithm, two participants were chosen to perform a task designed to generate spontaneous blinks. The participants were chosen from a group who had prior EOG testing experience. One participant was a 25 year-old male and the other a 25 year-old female. Standard EOG electrode placements (see Chapter 2) were used for horizontal and vertical recordings.

The participants were instructed that the test was to assess the integrity of the EOG system. Each participant was asked to look straight ahead and fixate only on the central LED display for approximately 2 minutes. EOG was recorded continuously during this time. Participants were not instructed to blink, but often did so spontaneously. The investigator then marked on the recorded signal at which points they observed the participant spontaneously blink. The task was performed twice by each participant; once for horizontal EOG recordings and once for vertical EOG recordings. Data that contained blinks were extracted. The signal was calibrated offline and then passed through the saccade detection algorithm to see if blinks were falsely identified as saccades.
3.5 Results

3.5.1 Simulated Smooth Pursuit Scanning

Figures 3.5.1a-c show the green simulated 0.75 Hz sinusoidal waveform with peak-to-peak amplitude of 56°. The unshaded areas (Figures 3.5.1a-c) signify the 1000 ms exposure time and indicate the cut-off point for when the algorithm both starts (1500 ms) and stops (2500 ms) searching for saccades. This simulates the normal blank pre-stimulus (up until 1500 ms) and visual mask (after 2500 ms) of the VSST. A saccade membership (denoted by the blue line in Figures 3.5.1a-c) of ten was obtained when the algorithm detected the signal rising above the velocity threshold. A saccade membership of zero was obtained when the velocity fell below the threshold. The orange line (Figures 3.5.1a-c) indicates that saccade registration has occurred after all algorithm conditions were met. The three graphs of Figure 3.5.1 represent the different algorithms with their own unique minimum velocity threshold [(a) 40°/s (b) 100°/s and (c) 130°/s]. Each had varying effects on the results.

In Figure 3.5.1a, the algorithm utilising a 40°/s velocity threshold detected three saccades with amplitudes of 6.64°, 53.34° and 6.64° respectively (denoted by the three orange lines). Further evaluation of these saccades are summarised in Table 3.5.1. In Figure 3.5.1b, the 100°/s velocity threshold algorithm detected only a single saccade and evaluated the amplitude as 36.16° and the Peak Saccade Velocity as 131.97°/s. Further evaluation of this saccade is shown in Table 3.5.1. In Figure 3.5.1c, the 130°/s velocity threshold algorithm detects only a single saccade and evaluates the amplitude as 9.57° and Peak Saccade Velocity of 131.97°/s. The saccade was summarised in Table 3.5.1.
Figure 3.5.1a-c: The simulated smooth pursuit waveform (0.75 Hz sinusoidal waveform) analysed using the various minimum velocity thresholds: The uppermost graph (A) was analysed with a minimum velocity threshold of 40°/s. The middle graph (B) with a minimum velocity threshold of 100°/s and the bottom graph (C) with a minimum velocity threshold of 130°/s. Amplitude values in degrees of visual angle are plotted on the y-axis and time in seconds on the x-axis. The lines are marked according to the following colours: Green - Simulated Signal, Blue - Saccade Membership and Orange - Saccade Registration. The Exposure Time, indicated by the non-shaded areas, lasts from 1500 ms to 2500 ms. Saccade Membership is accepted (value = 10) when signal velocity is above the velocity threshold. Non-membership receives a value = 0. Saccade Membership does not take into account Saccade Duration (minimum 12.5 ms) or Saccade Amplitude (minimum 5°) thresholds. Saccade Registration occurs when all criterion are accepted.
Table 3.5.1 is a summary table highlighting how the proposed minimum velocity thresholds of 40°/s, 100°/s and 130°/s process the simulated smooth pursuit waveform. If the simulated waveform had no amplitude, duration and velocity thresholds applied to it, three deflections would occur within the designated exposure time. The first and third deflections would measure 8.20° in amplitude and the second deflection 56°. The peak velocity for the first and third deflection measures 91.93°/s and the second deflection 131.97°/s. Average velocity and duration were also calculated.

Table 3.5.1
Impact of Minimum Velocity Thresholds on Simulated Smooth Pursuit Scanning

<table>
<thead>
<tr>
<th>Deflection Number</th>
<th>Saccade Amplitude (°)</th>
<th>Peak Saccade Velocity (°/s)</th>
<th>Average Saccade Velocity (°/s)</th>
<th>Saccade Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.20</td>
<td>91.93</td>
<td>49.76</td>
<td>166.64</td>
</tr>
<tr>
<td>1</td>
<td>6.64</td>
<td>91.93</td>
<td>67.22</td>
<td>99.98</td>
</tr>
<tr>
<td>2</td>
<td>53.34</td>
<td>131.97</td>
<td>92.92</td>
<td>537.41</td>
</tr>
<tr>
<td>3</td>
<td>6.64</td>
<td>91.93</td>
<td>67.22</td>
<td>99.98</td>
</tr>
</tbody>
</table>

(40°/s Threshold (Figure 3.5.1a)

| 1                 | -                      | -                           | -                             | -                     |
| 2                 | 36.16                  | 131.97                      | 121.25                        | 299.95                |
| 3                 | -                      | -                           | -                             | -                     |

(100°/s Threshold (Figure 3.5.1b)

| 1                 | -                      | -                           | -                             | -                     |
| 2                 | 9.57                   | 131.97                      | 131.28                        | 74.99                 |
| 3                 | -                      | -                           | -                             | -                     |

(130°/s Threshold (Figure 3.5.1c)

Table 3.5.1 highlights some important trends. As the algorithm’s minimum velocity threshold increases, both Saccade Amplitude and Saccade Duration decrease. This is understandable because fewer data points rise above the minimum velocity threshold and hence cause both variables to reduce in magnitude. In addition, the higher the minimum velocity threshold, the more Average Saccade Velocity is overestimated. This is also understandable because only higher velocity values are accepted, thus eliminating the lower velocities and raising the overall Average Saccade Velocity. Peak Saccade Velocity remains unchanged regardless of the velocity threshold used. Perhaps the greatest concern is that the lower the velocity threshold, the greater the likelihood of overestimating Saccade Rate. In a noise free simulation this is almost irrelevant.
however, the EOG recordings will not be noise free so it increases the probability of detecting noise and evaluating them as saccades.

The accuracy of the algorithm was demonstrated in a number of ways. Firstly, saccade 1 and 3 have peak saccade velocities of 91.93°/s, so the velocity thresholds of 100°/s and 130°/s should not cause saccade membership, which they do not. Secondly, all three velocity thresholds detect saccade 2 and all record the same Peak Saccade Velocity. As this is only a single point from each simulated signal, the algorithm was able to extract it consistently and accurately. Finally, the effect of changing the velocity threshold has predictable affects that would not be the case if the algorithm were inaccurate.

3.5.2 Normal EOG Amplitude Calibration Routine Recording

Following the completion of the EOG amplitude calibration routine, the data were calibrated using all six trials and one calibrated trial was taken at random from that group. The saccade detection and evaluation algorithm processed that trial using each minimum velocity threshold.

Figure 3.5.2a shows the calibrated amplitude result (green line) of the participant performing one trial of the EOG amplitude calibration routine. Figure 3.5.2b shows the same trial depicting velocity over time rather than amplitude over time (green line). The unshaded areas (Figures 3.5.2a-b) reveal the 3000 ms exposure time and indicate the cut-off point for when the algorithm both starts (1500 ms) and stops (4500 ms) searching for saccades. This simulates the normal pre-stimulus (up until 1500 ms) and visual mask (after 4500 ms) for the calibration routine. A saccade membership (denoted by the blue line in Figures 3.5.2a) of ten is obtained when the algorithm detects the signal rising above the velocity threshold. A saccade membership of zero was obtained when the velocity was below the threshold. An orange line (Figures 3.5.2a-b) reveals when saccade registration occurs after all algorithm conditions were met.

The expectation after calibration was that either 5 or 6 saccades would be made during each trial and that their amplitude would be consistent with the visual angle step of 14° or 28°. Figure 3.5.2a shows that the participant made six saccades beginning with a single saccade to the left (positive 28°), then four saccades to the right (decreasing in
$14^\circ$ increments). The participant made one final $28^\circ$ saccade back to the central segment. Fixations of approximately 500 ms were recorded at the completion of each saccade.

Figure 3.5.2a-b: Example of an EOG calibration trial analysed using the $130^\circ$/s minimum velocity threshold. The lines are marked according to the following colours: **Green** – Calibrated Signal, **Blue** - Saccade Membership, and **Orange** - Saccade Registration. The Exposure Time, indicated by the non-shaded areas, lasts from 1500 ms to 4500 ms. The Exposure Time is standard for an EOG amplitude calibration routine trial. **Saccade Membership** is accepted (value = 10) when signal velocity is above the velocity threshold. Non-membership receives a value = 0. **Saccade Membership** does not take into account Saccade Duration (minimum 12.5 ms) or Saccade Amplitude (minimum $5^\circ$) thresholds. **Saccade Registration** occurs when all criterion are accepted. Figure 3.5.2a plots amplitude over time while Figure 3.5.2b plots velocity over time. Both figures depict exactly the same trial.

Figure 3.5.2b shows the differentiated signal change over exactly the same time course as Figure 3.5.2a. An orange line (Figures 3.5.2b) reveals when saccade registration occurs after all algorithm conditions were met. The figure correctly shows that velocities below the $130^\circ$/s velocity threshold do not cause saccade registration. Table 3.5.2a shows a summary of values extracted from the three minimum velocity thresholds compared to the actual data. Although the actual amplitudes of the task are
known due to the nature of the task, the values for Peak Saccade Velocity, Average Saccade Velocity or Saccade Duration cannot be known.

Table 3.5.2a
Impact of Minimum Velocity Thresholds on Saccade Variables during the EOG Amplitude Calibration Routine

<table>
<thead>
<tr>
<th>Saccade Rate</th>
<th>Mean Saccade Amplitude (°)</th>
<th>Mean Peak Saccade Velocity (°/s)</th>
<th>Mean Average Saccade Velocity (°/s)</th>
<th>Mean Saccade Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Data</td>
<td>6</td>
<td>18.67</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>40°/s Threshold</td>
<td>6</td>
<td>20.35</td>
<td>498.66</td>
<td>306.34</td>
</tr>
<tr>
<td>100°/s Threshold</td>
<td>6</td>
<td>19.87</td>
<td>498.66</td>
<td>334.38</td>
</tr>
<tr>
<td>130°/s Threshold</td>
<td>6</td>
<td>19.50</td>
<td>498.66</td>
<td>349.15</td>
</tr>
</tbody>
</table>

n = 1 trial for each velocity threshold

Table 3.5.2a shows all three algorithms successfully detected all six saccades. Furthermore, all the algorithms proved accurate in their evaluation of Saccade Amplitude. The 130°/s minimum velocity threshold was marginally closer than the other velocity thresholds to the actual Mean Saccade Amplitude. Additionally, the results show the same trends as first observed in the simulated smooth pursuit scanning test: Mean Saccade Amplitude and Mean Saccade Duration decrease whilst Mean Average Saccade Velocity increases with an increasing minimum velocity threshold. Mean Peak Saccade Velocity remains unchanged.

Table 3.5.2b is a further break down of each amplitude of all six saccades performed during the amplitude calibration routine. The actual amplitudes are shown in the first row. The evaluated amplitudes for all three velocity thresholds are shown in the next three rows and are very close to the actual amplitude. It is worth noting that for all saccades except saccade 5, the evaluation overestimates amplitude. This is most likely due to the accuracy of the calibration as opposed to a limitation of the velocity thresholds.
Table 3.5.2b

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Saccade 1 Amplitude (°)</th>
<th>Saccade 2 Amplitude (°)</th>
<th>Saccade 3 Amplitude (°)</th>
<th>Saccade 4 Amplitude (°)</th>
<th>Saccade 5 Amplitude (°)</th>
<th>Saccade 6 Amplitude (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>28.0</td>
<td>14.0</td>
<td>14.0</td>
<td>14.0</td>
<td>14.0</td>
<td>28.0</td>
</tr>
<tr>
<td>40°/s</td>
<td>30.7</td>
<td>14.8</td>
<td>15.6</td>
<td>16.0</td>
<td>13.7</td>
<td>31.3</td>
</tr>
<tr>
<td>100°/s</td>
<td>30.0</td>
<td>14.5</td>
<td>15.3</td>
<td>15.5</td>
<td>13.5</td>
<td>30.5</td>
</tr>
<tr>
<td>130°/s</td>
<td>29.5</td>
<td>14.3</td>
<td>14.8</td>
<td>15.1</td>
<td>13.0</td>
<td>30.3</td>
</tr>
</tbody>
</table>

3.5.3 Visual Search Strategy Task

Following the completion of the 12-trial VSST at 1000 ms exposure time, the data were calibrated. The saccade detection and evaluation algorithm was performed three times on the 12-trials using a 40°/s, 100°/s and 130°/s velocity threshold.

Figure 3.5.3a shows the calibrated amplitude result (green line) of the participant performing one trial of the VSST chosen at random. Figure 3.5.3b shows the same trial depicting velocity over time rather than amplitude over time (green line). The unshaded areas (Figures 3.5.3a-b) reveal the 1000 ms exposure time and indicate the cut-off point for when the algorithm both starts (1500 ms), and stops (2500 ms), searching for saccades. This simulates the normal blank pre-stimulus (up until 1500 ms) and visual mask (after 2500 ms). A saccade membership (denoted by the blue line in Figures 3.5.3a) of ten is obtained when the algorithm detects the signal rising above the velocity threshold. A saccade membership of zero is obtained when the velocity is below the threshold. An orange line (Figures 3.5.3a-b) reveals when saccade registration occurs after all algorithm conditions are met.

Figure 3.5.3a shows 4 saccades were detected using the 130°/s velocity threshold. It appears that the participant initially focussed on the central LED display followed by a
leftward saccade to the furthest left LED display. A rightward saccade stops where the second from left LED display would be displayed. Another rightward saccade brings the second from right LED display in focus. A final saccade causes a fixation on what would be the furthest right LED display. If the numbers 1-5 were displayed from left to right in the five LED displays, the participant would have looked at 3 – 1 – 2 – 4 – 5. Figure 3.5.3a also shows that saccade membership was reached at about 2450 ms. However, the *Saccade Duration* and *Saccade Amplitude* criterion were not met and therefore saccade registration did not occur.

![Figure 3.5.3a-b: Example of a VSST trial analysed using the 130°/s minimum velocity threshold:](image)

The lines are marked according to the following colours: **Green** – Calibrated Signal, **Blue** - Saccade Membership, and **Orange** - Saccade Registration. The Exposure Time, indicated by the non-shaded areas, lasts from 1500 ms to 2500 ms. The 1000 ms Exposure Time is standard for some trials of the VSST. *Saccade Membership* is accepted (value = 10) when signal velocity is above the velocity threshold. Non-membership receives a value = 0. *Saccade Membership* does not take into account Saccade Duration (minimum 12.5 ms) or Saccade Amplitude (minimum 5°) thresholds. *Saccade Registration* occurs when all criterion are accepted. Figure 3.5.3a plots amplitude over time while Figure 3.5.3b plots velocity over time. Both figures depict exactly the same trial.
Table 3.5.3 shows a summary of the extracted values from the 12-trial VSST for each velocity threshold. All the trends that existed in Table 3.5.1 and some in Table 3.5.2a were also present here. As the velocity threshold increases, *Mean Saccade Amplitude*, and *Mean Saccade Duration* both decreased whilst *Average Saccade Velocity* increased which were all due to the exclusion of smaller velocity values. The surprise change was that *Saccade Rate* was lower for the 40°/s and 130°/s thresholds whilst *Mean Peak Saccade Velocity* was greater for the same thresholds when compared to the 100°/s threshold. These variations existed solely because of one trial out of the twelve. The trial in question had 4 saccades consistently detected from all three algorithms however, the 100°/s velocity threshold algorithm detected a fifth saccade at the beginning of the stimulus exposure time. The 40°/s velocity threshold detected this fifth saccade but excluded it because it was considered anticipatory. The 100°/s velocity threshold did not consider it anticipatory because it did not exceed 100°/s until the stimulus exposure time began. Finally, the 130°/s velocity threshold algorithm detected a deflection exceeding its threshold but did not consider it a saccade because the *Saccade Amplitude* criterion of 5° was not exceeded.

Table 3.5.3  
Impact of Minimum Velocity Thresholds on Saccade Variables during the VSST

<table>
<thead>
<tr>
<th>Velocity Threshold</th>
<th>Saccade Rate</th>
<th>Mean Saccade Amplitude (°)</th>
<th>Mean Peak Saccade Velocity (°/s)</th>
<th>Average Saccade Velocity (°/s)</th>
<th>Mean Saccade Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40°/s</td>
<td>μ: 4</td>
<td>σ²: 0.793</td>
<td>μ: 22.40</td>
<td>μ: 520.01</td>
<td>μ: 320.78</td>
</tr>
<tr>
<td></td>
<td>σ²: 4.42</td>
<td>σ²: 59.49</td>
<td>σ²: 520.01</td>
<td>σ²: 40.15</td>
<td>σ²: 7.77</td>
</tr>
<tr>
<td>100°/s</td>
<td>μ: 4.083</td>
<td>σ²: 0.793</td>
<td>μ: 21.57</td>
<td>μ: 515.07</td>
<td>μ: 349.35</td>
</tr>
<tr>
<td></td>
<td>σ²: 4.59</td>
<td>σ²: 67.14</td>
<td>σ²: 515.07</td>
<td>σ²: 43.42</td>
<td>σ²: 8.13</td>
</tr>
<tr>
<td>130°/s</td>
<td>μ: 4</td>
<td>σ²: 0.739</td>
<td>μ: 21.43</td>
<td>μ: 520.01</td>
<td>μ: 366.51</td>
</tr>
<tr>
<td></td>
<td>σ²: 4.49</td>
<td>σ²: 59.49</td>
<td>σ²: 520.01</td>
<td>σ²: 38.27</td>
<td>σ²: 7.99</td>
</tr>
</tbody>
</table>

n = 12 for each velocity threshold

Furthermore, the value for *Mean Peak Saccade Velocity* was not identical amongst all three algorithms. This was directly attributable to the reduction in *Saccade Rate*. Using the example here, if a saccade with peak velocity of 125°/s was excluded using a 130°/s velocity threshold, then the *Mean Peak Saccade Velocity* for that trial would likely increase (as well as *Saccade Rate* decrease). However, the same saccade would be
included using a 100°/s velocity threshold thereby increasing Saccade Rate and reducing Mean Peak Saccade Velocity. Therefore, although Peak Saccade Velocity is consistent for each saccade irrespective of the velocity threshold employed, Mean Peak Saccade Velocity could alter based on a reduction in Saccade Rate.

### 3.5.4 Blink Test

Following the completion of the blink test, the EOG data were calibrated using the amplitude calibration routine performed prior to the blinking task. Once calibrated, the three algorithms with different minimum velocity thresholds processed the EOG signal.

Figure 3.5.4 shows an example of a 10-second period of EOG recording. The green line represents the EOG signal calibrated in degrees of visual angle via an amplitude calibration routine performed before the blink test. The blue line depicts saccade membership; a value of 10 suggests the differentiated signal has exceeded the velocity threshold while a value of zero suggests the differentiated signal did not exceed velocity threshold. The orange line indicates saccade registration. The exposure time, indicated by the unshaded area, lasts from 1500 ms onwards.

![Figure 3.5.4: A vertical EOG recording of spontaneous blinks analysed using the 100°/s minimum velocity threshold: The lines are marked according to the following colours: Green – Calibrated Signal, Blue - Saccade Membership, and Orange - Saccade Registration. The Exposure Time, indicated by the non-shaded areas, lasts from 1500ms onwards. This recording was a continuous recording for almost 2 minutes designed to elicit spontaneous blinks. Saccade Membership is accepted (value = 10) when signal velocity is above the velocity threshold. Non-membership receives a value = 0. Saccade Membership does not take into account Saccade Duration (minimum 12.5ms) or Saccade Amplitude (minimum 5°) thresholds. Saccade Registration occurs when all criteria are accepted.](image)

The spontaneous blinks did not cause any displacement during the horizontal EOG recording in the two participants tested. However, the vertical electrodes picked-up a
greater change in polarity as seen in Figure 3.5.4. In this example, eight saccades were falsely detected during the exposure time using the algorithm with minimum velocity threshold of 100°/s. It is important to note that eyelid closing was evaluated as one saccade and eyelid re-opening as another saccade. This is because the velocity signal returns to zero (hence below velocity threshold) when the eyelid completely closes or when it is completely open. This is understandable because to stop and change direction, the eyelid must slow down before returning in the opposite direction. Saccades do not have this problem because a saccade in one direction followed by a saccade in the opposite direction is still two saccades. Therefore, the recording of a blink and its subsequent detection as two saccades drastically increases the inaccuracy of the evaluation for that trial.

Of less consequence but worth noting was the fact that three saccades were registered for the second and third blink. In these instances, the eyelid re-opening phase was split into two saccades. This was quite unexpected because usually the peak velocity is observed $\frac{1}{3}$ to $\frac{1}{2}$ way along the trajectory of the deflection (Bahill et al., 1975a). In both these cases, the movement was so slow where peak velocity is usually located that the detection algorithm further split the re-opening phase into two.

To compare the effects of each minimum velocity threshold algorithm, each algorithm processed the data from the single trial displayed in Figure 3.5.4 and the results appear in Table 3.5.4.
Table 3.5.4
Impact of Minimum Velocity Thresholds on Saccade Variables during the Blink Test

<table>
<thead>
<tr>
<th>Velocity Threshold</th>
<th>Saccade Rate</th>
<th>Mean Saccade Amplitude (°)</th>
<th>Mean Peak Saccade Velocity (°/s)</th>
<th>Average Saccade Velocity (°/s)</th>
<th>Mean Saccade Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6°/s</td>
<td>6</td>
<td>23.91</td>
<td>296.20</td>
<td>195.53</td>
<td>128.10</td>
</tr>
<tr>
<td>10°/s</td>
<td>8</td>
<td>16.77</td>
<td>271.81</td>
<td>203.03</td>
<td>80.20</td>
</tr>
<tr>
<td>13°/s</td>
<td>9</td>
<td>13.47</td>
<td>264.40</td>
<td>210.56</td>
<td>59.48</td>
</tr>
</tbody>
</table>

n = 1 trial for each velocity threshold

The results of Table 3.5.4 suggest that the presence of blinks during the exposure time of any trial will negatively influence the evaluation of that trial, regardless of the minimum velocity threshold chosen. This is clearly demonstrated because although no saccades were present, between 6 and 9 saccades were falsely detected. Furthermore, the results are unable to contribute to the overall discussion of which minimum velocity threshold was superior because the underlying detection was so inaccurate. Therefore, the selection of minimum velocity threshold should not be based on the results of this blink test.

Although the results of this test should not determine the choice of minimum velocity threshold, it was important to note that similar characteristics were observed to the previous three test situations i.e. the higher the minimum velocity threshold, the lower the Mean Saccade Amplitude and Mean Saccade Duration, and the higher the Average Saccade Velocity. However, for the first time, Saccade Rate increased with increasing minimum velocity threshold and Mean Peak Saccade Velocity decreased.

3.6 Discussion

By running the simulated and actual data through three minimum velocity threshold algorithms, it demonstrated the effect of each threshold value. Firstly, the number of saccades detected gave a clear indication to the accuracy of each algorithm when compared to the actual number of saccades generated. Secondly, the minimum velocity
threshold chosen also affected the evaluation of saccade data resulting in some very consistent trends. These trends revealed the limitation of each algorithm but did not necessarily make one algorithm more correct than the others did. If there were no difference in the detection and evaluation between each velocity threshold, then the selection of one threshold over another would be irrelevant. However, as Tables 3.5.1-3 reveal, the minimum velocity threshold had a number of effects on the data making the choice extremely important.

In terms of saccade detection, a successful algorithm in the first test situation involving simulated smooth pursuit scanning should have resulted in zero saccades detected. However, all three algorithms detected saccades and therefore to some extent were inaccurate. However, the $100^\circ/s$ and $130^\circ/s$ minimum velocity threshold algorithms detected only a single saccade whilst the $40^\circ/s$ algorithm detected three saccades. In this case, a higher velocity threshold seemed more capable of removing the simulated smooth pursuit eye movement (Figure 3.5.1a-c). Furthermore, it must be noted that the $130^\circ/s$ minimum velocity threshold would not have detected any saccades if the evaluated peak velocity of 131.97°/s was below the maximum smooth pursuit velocity of 130°/s ever observed (Bahill & LaRitz, 1984). Additionally, one could argue that because of the small number of studies which have had smooth pursuit witnessed above $100^\circ/s$ (Bahill & McDonald, 1983; Bahill & LaRitz, 1984) that the use of a $100^\circ/s$ minimum velocity threshold is more conservative in excluding smooth pursuit eye movements.

The remaining test situations were less conclusive. The second test situation involving the calibration routine revealed that all three algorithms successfully detected the six saccades performed. The third test situation involving the VSST revealed only a minor difference in the average of Saccade Rate across all 12 trials. When the difference was investigated and the trial in question reviewed, the difference was legitimately explained and each algorithm deemed accurate. The fourth test situation involving involuntary blinks showed how poor all three algorithms were at excluding blinks from saccade calculations because multiple saccades were falsely detected. Although the $40^\circ/s$ had the least saccades detected, it was still so grossly inaccurate that the results of the test
were not considered when appraising each algorithm. The exclusion of spontaneous blinks would have to occur by other means.

In terms of saccade evaluation, the results of all four tests showed consistent trends similar to observations by other researchers (Inchingolo & Spanio, 1985). Firstly, as the minimum velocity threshold increased, Saccade Amplitude and Saccade Duration decrease. Generally, this would mean that these variables have been underestimated because it does not include samples from the beginning of the saccade. However, as Table 3.5.2a-b show, the 130°/s minimum velocity threshold was closer to matching the actual saccade movements than the 40°/s and 100°/s thresholds were. Not all variables decrease though. When the minimum velocity threshold was higher, Average Saccade Velocity increased. This is understandable given that lower velocities have been excluded causing the average to be greater. Generally, this would mean that this variable has been overestimated because it did not include the smaller samples from the beginning of the saccade. Unfortunately for this variable, as distinct from Saccade Amplitude, there is no way of knowing whether this were actually true because we only have a subjective method of confirming what the correct determination should be. However, given the 100°/s and 130°/s algorithms did not underestimate Saccade Amplitude in Table 3.5.2a-b as expected, perhaps Average Saccade Velocity was not overestimated for the same reason.

The one consistently accurate saccade variable was Peak Saccade Velocity. Regardless of the velocity threshold used, the same value was always reported. However, Mean Peak Saccade Velocity takes into account all saccades registered in a given trial because it is the average of all Peak Saccade Velocities. As Mean Peak Saccade Velocity is a variable used to evaluate the performance of the participant during the VSST, it is important to remember that the number of saccades registered affects it. As the various minimum velocity thresholds had little effect on this variable, it was not particularly useful in helping decide the most appropriate algorithm.

The results of the four algorithm test situations would suggest that the 130°/s minimum velocity threshold was the most appropriate choice. It effectively excluded almost all smooth pursuit scanning from saccade detection and was surprisingly the most accurate
algorithm in evaluating *Saccade Amplitude* and *Saccade Duration* from the calibration routine trial. On the other hand, the $40^\circ/s$ minimum velocity threshold algorithm falsely detected the most saccades from the simulated smooth pursuit scanning and unexpectedly overestimated *Saccade Amplitude* and *Saccade Duration* from the calibration routine trial. Additionally, the $40^\circ/s$ velocity threshold increased the likelihood of registering noise or interference as a saccade even though this was not demonstrated in the test situations used. However, a more conservative approach was warranted considering the most accurate amplitude and duration values should have been obtained when a lower velocity threshold was used. This was not confirmed in Table 3.5.2, most likely because the original calibration was marginally inaccurate.

Therefore, a more appropriate approach would be a compromise between these two algorithms. The $100^\circ/s$ minimum velocity threshold appears to both conservatively and accurately evaluate all test situations. In the smooth pursuit scanning trial, both the $100^\circ/s$ and $130^\circ/s$ velocity threshold falsely detected an equivalent number of saccades. In fact, there was no difference in saccade detection accuracy between the $100^\circ/s$ and $130^\circ/s$ velocity threshold algorithms. It was only in the evaluation of saccade data that the two algorithms differed. Although, the $100^\circ/s$ underestimates *Saccade Amplitude* and *Saccade Duration* and overestimates *Average Saccade Velocity*, it does this less than the $130^\circ/s$ velocity threshold regardless of the fact this was not conveyed in Table 3.5.2. Furthermore, such a threshold would eliminate most forms of noise or interference although the choice of such a threshold is not perfect. Figure 3.5.4 shows that the $100^\circ/s$ velocity threshold incorrectly detects eyelid movements or blinks as saccades. Thankfully, this appears limited to vertical EOG recordings, but a subjective check of the data will be required as the last resort if *Saccade Amplitude*, duration and minimum velocity thresholds do not eliminate the blinks entirely.

The $100^\circ/s$ minimum velocity threshold algorithm was proven to be a reliable predictor of saccadic eye movements within the EOG signal. There is confidence that in most situations that the $100^\circ/s$ minimum velocity threshold algorithm will reliably detect saccades and to some extent avoid blinks and interference within the signal. A subjective check must still be employed to confirm blink artefact is not detected in all recordings, but most especially in vertical EOG data.
Chapter 4 Optimum Level of Illuminance for Electro-oculography

4.1 Introduction

Fluctuations in the corneo-retinal potential are known to occur following changes in ambient illuminance levels causing variation to the EOG signal (Arden et al., 1962; Kelsey, 1967; van Lith & Balik, 1970; Elenius & Aantaa, 1973; Hickson, 1983). Adaptation to a particular ambient illuminance level will be deceptively incorporated into EOG recordings over time causing incorrect angular displacement and velocity measurements (Becker & Fuchs, 1969; Gonshor & Malcolm, 1971; Hickson, 1983). For this reason, many authors suggest that participants pre-adapt for between 40 to 50 minutes prior to any EOG recording where the methodology includes a change in ambient illuminance level (Hickson, 1983; Gonshor & Malcolm, 1971).

The methodology of Morgan (1999), on which this thesis was based, could be criticised for such a point because electrode preparation occurred in a fully lit room followed by the VSST in complete darkness. Therefore, there was no way to know if there was a decrease in corneo-retinal potential over time, which was expected as participants progressively adapt to complete darkness (Kelsey, 1967; Becker & Fuchs, 1969; Gonshor & Malcolm, 1971). Gonshor and Malcolm (1971) believe the reduction could be as great as 50-60% of raw amplitude because their tests caused the same decrease in corneo-retinal potential from baseline recordings in normal illuminated environment. This would give the impression that potential changes from the same sized eye movements are smaller and slower than what they are. This suggests that going from a well-illuminated environment to a darkened room and back to the lightened environment must be avoided.

The optimum illuminance level for clinical EOG has been suggested as being 300 Lux, which produced both the maximum response and caused the minimum patient discomfort (Jackson, 1979). Beyond 300 Lux is a saturation point where EOG amplitude does not increase further (Jackson, 1979). However, these tests did not look at changes in raw EOG amplitude; they looked at changes in Arden Index that are changes in EOG potential when taken from a dark adapted state to a light adapted state.
(Arden et al., 1962). Therefore, the larger the Arden index, the greater the change in raw amplitude from the darkened state to a light adapted state. The Arden Index was significantly reduced from normal when an illuminance of less than 40 Lux was used (Jackson, 1979). This indicates that there is less change in EOG potential when taken from a dark adapted state to a ‘dim’ 40 Lux light adapted state.

However, the Arden Index is not representative of the sequence of events during these experiments. Generally, participants are pre-adapted to darkness when the Arden Index is recorded. However, participants for these trials will be pre-adapted to either sun light or room light prior to entering the testing laboratory. Therefore, illumination levels will adjust opposite to Arden Index recordings in that participants will be adapted to room light then adapt to a darkened environment. Perhaps then, a dim ambient illumination level (40 Lux) could be used rather than complete darkness (0 Lux) to ensure that correct angular displacement and velocity measurements are recorded. Maximum illumination was avoided due to the low contrast between LED luminance and background illumination.

4.1.1 Corneo–retinal Potential Varies with Changes in Illumination

A typical corneo-retinal potential response to a decrease in illumination levels causes a 10-30% amplitude reduction (or dark trough) after 6-15 min (Arden et al., 1962; Levett, 1971; Krogh, 1975; Taümer, Rohde, Pernice & Kohler, 1976). When re-illuminated, a light peak occurs after 6-10 min (Arden et al., 1962; Levett, 1971; Elenius & Aantaa, 1973; Taümer et al., 1976). Pre-adaptation in brighter conditions was also known to cause an increase in the Arden ratio (Timmins & Marmor, 1992).

One study more closely simulated the effects of entering a laboratory from external sunlight to reduced ambient illuminance levels (Hickson, 1983). Hickson (1983) observed minute-to-minute EOG amplitude variation was no more than 10% for all illumination levels (20, 40, and 400 Lux). Variation in any 4 minutes was no more than 20% ($M=13\%$). Maximum changes were observed within 15 minutes and amplitudes varied between 14-44% ($M=22\%$).

Hickson (1983) further studied the EOG amplitude variation when participants moved from a light adapted (20, 40, 400 Lux) to dark adapted (0 Lux) state for 10 minutes.
Minute to minute variations were on average 12% (max. change range 10-14%). Over the 10 minutes, a total decrease of 16-36% ($M = 28\%$) was observed. The 16% and the 36% decrease were both from participants entering dark from the highest illumination level (400 Lux).

### 4.1.2 Other Sources of EOG Variation

Although ambient illuminance level accounts for a great proportion of variation in the corneo-retinal potential, there are also many other factors which have been proven to contribute. Some are extrinsic factors such as electronic noise, laboratory conditions, technician error and measuring device precision (Anderson & Purple, 1980). Other intrinsic contributions include circadian rhythms, metabolic or emotional states or activity level (Anderson & Purple, 1980).

Diurnal effects are considered a major source of variation to the EOG signal and this has been observed in a number of studies (Wilson et al., 1993; Timmins & Marmor, 1992; Momirov, van Lith, van der Torren & Vijfvinkel-Bruinenga, 1982; Anderson & Purple, 1980; van Lith & Balik, 1970; Davis & Shackel, 1960). A peak occurs somewhere between 1200 and 1400 hours and a trough sometime during the night or early morning (Anderson & Purple, 1980). However, the wide range has been disputed by others (Davis & Shackel, 1960), who thought the variation was not common in all people with rises and falls in potential between 1100 and 1700 hours. The same authors further suggest that the irregular patterns continue overnight (Davis & Shackel, 1960). Additional research showed the greatest variation occurred between night and the early morning hours of the day (Anderson & Purple, 1980). Specifically values in the morning (before 1300) were 20% larger than early afternoon (after 1400 hours) (Timmins & Marmor, 1992). These inconsistent findings suggest fluctuations occur throughout the day and therefore it is important to allow for this factor.

Some authors suggest we need not concern ourselves with time of day variations since the fluctuation is very small during short recordings (Arden et al., 1962). However, 20-50% of the total EOG variability in Arden ratio was circadian contributions (Anderson & Purple, 1980), although other studies suggest time of day accounts for only 17% of EOG potential variance (Shackel & Davis, 1960).
The longer-term variation of EOG potential was examined with large EOG potential increases observed over an 8-week period (Davis & Shackel, 1960). However, variation within participants showed that changes from week-to-week were quite small (Davis & Shackel, 1960). Interestingly the same authors reported EOG potential levels were reasonably consistent over a 10 month period ($r = + 0.66$; Shackel & Davis, 1960). This does not refute the findings of the 8-week study but merely suggests that there may be some sort of seasonal effect on EOG potential.

The investigations into EOG potential variations due to gender and age have also been inconclusive. Some studies reported that there are not significant differences in EOG potential due to gender (Davis & Shackel, 1960; Krogh, 1975; Wilson et al., 1993) although other studies have observed female potentials to be greater (Adams, 1973; Krogh, 1976). Additionally, the menstrual cycle was found to be unrelated to variations in EOG (Kelsey, 1967). Furthermore, according to one study EOG potential does not change with men's age, but does significantly for women (Adams, 1973) although another has reported a significant correlation between both sexes (Krogh, 1976).

When comparing EOG potential across a number of sessions, numerous factors contribute to the test-retest reliability. Position of the electrode (Shackel & Davis, 1960; Arden et al., 1962; van Lith & Balik, 1970), bone structure (Arden et al., 1962; Krogh, 1976) and electrical resistance of the skin due to perspiration all cause EOG potential variations. Other factors effecting EOG potential are eyeball pressure and drug administration (Arden et al., 1962). If a within subjects calibration were performed, each factor is accounted for. However, if a group calibration was performed and there were differences between subjects, particularly drug administration, then these factors will not be accounted for.

Other factors such as lack of sleep (Davis & Shackel, 1960), body temperature (Davis & Shackel, 1960; Kolder, 1974) and pulse rates (Davis & Shackel, 1960) all had no correlation with variation in EOG potential. However, on very few occasions both an illness and drop in temperature had caused a decrease in EOG potential (Davis & Shackel, 1960). Variation in EOG is not caused by variation between the right and left eye (van Lith & Balik, 1970; Adams, 1973; Krogh, 1976; Momirov et al., 1982). Finally, alertness and interest of the participant play a part (Fricker, 1971).
4.1.3 Contrast between LED Luminance and Ambient Illuminance Level

Another important point to consider was the impact that LED luminance had on the tasks. It has been reported that in well-lit testing environments that participants or patients can experience pain due to the bright illuminance in addition to difficulty in following the eye movement stimulus itself (Jackson, 1979). If a fast moving stimulus does not have sufficient luminance it will go unseen because receptors will not absorb enough photons in time to cause a graded potential (Wheeless et al., 1967). Therefore, if the speed of the stimulus increases, the luminance of the stimulus must also increase to remain visible. Although the stimuli in the VSST are static as opposed to a moving stimulus in the example above, fast visual search is required to perform the VSST reinforcing the need for a high luminance stimulus. Unfortunately, the LEDs used in these experiments do not alter in luminance, which means the required contrast must be provided by the ambient illuminance level. Therefore, the choice of ambient illuminance level is essential for providing the high degree of contrast necessary to resolve the stimulus.

Many factors have proven to cause variations in the EOG signal, not least of all the ambient illuminance level. If the major causes corneo-retinal potential variation were minimised by holding time of day relatively constant and performing calibrations individually, then the optimum ambient illuminance level could be determined using a repeated measures protocol. The optimum level would be determined by observing which illuminance level produced the most stable EOG signal over an entire testing session whilst still providing a high degree of contrast. Therefore, a bright illuminance level may provide a very stable EOG signal but deliver very poor contrast for the participants. Alternatively, a very dark room would provide the greatest contrast between LED and ambient lighting but produce a fluctuating EOG signal. Consequently, the first step of this chapter must be to ascertain which illuminance level produces the most stable and reliable EOG signal. The subsequent step was to determine the optimum level, which was the darkest illuminance that was not significantly less reliable than the most stable ambient illumination.
4.2 Method

4.2.1 Participants

Nineteen participants were tested in this study; 11 males ($M = 24.8$ years, $SD = 9.9$ years) and 8 females ($M = 23.6$ years, $SD = 4.6$ years). All participants were university student and staff volunteers, or friends of the researcher. The participants did not have any history of eye disorders and did not exhibit any indication of colour blindness. The six participants who wore corrective lenses (prescription glasses or contact lenses) were asked to do so during this task. All participants had a visual acuity of at least 0.36 LogMAR (Left: $M = 0.1$, $SD = 0.14$; Right: $M = 0.06$, $SD = 0.13$) on either eye (the equivalent of 20/32 from Snellen charts) with correction.

4.2.2 Apparatus

A Dick Smith photometer capable of measuring between 0 Lux and 50,000 Lux was used to measure the ambient illuminance level in the testing room to 1 decimal place. The photometer accuracy was reported to be ±5% (DSE, Instruction Manual).

To test the ambient illuminance level in the testing room, the photometer sensor was faced towards the room’s light source and the displayed illuminance level checked. This test was performed repeatedly throughout the testing room. Regardless of the sensor placement, the illuminance level reading remained unchanged contradicting the general rule that illuminance decreases with increasing distance from the source (Brigell et al., 2003). The maximum reading obtained from the photometer in a fully lit environment was 185 Lux. In a fully darkened room with lights off the reading was 0 Lux.

The photometer sensor was then fixed to the internal wall of the testing room. A cable ran from the sensor to the photometer display panel fixed to the external wall (outside the testing room) beside the light dimmer switch. This allowed the experimenter to dim the lights and monitor any relative change in ambient illuminance level throughout the test.
4.2.3 Procedure

The electrode set-up was followed according to the protocol outlined in Chapter 2. During electrode preparation the participant pre-adapted to an illuminance level of 185 Lux, which was the maximum possible setting within the testing room. The total duration of pre-adaptation, which included signing consent form, task instructions, pre-test battery and electrode preparation was approximately 15 minutes. The lights to the room were then dimmed (or left unchanged in 1 case) to one of 6 illumination levels; 0 Lux, 2.5 Lux, 10 Lux, 25 Lux, 100 Lux and 185 Lux. Participants then performed the 6-trial EOG amplitude calibration routine (duration ~ 30 sec) five consecutive times at intervals of 2 ½ minutes i.e. 0 min, 2 ½ min, 5 min, 7 ½ min and 10 min. Therefore, the participant was subjected to the illuminance level for approximately 10 ½ minutes (this is the approximate total duration for performing the horizontal and vertical VSST and calibration routines).

Participants were tested at only one illumination level per day so that prior illumination levels did not influence the result. This meant participants attended 6 sessions over 6 non-consecutive days. Generally, participants were tested between the hours of 10am and 6pm and care was taken to ensure that participants were not tested at nighttime or in twilight hours. This ensured participants were not dark adapted prior to entry into the laboratory. Participants completed all their sessions within the same 2-hour window to individually control for time of day. The order of the 6 sessions was counterbalanced across all participants.

Of the 19 participants, only 12 managed to attend all six sessions. One participant attended 5 sessions and 3 participants attended 3 sessions. Another participant attended 2 sessions and 2 participants attended a single session. This resulted in less than 19 participants per illumination level [0 Lux (n=18), 2.5 Lux (n=13), 10 Lux (n=16), 25 Lux (n=15), 100 Lux (n=12), 185 Lux (n=16)].

On the day of testing, participants were asked not to consume caffeine or nicotine 90 minutes prior to any testing session.
4.3 Results

The raw serial values recorded from the 30 trials (5 repetitions of the 6-trial calibration routine per testing session) were plotted and a regression line obtained (see Figure 2.4.2a-b in Chapter 2). The level of variance was calculated and displayed as the coefficient of determination ($r^2$ value). The mean coefficient of determination was obtained from all 19 participants across all 6 illuminance levels (0 Lux, 2.5 Lux, 10 Lux, 25 Lux, 100 Lux, 185 Lux). The results of these calculations are depicted in Figure 4.3a.

![Figure 4.3a](image)

**Figure 4.3a**: Mean EOG potential variance for 19 participants across multiple illuminance levels. The average coefficient of determination ($r^2$) was plotted for each illuminance level for the 19 participants. The highest coefficient of determination ($r^2 = 0.9789$ at 25 Lux) corresponds to the smallest variation of EOG potential over the 10 minute test period for that illuminance level. The variance decreases ($r^2$ increases) as illuminance level increases until it peaks at 25 Lux and then begins to plateau at higher illuminance levels. The standard error bars shown in the graph are lowest for the 25 Lux condition.

Overall, the graph shows that the $r^2$ values were very high for all illuminance conditions. The greatest mean $r^2$ value and hence most reliable and consistent signals were obtained using an illuminance level of 25 Lux ($r^2 = 0.9789$). Using dimmer illuminance levels saw a decrease in mean $r^2$ value with the worst reliability achieved by the 0 Lux condition ($r^2 = 0.9584$). Illuminance levels greater than 25 Lux seemed to plateau at $r^2$ values just below that of 25 Lux.
A one-way repeated measures ANOVA was conducted to compare the coefficient of determination values across all illumination levels (0 Lux to 185 Lux). Unfortunately this statistic [Wilks’ Lambda = .26, F(5,7) = 3.948, p = .051, multivariate partial eta squared = .74] could only include the 12 participants who completed all six illumination sessions and was not found to be significant.

To include all 90 completed sessions from the 19 participants in the statistical analysis, a one-way ANOVA was repeated comparing the coefficient of determination values across the six illumination levels and was found to be significant [F(5, 84) = 4.378, p = 0.001]. Post-hoc planned comparisons were made between each illuminance level however, due to it’s exploratory nature and number of planned comparisons (15), a Bonferroni adjustment was made to the probability level reducing it to 0.004 (0.050 ÷ 15 = 0.004). Table 4.3 shows the results of the planned comparisons with the probability level displayed. It appears the darkest illuminance level (0 Lux) was significantly less stable than the 25 Lux, 100 Lux and 185 Lux but not 2.5 Lux or 10 Lux conditions. Interestingly there were no other significant planned comparisons so although the 25 Lux illuminance level had the highest mean $r^2$ value, it was not significantly more stable than any other illuminance level except the 0 Lux condition.

Table 4.3
Planned Comparisons for all 6 Illuminance Levels and their Respective Probabilities

<table>
<thead>
<tr>
<th></th>
<th>0 Lux</th>
<th>2.5 Lux</th>
<th>10 Lux</th>
<th>25 Lux</th>
<th>100 Lux</th>
<th>185 Lux</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Lux</td>
<td>-</td>
<td>p = 0.275</td>
<td>p = 0.049</td>
<td>p &lt; 0.001</td>
<td>p = 0.003</td>
<td>p = 0.001</td>
</tr>
<tr>
<td>2.5 Lux</td>
<td>p = 0.275</td>
<td>-</td>
<td>p = 0.443</td>
<td>p = 0.014</td>
<td>p = 0.063</td>
<td>p = 0.044</td>
</tr>
<tr>
<td>10 Lux</td>
<td>p = 0.049</td>
<td>p = 0.443</td>
<td>-</td>
<td>p = 0.067</td>
<td>p = 0.227</td>
<td>p = 0.184</td>
</tr>
<tr>
<td>25 Lux</td>
<td>p &lt; 0.001</td>
<td>p = 0.014</td>
<td>p = 0.067</td>
<td>-</td>
<td>p = 0.605</td>
<td>p = 0.594</td>
</tr>
<tr>
<td>100 Lux</td>
<td>p = 0.003</td>
<td>p = 0.063</td>
<td>p = 0.227</td>
<td>p = 0.605</td>
<td>-</td>
<td>p = 0.982</td>
</tr>
<tr>
<td>185 Lux</td>
<td>p = 0.001</td>
<td>p = 0.044</td>
<td>p = 0.184</td>
<td>p = 0.594</td>
<td>p = 0.982</td>
<td>-</td>
</tr>
</tbody>
</table>

Red = Significant to 0.001, Green = Significant to 0.004 (Bonferroni adjusted)

An additional comparison was made between individual and group calibrations to determine which procedure was more effective. Every data point for each participant was grouped according to the illumination level the calibration routine was performed under. Subsequently, six regression lines with $r^2$ values were obtained. The results of this analysis are shown in Figure 4.3b.
Figure 4.3b: Coefficient of determination for all combined data across multiple illuminance levels. The coefficient of determination ($r^2$) was plotted for each illuminance level for the entire group. The highest coefficient of determination ($r^2 = 0.8588$ at 2.5 Lux) corresponds to the smallest variation of EOG potential for that illuminance level. The lowest coefficient of determination (greatest variance) was observed for 25 Lux. Note that standard error bars are not possible because all data were combined so there is only one $r^2$ value per illuminance level. The number in each bar shows the number of data points or equivalent number of fixations detected during the EOG calibration routine used to plot the overall regression.

Figure 4.3b shows vastly contrasting results to the individual calibrations. The $r^2$ value for every illumination level is lower for the group calibration than the individual calibration. It is interesting to note that Figure 4.3b shows all $r^2$ values between 0.81 and 0.86, which are much lower than individual calibrations of 0.95 to 0.98 in Figure 4.3a. Even more interesting was that the greatest variation (lowest $r^2$ value) for group calibration was observed by the 25 Lux condition which by contrast had the highest individual $r^2$ value. This was probably because there were only small deviations within participants but large deviations between participants, which appears to be the case here.

### 4.4 Discussion

The major aim of this chapter was to ascertain under which illuminance condition the corneo-retinal potential proves to be most stable and most reliable. Leaving the illuminance level unchanged from a fully lit room should produce this, however the LEDs become almost impossible to see due to the minimal contrast between background lighting and stimulus. According to past researchers it was expected that the
highest ambient illuminance level would produce the most stable corneo-retinal potential because there is very little potential variance above 300 Lux (Jackson, 1979; Hickson, 1983). Furthermore, the level with least corneo-retinal variation would also cause the least decrease in peak saccade velocity over time.

The average coefficient of determination was plotted for individually calibrated data and the highest value was achieved by the 25 Lux illuminance condition with the 100 and 185 Lux conditions only marginally smaller. Post-hoc planned comparisons proved these differences were not significant. The 25 Lux condition was only significantly more reliable than the 0 Lux condition whilst the 2.5 Lux condition approached significance. The three brightest conditions all proved significantly more reliable than 0 Lux, which had the lowest coefficient of determination value.

Although the statistical appraisal of results proved inconclusive, it was apparent that individual calibration vastly improves the reliability and consistency of EOG amplitudes. Calibration using grouped data reduced the reliability down to 81-86% whilst individual calibration was as high as 95-98% regardless of the illuminance level used. This tells us that although illuminance levels do cause a variance in EOG potential over 10-11 minutes, it was much less of a factor than EOG changes from person to person. There is good justification for using individual EOG amplitude calibrations rather than an entire group calibration.

In contrast to Jackson (1979), the 185 Lux illuminance level did not achieve the greatest reliability in this study. The 25 Lux condition had the greatest reliability although it was not significantly higher than 185 Lux. Jackson previously found the optimum illuminance level for EOG testing was 300 Lux.

The reason why higher levels of illuminance (100 Lux and 185 Lux) have lower $r^2$ values than 25 Lux was hard to fathom. One explanation may be that ambient illuminance levels that remain reasonably high might still observe corneo-retinal changes by more than 14% (Hickson, 1983). Another explanation may be that the extra contrast between the LEDs and illuminance level may have inadvertently helped create a more stable EOG signal. The ability to resolve a brighter target could make the fixation more stable reducing the likelihood of overshoot or undershoot. However,
overshoot and undershoot were virtually non-existent throughout the tests, so this explanation was considered unlikely.

Whatever the reason, the 25 Lux condition proved more stable than its higher illuminance counterparts. For this reason, the 25 Lux ambient illuminance level was chosen as the light level to be used in the remaining studies as it clearly demonstrated the most stable corneo-retinal potential over the 10 ½ minute period. It was also easy to resolve the LEDs in this light so there was no need to decrease illuminance any further and perhaps inadvertently cause decreases over time in saccade velocity and duration (Becker & Fuchs, 1969).
Chapter 5  Horizontal Visual Search Strategy in Normal Participants

5.1 Introduction

Most studies involving visual search tasks use conditions that minimise eye movements and maximise fixations (Palmer et al., 2000). This is not surprising considering what we already know about the suppression of vision during saccades (see Chapter 1). Without exception, saccadic suppression studies have used only single eye movements until Morgan (1999) introduced a multiple eye movement paradigm incorporating various exposure times. The VSST described in chapter 2 was based on this research. Although less controlled, this method uses a more naturalistic approach considering standard visual search involves making numerous saccades each second (Goldberg et al., 1991). The major aim of this experiment was to determine why we make so many saccades during scanning when visual suppression offsets so much of our actual perception.

Four conditions were postulated regarding the limitations to scanning performance (Megaw, 1979). These include (1) visual acuity (2) the provision of feedback regarding error to the observer (3) background lighting conditions and (4) the time available for inspection. According to Morgan (1999), the most important condition was time available for inspection because even inefficient search strategies could produce successful outcomes if given long enough time. Tasks with temporal constraints force an optimization of the visual search strategy to ensure it maximises the acquisition of visual information during the task, within the confines of the human visual system.

The study outlined in this chapter was based on the horizontal VSST developed by Morgan (1999). It varies the time constraints placed on the visual system during visual search in an effort to extend our understanding of the relationship between saccadic eye movements and the acquisition of visual information. The findings of Morgan (1999) identified that outcomes that are more successful were produced when participants demonstrated faster, larger and more frequent saccades. These visual search characteristics were expected to be replicated in this study using a new sample of the normal population.
5.2 Method

5.2.1 Participants

Thirty-three people participated in this study. There were 17 males (M = 26.4 years, SD = 5.6 years) and 16 females (M = 23.4 years, SD = 3.9 years). All participants were friends of the researcher or university students whom volunteered. No participants had any history of eye disorders and did not exhibit any indication of colour blindness. Four participants wore corrective lenses (prescription glasses or contact lenses) and were asked to do so during this task. All participants had a visual acuity of at least 0.32 LogMAR in either eye (the equivalent of 20/32 from Snellen charts) with correction (Left: M = 0.02, SD = 0.12; Right: M = 0.05, SD = 0.19). The mean visual acuity of the dominant eye was LogMAR = 0.02 (SD = 0.20). There were 22 right dominant eyes, 10 left dominant eyes and 1 unknown. The dominant eye was also the same side as the dominant hand in 22/33 participants.

5.2.2 Procedure

The protocol and equipment outlined in Chapter 2 were adopted in this study on a sample of the normal population. Participants provided informed consent (see Appendix C), completed the pre-test battery and were explained the nature of the task. Participants were then electrode prepped in fully lit conditions for both horizontal and vertical EOG recordings. The Chapter 4 results were incorporated into this experiment with the lights dimmed to 25 Lux to maximise the contrast between LED brightness and room ambient illuminance whilst still maintaining stable corneo-retinal potentials.

Participants carried out the horizontal EOG Amplitude Calibration Routine followed by the horizontal VSST and then repeated the calibration routine. The combination of tasks took approximately 5 minutes.

Participants then performed the vertical EOG Amplitude Calibration Routine followed by the vertical VSST and then repeated the vertical calibration routine again. Once again, the duration of tasks was approximately 5 minutes. The results of the vertical EOG recordings will be discussed separately in Chapter 6.
All participants were tested during daylight hours and had not consumed caffeine, alcohol or nicotine within 2 hours of participating in the study.

5.3 Results

5.3.1 Horizontal Eye Movement Data

The horizontal EOG data was passed through the saccade detection algorithm (see Chapter 3 and Appendix F). All detected saccades were visually inspected to confirm blinks or other unwanted artefacts were not incorrectly incorporated into the results. The visual check was also used to identify anticipatory saccades (see Chapter 2) for eventual exclusion.

To validate the data set from this experiment against other normal data and further confirm the saccade detection algorithm, the Main Sequence relationships (Bahill et al., 1975a) were plotted (see Figure 5.3.1a-b). To accomplish this, Saccade Amplitude was grouped into integer values because of the large number of saccades detected (n = 4103). Failure to group in integer values produces a plot showing a cluster of data overlaid many times (see Appendix G1). This approach to the analysis replicates Morgan (1999) who also detected large saccade numbers although it is noted that Main Sequence relationships often plot smaller amounts of saccades (Garbutt et al., 2001). The mean integer values for Saccade Amplitude and the Peak Saccade Velocity of these saccades were plotted. Figure 5.3.1a shows the Main Sequence for 33 normal participants whom completed 4103 saccades during the 2376 horizontal VSST trials.
Figure 5.3.1a: Main Sequence: Saccade amplitude versus peak saccade velocity for all horizontal data. Peak velocity increases linearly with amplitude up to 20°. The trendline then curves in a logarithmic fashion conforming to the Main Sequence relationship. Standard error bars are displayed for peak saccade velocity at all saccade amplitude integer values. The coefficient of determination was shown for both trendlines.

Figure 5.3.1a verifies several aspects of the saccade detection algorithm and the normality of this data set. Firstly, it successfully confirms that Saccade Amplitudes below 5° were not detected because Figure 5.3.1a shows no values below 5° (Chapter 3 defined one inclusion criteria for saccades as a minimum amplitude of 5°). It was also interesting to note that some Saccade Amplitudes extended beyond the length of the 56° display, which likely indicates some form of saccade overshoot. Secondly, it confirms that a relationship exists between Saccade Amplitude and Peak Saccade Velocity conforming to the Main Sequence (Bahill et al., 1975a). Thirdly, the Saccade Amplitude and Peak Saccade Velocity exhibit a very high linear relationship up to 20° ($r = 0.997, r^2 = 0.993, p < 0.001, n = 15$) confirming earlier research (Bahill et al., 1975a). However, if raw Saccade Amplitude values less than 20° were used (see Appendix G1) instead of the mean integer values for Saccade Amplitude ($n = 15$), the correlation drops considerably but remains significant ($r = 0.771, r^2 = 0.594, p < 0.001, n = 2858$). Fourthly, for Saccade Amplitudes above 20°, Peak Velocities begin to plateau, which is consistent with other researchers (Bahill et al., 1975a; Garbutt et al., 2001; Leigh & Zee, 2006). The logarithmic function applied to the entire relationship is also very high ($r^2 = 0.935, n = 60$) but exhibits more variation at higher amplitudes. Using all raw
Saccade Amplitude values rather than integer values, this relationship is high, but considerably less ($r^2 = 0.688$, $n = 4103$) (see Appendix G1).

The Main Sequence also dictates that a linear relationship should exist between Saccade Duration and Saccade Amplitude (Bahill et al., 1975a; Becker, 1989; Garbutt et al., 2001; Leigh & Zee, 2006). Figure 5.3.1b shows this relationship for the 33 normal participants performing the horizontal VSST.

![Figure 5.3.1b: Main Sequence: Saccade duration versus saccade amplitude for all horizontal data.](image)

A positive linear relationship is shown between saccade duration and integer values of saccade amplitude ($r = 0.988$, $p < 0.001$). Standard error bars are displayed for saccade duration at integer values of saccade amplitude.

The correlation between Saccade Duration and integer values of Saccade Amplitude is both high and significant ($r = 0.988$, $r^2 = 0.976$, $p < 0.001$, $n = 60$). The coefficient of determination value is extremely high because only the mean of the integer values were plotted ($n = 60$) compared to all saccades ($n = 4103$). Even when Saccade Amplitude is no longer grouped by integer values, then the correlation is still both high and significant ($r = 0.905$, $r^2 = 0.819$, $p<0.001$, $n = 4103$) (see Appendix G2). Furthermore, there appears to be increased variability in this linear relationship above approximately 40°.

An additional feature of Saccade Amplitude is that most naturally occurring saccades are less than 15-20° in amplitude (Bahill et al., 1975a; Duchowski et al., 2002).
Supposedly 86% of saccades in normal viewing conditions are equal to or less than 15° amplitudes (Bahill, Adler & Stark, 1975). Morgan (1999), who used the same experimental display dimensions as those used in this experiment for the horizontal VSST, found the 85th percentile for *Saccade Amplitude* was 24.6° (M = 15.9°) which is considerably higher than those executed under normal viewing conditions. Similarly, the current study observed larger saccades were being executed with the 50th percentile equalling 16.21° and the 85th percentile equalling 28.58° (M = 19.06, SD = 10.36, Range = 5.00° to 65.61°) adding support to Morgan’s (1999) findings. It is worth mentioning that this data set has shifted even further towards higher *Saccade Amplitudes* than Morgan (1999). The frequency distribution for all integer values of *Saccade Amplitude* for horizontal data is displayed in Figure 5.3.1c.

![Figure 5.3.1c: Amplitude frequency distribution for all horizontal data.](image)

Figure 5.3.1c shows the frequency of occurrence for *Saccade Amplitude* skewed towards smaller amplitudes, similar to earlier studies (Bahill, Adler & Stark, 1975; Morgan, 1999). Morgan (1999) found the frequency peak for *Saccade Amplitude* was between 8° and 11° whilst Figure 5.3.1c clearly shows the peak at 14-15° suggesting that a shift towards larger *Saccade Amplitudes* had occurred. This very closely matches the visual angle between two alphanumeric displays of 14°. Similar peaks at other inter-target step sizes (28°, 42°, 56°) were expected but not observed.
The relationship between *Mean Peak Saccade Velocity* and *Saccade Rate per trial* was also explored. From the 2376 horizontal trials, there were 482 trials where saccades were not detected, which meant *Mean Peak Saccade Velocity* could not be calculated for those trials. Between one and six saccades were detected in the remaining 1894 trials across all exposure times. *Mean Peak Saccade Velocity* was plotted against *Saccade Rate* per trial for all 1894 trials however, the spread and overlap of data was such that no relationships could be gleaned (see Appendix G3). To explore the relationship more clearly, the average *Mean Peak Saccade Velocity* was plotted against *Saccade Rate per trial*. Therefore, six values were used instead of 1894 values. The results are shown in Figure 5.3.1d.

![Figure 5.3.1d: Mean peak saccade velocity versus saccade rate (per trial) for all horizontal data](image)

The relationship between *Saccade Rate per trial* and *Mean Peak Saccade Velocity* appears to be quite complex. At low saccade frequencies, the *Mean Peak Saccade Velocity* is reasonably consistent (between 467°/s and 489°/s). At higher saccade frequencies, there is a marked decline and increased variability in *Mean Peak Saccade Velocity*. The most accurate trendline to fit these data was a negative polynomial second order function ($r^2 = 0.869, n = 6$), as the linear trendline explained less variance ($r = -$...
0.719, \( r^2 = 0.516, p = 0.108, n = 6 \). Morgan (1999) demonstrated a positive linear trendline for his data although the correlation coefficient was very low \( (r = 0.073) \) and concluded that there was no evidence to support the claim that \textit{Mean Peak Saccade Velocity} was related to \textit{Saccade Rate}. The trendline from the current data set challenge Morgan’s (1999) results. Perhaps this was because \textit{Saccade Rate} was not standardised to the same time scale. A follow-up graph (see Figure 5.3.1e) was produced to standardise \textit{Saccade Rate} to number of saccades per second as opposed to number of saccades per trial. As with the previous graph, the Mean Peak Saccade Velocity was grouped for each \textit{Saccade Rate per second} and averaged because the spread and overlap of 1894 data points was too great (see Appendix G4). Therefore, 19 values were used instead of 1894 values. This directly replicates the comparison made by Morgan (1999). Neither the negative linear trendline \( (r = -0.204, r^2 = 0.042, p = 0.402, n = 19) \) nor the second order polynomial trendline \( (r^2 = 0.438, n = 19) \) adequately explained the variance observed.

![Figure 5.3.1e: Mean peak saccade velocity versus saccade rate (per second) for all horizontal data: The same data was replotted with saccade rate standardised per second. Standard error bars are displayed for peak saccade velocity variation for each saccade rate.](image)

It was not unreasonable to think that both graphs would show a decrease in \textit{Mean Peak Saccade Velocity} as \textit{Saccade Rate} increases. It might be expected that the higher the \textit{Saccade Rate} within a short period that saccades would be of smaller amplitude to allow them to be executed in time. The \textit{Main Sequence} tells us the smaller the \textit{Saccade}
Amplitude, the smaller the Peak Saccade Velocity. Therefore, a large number of small saccades would have lower Mean Peak Saccade Velocity than a smaller number of large saccades. This would lead us to expect that a negative slope would exist, which is exactly what was observed in both Figure 5.3.1e when Saccade Rate was standardised per second, and in Figure 5.3.1d when Saccade Rate was not standardised. In both instances, the coefficient of determination was higher for the second order polynomial equation rather than the linear equation. Although this value was higher when Saccade Rate per trial was used, this is believed to be due to the smaller number of data points (6 versus 19). Furthermore, there was very low incidence of high saccade frequencies (either per trial or per second), so it is feasible to think that higher saccade frequencies were outliers. This was not considered when observing Figure 5.3.1d-e, but was in Appendix G3-4. The graphed data did not provide categorical evidence that Mean Peak Saccade Velocity was related to Saccade Rate supporting Morgan (1999).

The frequency distribution of Saccade Latency for all horizontal trials with at least one saccade was calculated (see Figure 5.3.1f) to check for consistency with other studies. The plot shows that Saccade Latency is normally distributed with more than 62% of primary saccades performed between 180-280 ms after Exposure Time onset. Almost
13% of latencies are faster than 180 ms and another 24% slower than 280 ms. However, earlier research indicated that Saccade Latency would be less if targets consistently appeared in the same location 100% of the time, as was the case in the VSST (Jüttner & Wolf, 1992). The results of this study cannot support that particular finding. It was also interesting to note that in almost 3% of trials that saccades were not executed until 400 ms after the Exposure Time onset.

5.3.2 Horizontal Task Parameters

Response Accuracy was calculated by coding trials as either correct or incorrect and counting the total across each Exposure Time. The results were combined for all 33 participants and then plotted as an overall percentage in Figure 5.3.2a. There were 396 trials per exposure time (total = 2376). The percentage error for each Exposure Time equalled 100%.

![Figure 5.3.2a: Response accuracy for horizontal VSST.](image)

A one-way ANOVA was conducted between Response Accuracy and Exposure Time and was found to be significant \(F(5, 2370) = 32.023, \ p < 0.001\). The data revealed the highest Response Accuracy (70.2% correct) was when Exposure Time was longest (1000 ms). Response Accuracy deteriorated as Exposure Time shortened reaching 33.3%
at the 200 ms Exposure Time. It was interesting to note that Response Accuracy of 50% occurred near the 650 ms Exposure Time.

The results of the previous graph were extended to incorporate Number of Target Letters as a function of Exposure Time and Response Accuracy. The results were plotted in Figure 5.3.2b. Response Accuracy was changed to Response Error because of the complexity of the graph. A Response Error of 100% indicated participants responded incorrectly to all trials that contained a given number of target letters (0-3) at a given exposure time (200-1000 ms) e.g. during the 200 ms exposure time, 3 target letters were incorrectly determined 100% of the time.

Figure 5.3.2b: Horizontal VSST response error for number of target letters in each exposure time. The percentage for task error is displayed as a function of exposure time and number of target letters (n = 2376).

A two-way between groups ANOVA explored the impact of Exposure Time and Number of Target Letters on Response Error. The main effect for Number of Target Letters \(F(3, 2352) = 527.124, p < 0.001\) and Exposure Time \(F(5, 2352) = 55.775, p < 0.001\) were both significant, as was the interaction effect \(F(23, 2352) = 12.916, p < 0.001\). This indicated that the horizontal VSST was more difficult to complete successfully when there were more target letters to detect and less time available to scan the display. This result is consistent with Morgan (1999). The only discrepancy with Morgan (1999) was that Response Error did not increase for the No Target trials at
shorter Exposure Times. Response Error is virtually nil at the 200 ms Exposure Time for no targets and this is because participants adhered to the task instructions and only responded to target letters they were certain of seeing. Unfortunately, not all No Target trials had a Response Error of zero (highest was 11.1%). Therefore, errors of commission were said to occur whereby participants over-estimated the number of targets in a trial. Although participants were under strict instructions not to make this type of error, it was obvious that this still occurred, albeit much less frequently in this sample than in Morgan’s (1999).

5.3.3 Horizontal Saccade Parameters

For these analyses, each of the 72 trials performed per VSST were treated as separate cases. The saccade parameters calculated for each trial included Saccade Rate per second, Cumulative Saccade Amplitude, Mean Saccade Amplitude, Cumulative Peak Saccade Velocity, Mean Peak Saccade Velocity, and Saccade Latency. The parameters for each trial were then grouped according to Response Accuracy (correct or incorrect) and Exposure Time (200, 350, 500, 650, 800, 1000 ms) and the various interactions analysed.

5.3.3i Horizontal Mean Saccade Rate

The relationship between Saccade Rate per second and Response Accuracy was analysed and compared across all Exposure Times and displayed in Figure 5.3.3i. A two-way between groups ANOVA was conducted to explore the impact of Exposure Time and Response Accuracy on Saccade Rate per second during the horizontal VSST. A significant interaction effect was observed \([F(5,2364) = 3.08, p = 0.009]\), as were the main effects for Exposure Time \([F(5,2364) = 311.28, p < 0.001]\) and Response Accuracy \([F(1,2364) = 11.39, p < 0.001]\).
Figure 5.3.3i: Horizontal saccade rate per second. Saccade Rate was standardised for each exposure time to saccade rate per second and determined for correct and incorrect trials. Standard error bars are displayed for mean saccade rate per second.

Subsequent post hoc t-tests revealed that at the 0.05 level, significant differences were observed between correct and incorrect trials at 650 ms, 800 ms and 1000 ms Exposure Times. However, a Bonferroni adjustment was applied to the significance level to take into account the number of t-test comparisons performed (0.05 ÷ 6 = 0.009). The Bonferroni adjustment will be applied to all post-hoc t-tests herein. All three Exposure Times remained significantly different after Bonferroni adjustment and in these three instances, more successful trials were characterised by more frequent saccades. The post hoc t-test data are displayed in Table 5.3.3i.

Table 5.3.3i
Post-hoc t-test scores for Horizontal Saccade Rate per second by Exposure Time and Response Accuracy

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>394</td>
<td>394</td>
<td>394</td>
<td>394</td>
<td>394</td>
<td>394</td>
</tr>
<tr>
<td>t-value</td>
<td>0.000</td>
<td>-1.147</td>
<td>1.255</td>
<td>3.074</td>
<td>2.616</td>
<td>4.200</td>
</tr>
<tr>
<td>significance</td>
<td>1.000</td>
<td>0.252</td>
<td>0.210</td>
<td><strong>0.002</strong></td>
<td>0.009</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Red = Significant to less than 0.001, Green = Significant to 0.009
5.3.3i  Horizontal Saccade Amplitude

Cumulative Saccade Amplitude and Mean Saccade Amplitude were calculated per trial and split by Exposure Time and Response Accuracy and then plotted in Figure 5.3.3ii.

![Figure 5.3.3ii: Horizontal saccade amplitude.](image)

A significant interaction effect was observed for Cumulative Saccade Amplitude by Exposure Time and Response Accuracy \[F(5,1882) = 2.584, \ p = 0.024\] as was each main effect for Exposure Time \[F(5,1882) = 514.505, \ p < 0.001\] and Response Accuracy \[F(1,1882) = 11.893, \ p < 0.001\]. Post-hoc t-tests revealed that successful and unsuccessful trials were significantly different at the 650 and 1000 ms Exposure Times.
to the 0.009 level, and approached significance at the 800 ms Exposure Time (see Table 5.3.3b). A characteristic of these differences was that saccades in successful trials covered larger amplitudes. It was interesting to note that only trials from the 1000 ms exposure time, regardless of trial success, covered the full 56° range of the experimental display board.

A significant interaction effect was not observed \[ F(5,1882) = 1.032, p = 0.397 \] for Mean Saccade Amplitude although the main effect for Exposure Time \[ F(5,1882) = 19.862, p < 0.001 \] and Response Accuracy \[ F(1,1882) = 9.968, p = 0.002 \] were significant. However, post-hoc t-tests were still conducted in successful and unsuccessful trials at all exposure times to ensure that individual differences observed by Morgan (1999) were not hidden by the overall interaction effect, especially given that visually it appears there Mean Saccade Amplitude was greater in correct trials than incorrect trials. However, the post-hoc t-tests did not reveal any significant differences at the 0.009 level (see Table 5.3.3ii).

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>27</td>
<td>319</td>
<td>374</td>
<td>386</td>
<td>389</td>
<td>387</td>
</tr>
<tr>
<td>Cumulative Saccade Amplitude</td>
<td>t = 1.865</td>
<td>t = -0.271</td>
<td>t = 1.721</td>
<td>t = 3.418</td>
<td>t = 2.407</td>
<td>t = 3.649</td>
</tr>
<tr>
<td></td>
<td>p = 0.073</td>
<td>p = 0.787</td>
<td>p = 0.086</td>
<td>p &lt; 0.001</td>
<td>p = 0.017</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Mean Saccade Amplitude</td>
<td>t = 2.013</td>
<td>t = 0.250</td>
<td>t = 2.040</td>
<td>t = 1.763</td>
<td>t = 1.202</td>
<td>t = 0.580</td>
</tr>
<tr>
<td></td>
<td>p = 0.054</td>
<td>p = 0.803</td>
<td>p = 0.042</td>
<td>p = 0.079</td>
<td>p = 0.230</td>
<td>p = 0.562</td>
</tr>
</tbody>
</table>

Red = Significant to less than 0.001
5.3.3iii  *Horizontal Peak Saccade Velocity*

*Cumulative Peak Saccade Velocity* and *Mean Peak Saccade Velocity* were grouped by *Exposure Time* for correct and incorrect trials and plotted in Figure 5.3.3iii.

![Graph showing horizontal peak saccade velocity](image)

**Figure 5.3.3iii: Horizontal peak saccade velocity.** The peak velocity for all saccades per trial was combined (top) to demonstrate the interaction between number of saccades and their velocity. Conversely, peak saccade velocity (bottom) for all saccades per trial was averaged to account for saccade rate. Both graphs show correct and incorrect trials across all exposure times. Standard error bars are displayed for peak saccade velocity.

The interaction between *Cumulative Peak Saccade Velocity* by *Exposure Time* and *Response Accuracy* was significant \[ F(5,1882) = 3.662, p = 0.003 \] as was the main effect for *Exposure Time* \[ F(5,1882) = 470.083, p < 0.001 \] and *Response Accuracy* \[ F(1,1882) = 15.672, p < 0.001 \]. *Post-hoc* t-tests revealed that *Cumulative Peak*
Saccade Velocity was significantly greater in correct trials than incorrect trials at the 0.009 level during the 200, 650, 800 and 1000 ms Exposure Times (see Table 5.3.3iii).

A significant interaction effect was observed for Mean Peak Saccade Velocity $[F(5,1882) = 3.16, p = 0.008]$ and the main effect for Response Accuracy $[F(1,1882) = 20.73, p < 0.001]$. However, the main effect for Exposure Time was not significant $[F(5,1882) = 2.21, p = 0.051]$. Subsequent post-hoc t-tests revealed that only at the 200 and 800 ms Exposure Times that Mean Peak Saccade Velocity was significantly faster for correct trials than incorrect trials. Figure 5.3.3iii shows that Mean Peak Saccade Velocity was visibly higher for correct than incorrect trials at the 200, 500, 650 and 800 ms Exposure Times, so it was surprising that only two were statistically significant. The 500 ms Exposure Time approached significance, but neither that nor the 650 ms Exposure Time were significant at the 0.009 level (see Table 5.3.3iii). These findings are reasonably consistent with Morgan (1999) who observed significantly faster Mean Peak Saccade Velocities at the 500 and 800 ms Exposure Times for correct trials than incorrect trials.

Table 5.3.3iii
Post-hoc t-test scores for Horizontal Peak Saccade Velocity by Exposure Time and Response Accuracy

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>df</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative Peak Saccade Velocity</td>
<td>t = 2.908</td>
<td>t = -0.921</td>
<td>t = 1.730</td>
<td>t = 3.526</td>
<td>t = 3.353</td>
<td>t = 4.208</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p = 0.007</td>
<td>p = 0.358</td>
<td>p = 0.084</td>
<td>p &lt; 0.001</td>
<td>p &lt; 0.001</td>
<td>p &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>Mean Peak Saccade Velocity</td>
<td>t = 3.293</td>
<td>t = -0.366</td>
<td>t = 2.046</td>
<td>t = 1.635</td>
<td>t = 2.902</td>
<td>t = 0.746</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p = 0.003</td>
<td>p = 0.714</td>
<td>p = 0.041</td>
<td>p = 0.103</td>
<td>p = 0.004</td>
<td>p = 0.456</td>
<td></td>
</tr>
</tbody>
</table>

Red = Significant to less than 0.001, Green = Significant to 0.009

The results also revealed for the first time that a significant difference existed between correct and incorrect trials at the 200 ms Exposure Time. This was most likely due to the small number of observations (n = 29) for the 200 ms Exposure Time which was
considerably less than the next smallest number of observations from all other Exposure Times (n = 321 at 350 ms).

5.3.3iv Horizontal Saccade Latency

Saccade Latency was grouped by Exposure Time and Response Accuracy and the mean of these groups is shown in Figure 5.3.3iv. Trials without saccades, as well as anticipation saccades, were excluded leaving 1894 trials out of a possible 2376 performed to include in the analysis.

![Figure 5.3.3iv: Horizontal saccade latency.](image)

The time taken to initiate the first saccade was measured in each individual trial. The graph shows the mean latency for correct and incorrect trials across all exposure times. Standard Error bars are displayed.

The interaction effect for Saccade Latency by Exposure Time and Response Accuracy was not significant \( F(5,1882) = 2.12, p = 0.061 \). However, the main effect for Exposure Time was significant \( F(5,1882) = 30.270, p < 0.001 \) but not Response Accuracy \( F(1,1882) = 0.565, p = 0.452 \). Morgan (1999) did not examine Saccade Latency across Exposure Time or Response Accuracy and combined with the fact that there was no significant interaction between these variables suggests that post-hoc t-tests should not be conducted. However, the interaction effect approached significance and there was visibly a trend for Exposure Times above 500 ms that Saccade Latency was faster for correct responses than incorrect responses. These two reasons provided enough justification to perform some exploratory t-tests. The results showed that the
only significant post-hoc t-test was for the 1000 ms Exposure Time at the 0.009 level (see Table 5.3.3iv).

Table 5.3.3iv
Post-hoc t-test scores for Horizontal Saccade Latency by Exposure Time and Response Accuracy

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>27</td>
<td>319</td>
<td>374</td>
<td>386</td>
<td>389</td>
<td>387</td>
</tr>
<tr>
<td>t-value</td>
<td>1.202</td>
<td>0.308</td>
<td>-0.055</td>
<td>-0.664</td>
<td>-1.845</td>
<td>-3.052</td>
</tr>
<tr>
<td>significance</td>
<td>0.240</td>
<td>0.758</td>
<td>0.956</td>
<td>0.507</td>
<td>0.066</td>
<td><strong>0.002</strong></td>
</tr>
</tbody>
</table>

Green = Significant to 0.009

5.4 Discussion

There were a number of key findings from this study of 33 normal participants. Firstly, the saccade detection algorithm proved to be very accurate because all deflections below 5° were excluded (Figure 5.3.1a) and all durations less than 12 ms were excluded (Figure 5.3.1b). Secondly, the 33 participants conformed to existing saccade Main Sequence relationships suggesting that the sample of the normal population were within normal limits. More specifically, as Saccade Amplitude increased, Peak Saccade Velocity increased linearly up until 20° before the relationship became logarithmic at increasingly higher amplitudes (Figure 5.3.1a). Saccade Duration also increased linearly with Saccade Amplitude with the rate of rise consistent with earlier research (Becker, 1989; Garbutt et al., 2001).

The most frequent Saccade Amplitude occurred around the inter-target step size of 14°, but high frequencies were not observed for larger step sizes of 28°, 42° and 56° (Figure 5.3.1c). This would suggest that the majority of saccades were executed with a high degree of accuracy requiring fewer corrective saccades to targets. It is not readily obvious why the saccades generated in this experiment more accurately reflected the inter-target step size than those from Morgan (1999) except to speculate that the amplitude calibration was more accurate for these experiments. Considering the trendlines for the individual calibrations of this study were calculated as mean $r^2 = 0.975$, it was likely Morgan (1999) was unable to better $r^2 = 0.86$ which was the most
reliable grouped data calibration method (see Figure 4.3b) and the same method as Morgan’s, providing some credibility to the argument.

The relationship between Peak Saccade Velocity and Saccade Rate in this study refuted the findings of Lueck et al., (1991) instead finding Peak Saccade Velocity did not increase with Saccade Rate regardless of whether rate was standardised per trial or per second. This makes sense considering that to generate large amounts of saccades within a limited Exposure Time meant that the saccades would have to be small by nature. The Main Sequence dictates that smaller saccades have slower velocities suggesting that as Saccade Rate increases, Peak Saccade Velocity decreases. A negative relationship was observed (Figure 5.3.1d) but the small amount of data at some Saccade Rates mistakenly implies the relationship was significant. When all trials were considered (see Appendix G3 & G4), it clearly showed that no relationship existed supporting the conclusion by Morgan (1999).

Detailed analysis of Response Accuracy as a function of task parameters yielded evidence that target numbers and Exposure Time significantly changed the difficulty of the task. As Exposure Time decreased and the Number of Target Letters increased, Response Accuracy reduced (Figure 5.3.2b). The horizontal VSST was obviously quite challenging because even the longest Exposure Time did not demonstrate 100% success (70.2% correct). Success deteriorated as the Exposure Times shortened almost reducing to chance (33.3% correct) at the 200 ms Exposure Time (Figure 5.3.2a). Due to the instructions of the VSST, a Response Accuracy of 25% (one forced response from four choices) indicates chance. The nature of the forced choice task means that even if the participant never identifies a target letter (therefore responding with zero), 3 out of 12 trials per exposure time will be correct because this is the frequency of zero target letters. The task clearly produced an appropriate level of varied success (33.3% to 70.2%) because it was important to demonstrate under demanding conditions a variety of visual search strategies. Studies which observed 100% success have realised post-study that the task was not difficult enough (Fischman & Sanders, 1991) which vindicates the decision to conduct the experiment over the same Exposure Times as Morgan (1999).
Response Accuracy was also analysed as a function of saccade behaviour. Saccade Rate per second was found to be significantly related to the period the stimulus was displayed. The 200 ms Exposure Time exhibited the fewest saccades per second, which was expected because normal Saccade Latency is between 180-250 ms (Jüttner & Wolf, 1992; Kalesnykas & Hallett, 1994) making it almost impossible to initiate a saccade. At smaller Exposure Times (200 and 350 ms), there was no difference in Saccade Rate for correct and incorrect trials. At larger Exposure Times (650, 800 and 1000 ms), successful trials were characterised by more frequent saccades. Morgan (1999) observed a similar trend albeit for trials at the 500, 650 and 800 ms Exposure Times. The results can be explained by a cost-benefit approach to visual acquisition. The cost being that saccades suppress vision just prior to and following saccades (Latour, 1962) but the benefit is that saccades bring information from the periphery onto the fovea. In this respect, the most appropriate search strategy may be one that provides the greatest balance between cost and benefit. At smaller Exposure Times where speed was imperative, the strategy may be to minimise or eliminate saccades because there is insufficient time to make several accurate saccades making it more effective to use peripheral vision. At longer Exposure Times, the optimal strategy may be to sacrifice speed for accuracy and make several saccades that bring targets on the fovea. At no point during the VSST was there evidence to suggest that making more frequent saccades caused a perceptual disadvantage.

Further analysis of Response Accuracy as a function of eye movement behaviour identified that the larger the Cumulative Saccade Amplitude, the greater the likelihood of responding correctly to trials at longer Exposure Times (650-1000 ms). Morgan (1999) also showed larger Saccade Amplitudes were associated with successful trials but at slightly lower Exposure Times (500-800 ms). However, studies have shown saccadic suppression increases as a function of Saccade Amplitude (Ridder & Tomlinson, 1997) indicating that larger saccades would be counter-productive to successful visual search. This was refuted by the current results because scanning larger areas of the experimental display was associated with successful task completion (Figure 5.3.3ii-top). Unfortunately, Mean Saccade Amplitudes were not significantly related to increased Response Accuracy even though amplitudes were higher for correct responses at every Exposure Time (Figure 5.3.3ii-bottom). Therefore, the results
suggested there was a perceptual advantage to making frequent saccades that collectively covered wider areas of the experimental display.

The fact *Cumulative Saccade Amplitude* was significantly different was not surprising given that higher *Saccade Rates* were observed at these *Exposure Times*. *Cumulative Saccade Amplitude* is directly related to *Saccade Rate* so if one were significant then there is increased likelihood that the other were too. However, the surprising thing is that only at the 1000 ms *Exposure Time* was *Cumulative Saccade Amplitude* greater than 56°, which was the visual angle subtended by the experimental display. The simplest explanation was that the reducing *Exposure Time* provided less time to scan the entire display. This was supported by the fact that when *Cumulative Saccade Amplitude* was greater, that *Response Accuracy* was also greater. However, as the twelve 1000 ms trials were performed first, and subsequent *Exposure Times* displayed a decrease in *Cumulative Saccade Amplitude*, perhaps a more efficient search strategy was employed resulting in the entire display not being scanned. Unfortunately, a more efficient strategy did not translate into a more effective strategy given the continued decline in *Response Accuracy* as both *Exposure Time* and *Cumulative Saccade Amplitude* reduced. Therefore, it was far more likely that the entire display was not scanned for *Exposure Times* less than 1000 ms due to increasing time constraints rather than more efficient strategies being employed.

Similar results were observed for peak velocity with the *Cumulative Peak Saccade Velocities* greater for successful trial outcomes (Figure 5.3.3iii-top). Additionally, *Mean Peak Saccade Velocity* was higher for correct trials (Figure 5.3.3iii-bottom), but the results were not significant mirroring the *Mean Saccade Amplitude* findings. *Cumulative Peak Saccade Velocity*, as with *Cumulative Saccade Amplitude* did show significant differences between correct and incorrect trials at *Exposure Times* 650 ms and greater. Therefore, there is a perceptual advantage in making more frequent saccades that are cumulatively larger and cumulatively faster during longer *Exposure Times*. Conversely, there is no perceptual advantage in making fewer, smaller and slower saccades at shorter *Exposure Times*.

*Saccade Latency* was the last eye movement behaviour assessed. Preliminary analysis indicated there was no relationship between *Response Accuracy* and *Saccade Latency*.
except at the 1000 ms *Exposure Time* where faster latencies resulted in greater trial success (Figure 5.3.3iv). The fact that only one significant difference occurred across the six *Exposure Times* would suggest that the result was out of place. In fact, it appears as though there is a learning effect on the task for this *Exposure Time* only because *Saccade Latencies* are almost identical at all other *Exposure Times*. It just so happens that these were the first twelve trials always performed, so participants may not have refined their search strategy at task onset. This overall result for *Saccade Latency* and *Response Accuracy* was consistent with Morgan (1999) who also found no difference and attributed this result to there being no relationship between *Saccade Latency* and saccadic suppression.
Chapter 6   Vertical Visual Search Strategy in Normal Participants

6.1 Introduction

Traditionally, vertical saccadic eye movements have received far less attention from researchers than horizontal eye movements primarily because eye movement recording systems could not measure them reliably (Collewijn, Erkelens & Steinman, 1988b). Vertical EOG recordings are contaminated by eyelid artefact due to electrode placement (Barry & Jones, 1965; Yee et al., 1985) and IR limbus tracking shows serious distortions beyond 10° upwards and 20° downwards (Yee et al., 1985). Arguably, the most reliable method for recording vertical saccades is the magnetic scleral search coil (Yee et al., 1985; Collewijn et al., 1988b). The fact that the system is expensive, causes irritation to the eye and requires more cooperation from the participant makes this recording system of limited use.

Regardless of the method chosen, EOG, scleral search coil and to a lesser extent IR all exhibit the known logarithmic Main Sequence relationship between Saccade Amplitude and Peak Saccade Velocity (Yee et al., 1985; Chioran & Yee, 1991). IR and scleral search coil have also reported a linear relationship between vertical Saccade Amplitude and Saccade Duration although this relationship has greater variance than horizontal saccade recordings using the same equipment (Bahill & Kallman, 1983; Collewijn et al., 1988b). EOG and IR have additional impacts on the actual saccade parameters. EOG is known to have consistently higher peak velocities for upwards saccades than downwards saccades. In some cases, peak velocity is almost 300°/s faster in 30° upward saccades ($M = 709°/s$) than 30° downward saccades ($M = 557°/s$) and about 200°/s faster than either upward ($M = 443°/s$) or downward ($M = 436°/s$) saccades measured by the scleral search coil (Yee et al., 1985). IR on the other hand severely underestimates Saccade Amplitude especially in the upwards direction which subsequently affects Peak Saccade Velocity (Yee et al., 1985). The conclusion regarding the experimental use of EOG was that artefacts from eyelid movement had major effects on both the trajectory and peak velocity of saccades (Yee et al., 1985). However, EOG had already proven simple to administer and demonstrated high linearity during horizontal VSST (Chapter 4 & 5). Therefore, the success of these
studies leads to the assertion that EOG would also be suitable for vertical VSST recordings. Nevertheless, it was imperative to take into account the known problems associated with vertical EOG recordings by either reducing the amount of eyelid artefact present in the vertical EOG signal or reducing its impact on the analysis following data acquisition.

Eyelid artefact has been successfully reduced within EOG recordings in the past when the eyelids have been mechanically retracted (Yee et al., 1985), held open by a wire lid speculum, or rolled towards the superior orbital rim using the lid-roll procedure (Chioran & Yee, 1991). An example of the improved EOG signal resulting from the use of the lid speculum is demonstrated in Figure 6.1a. The figure shows the simultaneous EOG recording from left and right eyes during a 25° saccade to target. The interesting thing to note is that the right eye contains no sign of eyelid artefact because the upper eyelid had been fixed, whilst the recording in the left eye clearly shows the artefact.

![Figure 6.1a Example of eyelid artefact present in an EOG recording](image)

Apart from the obvious conclusion that the upper eyelid is somehow responsible for eyelid artefact, it would be remiss not to mention that the combination of saccade and artefact from the left eye produce a deflection with the same-sized amplitude as the target. Although the EOG signal looks similar to overshoot, the comparison between right and left eye confirm the artefact is the result of the upper eyelid and not overshoot.
Following the eyelid artefact in the left eye, the subsequent fixation finishes short of the target position, which is quite unexpected (Chioran & Yee, 1991). Although this method reduced the amount of eyelid artefact present in the signal, it was also beyond the ability of the experimenter to implement. Therefore, the only alternative was to reduce the impact of eyelid artefact by eliminating it from the analysis following data acquisition.

Other considerations had to be taken into account when recording vertical saccades. Spontaneous blinks are more frequent during vertical eye movements than horizontal eye movements (Tada & Iwasaki, 1985). More specifically, frequent eye blinks were associated with upwards rather than downwards saccades (Tada & Iwasaki, 1985). Vertical saccades that are accompanied by a blink are slower in mean velocity, have longer durations and more prone to overshoot than saccades unaccompanied by a blink (Rottach et al., 1998; Rambold et al., 2002). However, there is no difference in Peak Saccade Velocity, peak acceleration or peak deceleration between upward or downward saccades whether accompanied by a blink or not (Rambold et al., 2002). Therefore, blinks slow all vertical eye movements in a consistent manner (Rambold et al., 2002), so this information may be useful when eradicating blinks or eyelid artefact from recordings.

Although this chapter extends the findings of the horizontal VSST, the vertical VSST study is primarily exploratory. Studies on vertical visual search strategies are non-existent, as is the attention paid to saccadic suppression studies during vertical saccades. Therefore, there was no reason to believe that the results observed during the horizontal VSST would not be replicated during the vertical VSST. It was hypothesised that correct trials would be heavily associated with faster, larger and more frequent saccades and that Response Accuracy should be comparable to horizontal VSST results.

6.2 Method

6.2.1 Participants

The 33 participants from Chapter 5, with the exception of one male, performed the tasks.
6.2.2 Procedure

The 32 participants performed the vertical EOG Amplitude Calibration Routine followed by the 72 trial vertical VSST and then repeated the vertical calibration routine again. As with the horizontal tasks, the duration of the vertical tasks was approximately 5 minutes.

There were two major differences with how the horizontal raw data was processed in Chapter 5 to how the vertical raw data was processed in this Chapter; firstly relating to the calibration (varied from Chapter 2) and secondly relating to the exclusion of eyelid artefact (additional steps from Chapter 3).

6.2.3 Improving the Calibration

The $r^2$ values for the linear trendline determined for each participant following completion of the vertical EOG amplitude calibration routine ($M = 0.911$, $SD = 0.042$) showed greater variation than the horizontal EOG amplitude calibration ($M = 0.975$, $SD = 0.016$). An attempt was made to decrease the variance around the fitted trendline by experimenting with non-linear trendlines. Figure 6.2.3a shows an example of one such experiment where the $r^2$ value for the linear trendline ($r^2 = 0.9633$) was less than for the non-linear (cubic) trendline ($r^2 = 0.9833$).

![Calibration equations using linear and cubic regressions](image)

**Figure 6.2.3a: Calibration equations using linear and cubic regressions.** The graph above shows how the raw serial values were calibrated in degrees of visual angle (method outlined in Chapter 2) from participant Norm21. The linear equation has greater variation ($r^2 = 0.9633$) than the cubic equation ($r^2 = 0.9833$).
However, for these participants, it proved very difficult to transpose a cubic equation (and must be noted that this was beyond the scope of this thesis), so the axes were switched to allow easier calibration. An example of this was shown in Figure 6.2.3b. This figure is a replica of Figure 6.2.3a, but with the axes transposed.

Following successful attempts to improve the calibration process by utilising non-linear trendlines, all participants had their vertical EOG amplitude calibration routine fitted with both a linear and non-linear cubic trendline. Seventeen participants out of the 32 had improved calibration equations using non-linear cubic trendlines, whilst the other 15 participants were adequately fit using a linear trendline. In all circumstances, the highest $r^2$ value dictated which trendline was applied and in cases where the $r^2$ value was the same for both trendlines, the linear trendline was used. This increased the overall $r^2$ value slightly ($M = 0.922$, $SD = 0.043$). As a *post-hoc* check of the horizontal EOG amplitude calibration equations, all 33 equations showed the linear equation to have the same or smaller variance. This attempt at calibration improvement didn’t work for the horizontal recordings presumably because of the initially high $r^2$ values.
6.2.4 Eliminating Eyelid Artefact

Most researchers subjectively identify blinks in the EOG signal and remove them on that basis alone (Balloh et al., 1975b; Baloh et al., 1976a; Smith et al., 1981; Bahill et al., 1981). However, as Figure 6.1a showed, eyelid artefact is considerably smaller in both amplitude and duration than blinks making it more difficult to identify. An objective method for determining eyelid artefact was required. The objective method would complement the saccade detection algorithm developed in Chapter 3, because only falsely detected saccades required exclusion. As a starting point, blinks were subjectively identified (n = 119) in all vertical VSST trials (n = 2304) according to blink definitions described in Chapter 3. The blinks were then placed in a database to quantify their features. The purpose of this database was to make comparisons between (1) blinks (2) subjectively identified eyelid artefact (similar to Figure 6.1a) and (3) consecutive saccades that deflect in opposite directions (similar, but larger than overshoot). All three physiological movements have two consecutive deflections; one being positive the other negative (but not always in that order). The consecutive saccades were unlikely to be overshoot because overshoot is generally not greater than 5° (Bahill, Clark & Stark, 1975b; Becker, 1989), whereas all the deflections in this database were. The premise being that consecutive saccades should be separated by a fixation where perceptual benefit is gained whilst eyelid artefact (time between saccade and artefact) and blinks (time between closing and reopening phases) do not. Therefore, the fixation between the consecutive saccades was expected to have a longer duration than the pause between deflections from blinks or eyelid artefact.

The simplest approach would be to determine the smallest fixation or ISI between two consecutive saccades that still permit perceptual benefit. The deflections that do not have a long enough fixation or ISI between them would be treated as eyelid artefact or noise. The difficulty with this approach was the varied literature on normal ISI ranging from approximately 200 ms (Bahill, Bahill, Clark, & Stark, 1975; Levy-Schoen & Blanc-Garin, 1974; Salthouse & Ellis, 1980) to as low as 20 ms (Barmack, 1970) or even 0 ms (Levy-Schoen et al., 1974), although the last two studies did not determine if perceptual benefit was gained. Using the lowest ISI value from previous literature (0 ms) would imply that all consecutive deflections were saccades and therefore eyelid artefact could never be distinguished. This was completely unacceptable. The minimum
ISI value could be determined with additional experiments, but it was considered beyond the scope of this thesis. Therefore, the problem had to be approached from an alternate direction.

Consecutive deflections also occur when observing the closing and re-opening phase of a blink (Tucker & Johns, 2005). In between these two phases is the period in which the eyelids are closed. In alert participants, the duration of this period is $0.3 \pm 4\text{ ms}$ (Tucker & Johns, 2005). This very short period could be determined in this thesis by calculating when velocity for the first deflection dipped below a critical threshold and until the velocity for the second deflection rose above the same threshold. If this period of low velocity for the 119 blinks was similar to the durations reported by Tucker and Johns (2005), then this criterion could be applied to eyelid artefact for exclusion. For example, if the time between two consecutive deflections were less than or equal to the low velocity period of a blink ($< 0.3 \pm 4\text{ ms}$), then eyelid artefact was said to occur, whilst if the time were greater than the low velocity period ($> 0.3 \pm 4\text{ ms}$) then a fixation was said to occur and consecutive saccades identified.

The database of blinks ($n = 119$) was analysed in such a way as to determine the duration that the eyes remained closed during normal blinks in these EOG studies. The velocity threshold heavily effected the duration of the eyelid closure, so three potential low velocity thresholds were chosen; $100^\circ/s$, $40^\circ/s$ and $10^\circ/s$. Table 6.2.4a shows how each velocity threshold effected the duration of eyelid closure, determined by the period of low velocity, for the 119 subjectively determined blinks.

Table 6.2.4a

<table>
<thead>
<tr>
<th>Duration (ms) of Eyelid Closure</th>
<th>M</th>
<th>SD</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^\circ/s$ threshold</td>
<td>0.8</td>
<td>1.0</td>
<td>0.0</td>
<td>2.1</td>
</tr>
<tr>
<td>$40^\circ/s$ threshold</td>
<td>3.0</td>
<td>1.7</td>
<td>0.0</td>
<td>6.3</td>
</tr>
<tr>
<td>$100^\circ/s$ threshold</td>
<td>9.3</td>
<td>8.3</td>
<td>2.1</td>
<td>54.2</td>
</tr>
</tbody>
</table>

$n = 119$
The $10^\circ$/s velocity threshold produced similar mean durations to Tucker and Johns (2005) ($M = 0.8$ ms vs 0.3 ms) and a maximum duration of 2.1 ms. The maximum duration of the eyelid closure was as equally important as the velocity threshold itself. This was because it was required as a secondary threshold for two reasons. Firstly, to ensure that similar means to Tucker and Johns (2005) were reproduced. If values above the maximum duration were included, it would inflate the mean causing a discrepancy with prior research. Secondly, it provided an upper limit for the eyelid closure duration because anything above this was assumed to be a fixation between saccades. Therefore, any deflections that occurred within 2.1 ms (1 sample) or less of each other and using the $10^\circ$/s velocity threshold to determine the start and end points, was likely a blink. Any duration greater than this would be considered two saccades.

However, the $40^\circ$/s threshold also produced similar means to Tucker and Johns (2005), especially after taking the smaller standard deviation into account ($3 \pm 1.7$ ms vs $0.3 \pm 4$ ms). If this threshold were chosen then the period of low velocity could not be longer than 6.3 ms in duration (3 samples) to be considered eyelid artefact. Conversely, the $100^\circ$/s threshold had durations drastically higher than Tucker and Johns (2005). If a threshold of this value were chosen, it would conclude that all consecutive deflections within 54 ms of each other were eyelid artefact. This threshold was considered unacceptable because firstly, it was not close to values in previous literature and secondly it would increase the likelihood of eliminating saccades. The purpose of the study was to eliminate eyelid artefact only, but not at the expense of eliminating some saccades. Allowing small amounts of eyelid artefact through was preferential to eliminating a small number of saccades.

A search was conducted of all vertical VSST trials for eyelid artefact based on the depiction of eyelid artefact in Figure 6.1. A total of 267 examples of eyelid artefact were subjectively identified, two of which are shown in Figure 6.2.4.
In the example above (Figure 6.2.4), five deflections conform to saccade detection criteria and would be included as saccades. The first (downwards), second (upwards) and fourth (upwards) are understandably considered saccades. However, the third (downwards) and fifth (downwards) movements are questionable considering that there is no perceptual benefit in not fixating after making saccades 2 and 4. Between saccade 2 and 3, the velocity dips below 100°/s for 6.249ms, below 40°/s for 2.083 and below 10°/s for 2.083ms. Between saccade 4 and 5 the velocity dips below 100°/s for 8.332 ms, 40°/s for 4.166 ms and below 10°/s for 0 ms. Therefore, using any of the three velocity threshold combinations from Table 6.2.4a would have caused the third and fifth deflection to be excluded as eyelid artefact.

The 267 examples of subjectively identified eyelid artefact were placed in a database to determine whether the pause was long enough between the positive and negative deflections to deem that a fixation had taken place and was therefore incorrectly included. Table 6.2.4b demonstrates the breakdown of these durations.
Table 6.2.4b

Duration of Low Velocity for Deflections Subjectively Considered Eyelid Artefact

<table>
<thead>
<tr>
<th>Duration (ms) of Low Velocity</th>
<th>M</th>
<th>SD</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°/s threshold</td>
<td>1.0</td>
<td>1.5</td>
<td>0.0</td>
<td>18.7</td>
</tr>
<tr>
<td>40°/s threshold</td>
<td>3.6</td>
<td>2.7</td>
<td>0.0</td>
<td>27.1</td>
</tr>
<tr>
<td>100°/s threshold</td>
<td>9.0</td>
<td>5.7</td>
<td>4.2</td>
<td>37.5</td>
</tr>
</tbody>
</table>

The database of subjectively identified eyelid artefact (Table 6.2.4b) shows that although the means and standard deviations increased only slightly, the maximum durations increased substantially for the 10°/s and 40°/s velocity thresholds when compared to the blink database. This suggests that some instances of eyelid artefact were incorrectly included and were in fact consecutive saccades. This confirmed that a maximum duration threshold must be applied otherwise the mean durations would never replicate the findings of Tucker and Johns (2005). Therefore, the maximum durations reported for blinks (Table 6.2.4a) was applied as a secondary criterion to the database of subjectively identified eyelid artefact (Table 6.2.4b) to recalculate the descriptive statistics. In addition to these statistics were two additional columns. These columns state the number of subjectively identified eyelid artefacts and number of objectively determined saccades that would be excluded using the low velocity and maximum duration criteria. These thresholds were applied to all 2292 vertical VSST trials.

Table 6.2.4c

Duration of Low Velocity for Deflections Subjectively Considered Eyelid Artefact with additional Duration Criterion

<table>
<thead>
<tr>
<th>Thresholds</th>
<th>Duration (ms) of Low Velocity Period</th>
<th>No. of Eyelid Artefacts Excluded</th>
<th>No. of Saccades Excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°/s velocity and 2.1 ms duration</td>
<td>M 0.8</td>
<td>SD 1.0</td>
<td>Min 0.0</td>
</tr>
<tr>
<td>40°/s velocity and 6.3 ms duration</td>
<td>M 3.2</td>
<td>SD 1.3</td>
<td>Min 0.0</td>
</tr>
<tr>
<td>100°/s velocity and 54.2 ms duration</td>
<td>M 9.0</td>
<td>SD 5.7</td>
<td>Min 4.2</td>
</tr>
</tbody>
</table>
The addition of the maximum duration threshold reduced the mean and standard deviations for the low velocity period using the 10°/s and 40°/s velocity thresholds. The values for the 100°/s velocity threshold were unchanged. Consequently, the means and standard deviations more closely resembled the values of Tucker and Johns (2005). Of the 267 subjectively identified eyelid artefacts, 100% were successfully excluded using the 100°/s velocity and 54.2 ms maximum duration thresholds, which satisfies this sections major aim. However, the trade-off of such high thresholds was the number of saccades inadvertently excluded by the same criteria, which was the concern with using such a high maximum duration threshold. According to Table 6.2.4c, the best threshold to choose was the 40°/s velocity and 6.3 ms maximum duration thresholds because although it only excluded 94% (253/267) of eyelid artefact, it excluded the least number of saccades. If the 10°/s velocity and 2.1 ms maximum duration thresholds were chosen, 99% of eyelid artefact would have been excluded. Although superior to the 40°/s velocity and 6.3 ms maximum duration thresholds, it was very likely oversensitive. The amount of noise within the EOG signal meant it was very difficult to obtain consecutive velocity values below 10°/s because of the sensitivity of the 2-point central differentiation method. Even during long periods of fixation the velocity did not remain steadily below 10°/s for long, which is why twice as many saccades were excluded as compared to the 40°/s threshold.

6.3 Results

6.3.1 Vertical Eye Movement Data

Following adjustment of the calibration equations and successfully eliminating 94% of eyelid artefact from the results, all vertical VSST saccades were plotted to check the Main Sequence relationships. Plotting all 3684 vertical saccades produced a cluttered graph (see Appendix G5) so Saccade Amplitude was grouped into integer values as per the horizontal results in Chapter 5. Peak Saccade Velocity values were plotted against integer values of Saccade Amplitude and shown in Figure 6.3.1a.
The **Main Sequence** was observed for **Peak Saccade Velocity** and integer values of **Saccade Amplitude** for vertical saccades in this study. The relationship proved highly linear up to 20° ($r = 0.9982$, $r^2 = 0.9965$, $p < 0.001$, $n = 15$) and then becomes logarithmic for increasingly larger saccades. The logarithmic relationship was exceptionally high ($r^2 = 0.8841$, $n = 62$), but less than its horizontal counterpart ($r^2 = 0.9347$; see Figure 5.3.1a) probably due to the less accurate calibrations. The logarithmic relationship also reveals an increased variability above 35° which was much earlier than for the horizontal **Main Sequence** in Chapter 5. The saccade detection algorithm proved accurate again with no saccades less than 5° in amplitude included, however much higher **Saccade Amplitudes** were observed beyond the dimensions of the experimental display. The greatest amplitude exceeded the experimental display by 14° (70° **Saccade Amplitude**) and was thought to be far too high for overshoot. The calibration factor for this participant revealed a lower than average coefficient of determination ($r^2 = 0.8985$) and might suggest that the 70° was inaccurate due to the calibration.
Saccade Duration and integer values of Saccade Amplitude were also plotted to check this Main Sequence relationship for vertical saccades. The results can be seen in Figure 6.3.1b.

![Linear Trendline](image)

Figure 6.3.1b: Main Sequence: Saccade duration versus saccade amplitude for all vertical data. A positive linear relationship is shown between saccade duration and saccade amplitude ($r = 0.956, p = 0.000$).

The correlation between Saccade Duration and integer values of Saccade Amplitude is both high and significant ($r = 0.9564, r^2 = 0.9148, p < 0.001, n = 62$). Had the entire vertical saccade database been plotted (see Appendix G6), the correlation is still both high and significant ($r = 0.8222, r^2 = 0.6759, p < 0.001, n = 3684$). Consistent with the horizontal VSST results, there appears to be increased variability in this linear relationship above approximately 40°. The gradient of the trendline was also very close to the normal range of 1.5-3 ms/deg whilst the intercept was within the normal range of 20-30 ms for horizontal saccades (Becker, 1989; Garbutt et al., 2001). In a comparison to one of the few studies which mentioned the vertical linear relationship, our trendline had a smaller gradient (1.45 vs. 3.3) and intercept (26.8 vs. 31) (Collewijn et al., 1988b). It is worth noting that both values mentioned by Collewijn et al., (1988b) are outside those mentioned as the normal horizontal range (Becker, 1989; Garbutt et al., 2001). This is not surprising considering their values are based on only four participants, so although the values above differ to Collewijn et al. (1988b), they are likely to be more accurate.
The frequency distribution of all integer values of vertical Saccade Amplitude was calculated for comparison to the horizontal VSST data and is shown in Figure 6.3.1c.

As opposed to the horizontal results which revealed a peak around 14-15°, the vertical results revealed two peaks; the first at 5° and the second at 15-19°. The same level of accuracy was obviously not observed with participants revealing greater difficulty in generating Saccade Amplitudes subtending the difference between two displays (14°). This could be explained as the second peak may indicate a high amount of overshoot and the first peak may indicate the high number of corrective saccades required in response to the overshoot. Alternatively, the second peak of 15-19° may just indicate the reduced accuracy of the calibrations whilst the peak at 5° may just indicate a greater level of noise that conforms to saccade detection criteria. Vertical Saccade Amplitude was larger on average (M = 18.48°, SD = 9.62°, Range = 5.00° to 70.33°) than horizontal VSST (M = 19.06) as was the 50th percentile (vertical: 17.23° vs. horizontal: 16.21°) but the 85th percentile was smaller (vertical: 26.41° vs. horizontal: 28.58°).

Although horizontal Saccade Rate per trial and Mean Peak Saccade Velocity showed no conclusive evidence that a relationship existed between the two dependent variables, an
exploratory test was conducted on the vertical VSST data. From the 2304 vertical VSST trials, there were 455 trials in which no saccades were detected. The remaining 1849 trials were plotted as the *Mean Peak Saccade Velocity* at each *Saccade Rate per trial*. Figure 6.3.1d displays the relationship.

![Figure 6.3.1d: Mean peak saccade velocity versus saccade rate (per trial) for all vertical data. A negative relationship exists between saccade velocity and rate per trial for vertical data. The linear (r² = 0.9213) and polynomial (r² = 0.9596) trendlines match the data accurately with the polynomial trendline fitting the data better. Standard error bars are displayed for mean peak saccade velocity at each saccade rate per trial.](image)

There is an apparent trend between *Saccade Rate per trial* and *Mean Peak Saccade Velocity* with a 2nd order polynomial trendline fitting the data more accurately (r² = 0.9596, n = 7) than a linear trendline (r² = 0.9213, n = 7). However, if all *Saccade Rate per trial* values are plotted (n = 1849) (see Appendix G7) rather than integer values (n = 7), the relationship is almost non-existent, regardless of the trendline used (linear: r² = 0.0273 or polynomial: r² = 0.0277). One would need to be very careful in assuming there is a relationship based solely on Figure 6.3.1d.

When *Saccade Rate* is standardised per second and plotted against *Mean Peak Saccade Velocity* (see Figure 6.3.1e) the relationship is still negative and reasonably linear.
A negative relationship exists between saccade velocity and rate per second for vertical data. The linear ($r^2 = 0.7901$) and polynomial ($r^2 = 0.8002$) trendlines match the data accurately with the polynomial trendline fitting the data better. Standard error bars are displayed for mean peak saccade velocity at each saccade rate per trial.

The coefficient of determination for either the linear ($r^2 = 0.7901$, $n = 21$) or the polynomial ($r^2 = 0.8002$, $n = 21$) trendline are both lower than when Saccade Rate per trial was plotted (Figure 6.3.1d). The apparent contrast is probably due to the increase in total number of data points. When the Mean Peak Saccade Velocity and Saccade Rate per second are plotted ($n = 1849$) (see Appendix G8) for each trial there is no relationship regardless of the trendline used (linear: $r^2 = 0.0381$ or polynomial: $r^2 = 0.0383$). This leads to the conclusion that no relationship exists between Rate and Mean Peak Velocity in either vertical saccades or horizontal saccades (Chapter 5) supporting the findings of Morgan (1999).

An investigation was also conducted into the frequency distribution of Saccade Latency for all vertical VSSST trials in which at least one saccade was detected. Only the latency of the primary saccade in these trials was plotted ($n = 1849$).
Vertical Saccade Latency appears to be normally distributed with almost 66% of saccades initiated between latencies of 180 and 280 ms which is reasonably consistent with reported values (Wheeless et al., 1967; Becker, 1989; Juttner & Wolf, 1992; Kalesnykas & Hallett, 1994). Furthermore, almost 13% of latencies are faster than 180 ms and another 21% slower than 280 ms which is almost identical to the horizontal VSST results suggesting both Saccade Latency distributions match very closely to earlier research (Kalesnykas & Hallett, 1994). The largest difference between the horizontal and vertical distribution was observed at the 220-239.99 ms period even though this was still the most frequent Saccade Latency for either visual field.

### 6.3.2 Vertical Task Parameters

Response Accuracy was combined for all 32 participants and analysed across all Exposure Times. Response Accuracy was coded as either correct or incorrect and the results are shown and displayed in Figure 6.3.2a. There were 384 trials per exposure time (total = 2304). When the Response Accuracy for each Exposure Time is combined (correct plus incorrect), it equals 100%.
Figure 6.3.2a: Response accuracy for vertical VSST. Response accuracy results in 32 normal participants across the six exposure times (n = 2304). The combination of correct and incorrect percentages total 100% for each exposure time. For longer exposure times, increased accuracy was observed.

Figure 6.3.2a shows the Response Accuracy for the vertical VSST. Visual inspection of the graph shows the lowest Response Accuracy (32.3% correct) was when Exposure Time was shortest. Response Accuracy increased as Exposure Time increased reaching 60.4% at the 1000 ms Exposure Time. A one-way ANOVA was conducted between Response Accuracy and Exposure Time and was found to be significantly different \( F(5, 2298) = 18.417, p < 0.001 \). The same trends were observed in horizontal VSST confirming that the task demand was greater when Exposure Time was shorter as demonstrated by the decreased percentage of correct responses. It was interesting to note that 50% Response Accuracy would have occurred somewhere in-between the 650 and 800 ms Exposure Times.

Response Accuracy was compared across vertical and horizontal VSST trials and found to be significantly different \( F(1, 4668) = 12.819, p < 0.001 \) with more correct responses observed during the horizontal VSST. However, the interaction of Response Accuracy across all Exposure Times and Type of VSST Task (either horizontal or vertical) was not significant \( F(5, 4668) = 0.804, p = 0.546 \) even though Response Accuracy was higher during all horizontal VSST Exposure Times. Only during the 1000 ms Exposure Time did horizontal VSST trials reveal significantly less error than the vertical VSST trials.
[t(778) = 2.884, \( p = 0.004 \)] to the 0.009 significance level. A number of possible conclusions can be made from these results. Firstly, it may suggest that practice effects were negligible otherwise performance on vertical VSST would have been better than on horizontal VSST. Secondly, it may suggest that participants were fatiguing because of the high number of saccades made in such a short time. This must be ruled out because the vertical Main Sequence (Figure 6.3.1a) saturates at higher Peak Saccade Velocities than horizontal Main Sequence does (Figure 5.3.1a). If there were signs of fatigue, vertical Main Sequence would show a trendline saturating at lower Peak Velocities than the horizontal Main Sequence. The third and most likely explanation is that the vertical VSST was more difficult to perform (participants anecdotally confirmed this) but this factor was hidden because practice effects improved vertical VSST performance to near-equivalent accuracy as horizontal VSST trials.

Further examination of Response Accuracy included Number of Target Letters as a function of Exposure Time. The results are plotted in Figure 6.3.2b using Response Error to indicate how often incorrect responses occurred.

![Figure 6.3.2b](image.png)

Figure 6.3.2b: Vertical VSST response error for number of target letters in each exposure time. The percentage for task error is displayed as a function of exposure time and number of target letters (n = 2304).

Figure 6.3.2b shows that correctly responding to 3 target letters was exceedingly difficult, especially at shorter Exposure Times. It was apparent that as the Number of
Target Letters decreased, the number of incorrect responses significantly decreased \[ F(3,2280) = 782.326, p < 0.001 \]. Additionally there was a statistically significant interaction effect \[ F(15,2280) = 11.170, p < 0.001 \] between Exposure Time and Number of Target Letters on Response Error. Although we have just seen in the previous analysis that horizontal and vertical Response Accuracy is statistically significant, vertical Response Error follows almost identical trends to horizontal Response Error (Figure 5.3.2b).

6.3.3 Vertical Saccade Parameters

As with the horizontal saccade parameters analysed in Chapter 5, vertical saccade parameters were determined from the 72 individual trials performed per vertical VSST. Once again, each trial was treated as a separate case. As in Chapter 5, any post-hoc t-tests needed to be significant to the 0.009 level due to the Bonferroni adjustment to account for type 2 errors.

6.3.3i Vertical Mean Saccade Rate

The number of saccades detected per trial was standardised to the number of saccades detected per second to ensure this value could be compared across all exposure times. The results for this are shown in Figure 6.3.3i.

Figure 6.3.3i: Vertical saccade rate per second. Saccade rate was standardised for each exposure time to saccade rate per second and determined for correct and incorrect trials. Standard Error bars are displayed for mean saccade rate.
A two-way between groups ANOVA was conducted to explore the impact of Exposure Time and Response Accuracy on Saccade Rate per second during the vertical VSST. The interaction effect was not significant $[F(5,2292) = 0.551, \ p = 0.738]$ even though the graph depicts correct trials having higher saccade frequencies at all Exposure Times. The main effect of Exposure Time $[F(5,2292) = 280.169, \ p < 0.001]$ and Response Accuracy $[F(1,2292) = 12.555, \ p < 0.001]$ were significant. The trend for Response Accuracy suggested a higher Saccade Rate was responsible for correct trials and the trend for Exposure Time indicated saccade frequency increased as stimulus exposure increased. Post hoc t-tests were still conducted to see if there were similar trends to horizontal Saccade Rate at some Exposure Times. Chapter 5 revealed that there were significantly higher saccade frequencies for correct trials at 650, 800 and 1000 ms exposure times. Table 6.3.3i shows that vertical saccade frequencies were not similar to horizontal saccade frequencies at the 0.009 level. Only the 350 and 800 ms exposure times approached this level of significance.

Table 6.3.3i
Post-hoc t-test scores for Vertical Saccade Rate per second by Exposure Time and Response Accuracy

<table>
<thead>
<tr>
<th>Exposure Times (ms)</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>382</td>
<td>382</td>
<td>382</td>
<td>382</td>
<td>382</td>
<td>382</td>
</tr>
<tr>
<td>t-value</td>
<td>0.970</td>
<td>2.126</td>
<td>0.708</td>
<td>1.136</td>
<td>2.492</td>
<td>1.406</td>
</tr>
<tr>
<td>significance</td>
<td>0.333</td>
<td>0.034</td>
<td>0.479</td>
<td>0.257</td>
<td>0.013</td>
<td>0.161</td>
</tr>
</tbody>
</table>

6.3.3ii Vertical Saccade Amplitude

Saccade Amplitude was combined for all saccades within a trial to calculate the Cumulative Saccade Amplitude of a trial. The Mean Saccade Amplitude was also calculated from the average amplitude of all saccades within a trial. Both variables were split by Response Accuracy (correct or incorrect) and by Exposure Time and displayed in Figure 6.3.3ii.
Both graphs in Figure 6.3.3ii do not readily identify any visible trends. A two-way between groups ANOVA was conducted to explore the impact of Exposure Time and Response Accuracy on Cumulative Saccade Amplitude and Mean Saccade Amplitude during the vertical VSST. The interaction effect was not significant for Cumulative Saccade Amplitude \( F(5,1837) = 0.380, p = 0.863 \) or Mean Saccade Amplitude \( F(5,1837) = 0.436, p = 0.823 \). There was a significant main effect for Exposure Time \( F(5,1837) = 292.431, p < 0.001 \) but not Response Accuracy \( F(1,1837) = 0.325, p = \)
0.569] for Cumulative Saccade Amplitude. Similar main effect results were observed for Mean Saccade Amplitude with a significant main effect for Exposure Time \([F(5,1837) = 5.875, p < 0.001]\) but not Response Accuracy \([F(1,1837) = 0.108, p = 0.743]\).

Although there was no significant interaction effect, post-hoc t-tests were conducted to ensure that differences that were present in the horizontal VSST, were not hidden because of the other factors such as several values being equal across multiple Exposure Times. Horizontal VSST results revealed significant differences for Cumulative Saccade Amplitude at the 650 and 1000 ms Exposure Times. Post-hoc t-test analysis did not identify any significant differences between successful and unsuccessful trials at all Exposure Times for either Cumulative Saccade Amplitude or Mean Saccade Amplitude (see Table 6.3.3ii).

Table 6.3.3ii
Post-hoc t-test scores for Vertical Saccade Amplitude by Exposure Time and Response Accuracy

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>17</td>
<td>315</td>
<td>371</td>
<td>378</td>
<td>378</td>
<td>378</td>
</tr>
<tr>
<td>Cumulative Saccade Amplitude</td>
<td>t = -0.861</td>
<td>p = 0.401</td>
<td>t = -0.385</td>
<td>p = 0.701</td>
<td>t = 1.139</td>
<td>p = 0.255</td>
</tr>
<tr>
<td>Mean Saccade Amplitude</td>
<td>t = -0.335</td>
<td>p = 0.742</td>
<td>t = 0.662</td>
<td>p = 0.509</td>
<td>t = -0.411</td>
<td>p = 0.681</td>
</tr>
</tbody>
</table>

6.3.3iii Vertical Peak Saccade Velocity

Peak Saccade Velocity was combined for all saccades executed in each vertical trial. A cumulative count and mean calculation were performed on Peak Saccade Velocity and grouped by Response Accuracy and Exposure Time. The results are shown in Figure 6.3.3iii.
The Cumulative Peak Saccade Velocity graph shows an apparent trend towards longer Exposure Times indicating larger velocities result in more correct responses. This same trend proved significant in the horizontal VSST results at Exposure Times of 650 ms and above (see Figure 5.3.3iii). A two-way between groups ANOVA was conducted to investigate the trend and was unable to detect a significant interaction effect [$F(5,1837) = 1.003, p = 0.414$] or main effect for Response Accuracy [$F(1,1837) = 0.496, p =$...
Therefore, there was no significant difference between correct and incorrect trials overall, as well across all Exposure Times. There was a significant main effect for Exposure Time \( F(5,1837) = 284.453, p < 0.001 \) suggesting Cumulative Peak Velocities increased as Exposure Time increased. Individual post-hoc t-tests were conducted to check whether there were differences in Response Accuracy at longer Exposure Times (see Table 6.3.3iii) but these proved non-significant at the 0.009 level.

Contrary to the cumulative characteristics of Peak Saccade Velocity, the Mean Peak Saccade Velocity showed no distinct trends in the data. This was supported by the results of a two-way ANOVA which showed non-significant interaction effect \( F(5,1837) = 1.205, p = 0.304 \) as well as non-significant main effect for Response Accuracy \( F(1,1837) = 0.300, p = 0.584 \). Once again, the main effect for Exposure Time was significant \( F(5,1837) = 6.865, p < 0.001 \). All post-hoc t-tests (Table 6.3.3iii) for Mean Peak Saccade Velocity were non-significant also.

Table 6.3.3iii
Post-hoc t-test scores for Vertical Peak Saccade Velocity by Exposure Time and Response Accuracy

<table>
<thead>
<tr>
<th>df</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative Peak Saccade Velocity</td>
<td>-1.021</td>
<td>1.668</td>
<td>-0.634</td>
<td>1.911</td>
<td>0.780</td>
<td>1.701</td>
</tr>
<tr>
<td>Mean Peak Saccade Velocity</td>
<td>-0.344</td>
<td>-0.222</td>
<td>-1.149</td>
<td>1.953</td>
<td>-1.122</td>
<td>-0.092</td>
</tr>
</tbody>
</table>

6.3.3iv Vertical Saccade Latency

Saccade Latency was calculated then grouped by Exposure Time and Response Accuracy and plotted in Figure 6.3.3iv. Trials without saccades as well as anticipation saccades were excluded. Therefore, 1849 trials remained out of a total 2304 trials.
Figure 6.3.3iv: Vertical saccade latency. The time taken to initiate the first saccade was measured in each individual trial (trials without a saccade were excluded). The graph shows the mean latency for correct and incorrect trials across all exposure times. Standard Error bars are displayed.

At all Exposure Times, correct trials had shorter latencies than incorrect trials which was surprisingly not significant \( F(5,1837) = 0.305, p = 0.910 \). Also unexpected was the fact that all correct trials were not significantly less than all the incorrect trials \( F(1,1837) = 0.904, p = 0.342 \). The main effect for Exposure Time was significant \( F(5,1837) = 22.967, p < 0.001 \) which is not readily noticed when looking at Figure 6.3.3d. Post-hoc t-test analysis did not identify any significant differences at the 0.009 level between correct and incorrect vertical trials at all Exposure Times.

Table 6.3.3iv
Post-hoc t-test scores for Vertical Saccade Latency by Exposure Time and Response Accuracy

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
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</thead>
<tbody>
<tr>
<td>df</td>
<td>17</td>
<td>315</td>
<td>371</td>
<td>378</td>
<td>378</td>
<td>378</td>
</tr>
<tr>
<td>t-value</td>
<td>-0.147</td>
<td>-1.385</td>
<td>-0.249</td>
<td>-0.424</td>
<td>-0.632</td>
<td>-1.462</td>
</tr>
<tr>
<td>significance</td>
<td>0.885</td>
<td>0.167</td>
<td>0.803</td>
<td>0.671</td>
<td>0.527</td>
<td>0.145</td>
</tr>
</tbody>
</table>
6.4 Discussion

This experiment was an exploration into vertical visual search strategies performed by 32 participants of the normal population. As with the horizontal VSST task, a number of key findings were observed. Firstly, the saccade detection algorithm again proved to accurately include saccades that were only of predetermined amplitude (Figure 6.3.1a), velocity and duration (Figure 6.3.1b). Secondly, the Main Sequence relationships were demonstrated with vertical Saccade Duration and velocity increasing as a function of amplitude. Comparisons between the vertical Main Sequence and horizontal Main Sequence showed that vertical saccades as great as 70° approach saturation at almost 1000°/s (Figure 6.3.1a) whilst saturation is more pronounced for horizontal saccades near 800°/s (Figure 5.3.1a). The ability to produce such a consistent relationship from the data showed that the equipment (Chapter 2), saccade detection algorithm (Chapter 3), illuminance level (Chapter 4) and saccade calibration and eyelid artefact removal algorithm (Chapter 6) were all effective. However, the fact that the vertical Main Sequence relationship was higher than the horizontal relationship may suggest that some inaccuracies may still be present.

The frequency distribution for vertical Saccade Amplitude revealed dual peaks, the first around 5° and the second at 15-19° which was just a little higher than the inter-target step size of 14°. Once again, there were no peaks for larger step sizes of 28°, 42° and 56°. The reason for two peaks was not directly evident although one theory may suggest that the two peaks were a combination of overshoot of the target followed by corrective saccades. The second theory was that the reduced accuracy of the calibration may have caused some inaccuracies in the Saccade Amplitude and the amplitude should be centred around 14°. However, this was less likely because even though the coefficient of determination for the calibration was lower than the horizontal recordings (Mean $r^2 = 0.922$ vs $r^2 = 0.975$), there was still very little variance around the trendline.

Plots of Mean Peak Velocity and Saccade Rate showed very similar trendlines to those calculated for the horizontal VSST results. When the entire saccade pool was plotted (see Appendix G7 and G8), the results did not yield any visible trends. This leads to the conclusion that no relationship exists between Rate and Mean Peak Velocity in either horizontal or vertical saccades refuting the findings of Lueck et al., (1991).
Response Accuracy was analysed as a function of task parameters and compared against the horizontal VSST. Very similar results were obtained to the horizontal VSST with target numbers and Exposure Time significantly changing the difficulty of the task. As Exposure Time decreased, and Number of Target Letters increased, Response Accuracy reduced which was an identical finding to the horizontal VSST. The vertical VSST proved even more difficult than the horizontal VSST because percentage of correct responses was lower at all Exposure Times. The longest Exposure Time demonstrated the greatest success (60.4% correct) although this deteriorated as the Exposure Times shortened almost reducing to chance (32.3% correct) at the 200 ms Exposure Time. Chance in these tasks was 25% (one response out of four possibilities) Attempts to explain differences in Response Accuracy between horizontal and vertical visual search strategies stem from our exposure to real world situations. Collewijn and Tamminga (1984) postulated that we track better with horizontal smooth pursuit than vertical smooth pursuit because we are exposed to this more in everyday life citing examples such as watching the predominant direction of a train or vehicular traffic. Although this was smooth pursuit tracking, the theory can be extended into saccadic visual search. For example, western society teaches children to read left to right at a young age so it is speculated that this learned and trained ability allows us to scan more accurately horizontally than we do vertically. Collewijn et al. (1988b) believe most oculomotor parameters respond adaptively to the particular behavioural requirements to which a participant is exposed.

When Response Accuracy was further analysed as a function of saccadic behaviour for vertical VSST, no saccade parameters proved significant. Although the vertical saccade results were normal as determined by the Main Sequence, it was bizarre that no vertical saccade parameters were significant. Saccade Rate per second was higher for correct than incorrect trials at all Exposure Times but the data was not significant to the 0.009 level. Cumulative Saccade Amplitude and Cumulative Peak Saccade Velocity both showed that Exposure Times above 650 ms that correct trials had marginally higher values than incorrect trials, although none were significant. No trends were identified for Mean Saccade Amplitude and Mean Peak Saccade Velocity. Saccade Latency was also not significant although correct trials had slightly faster Saccade Latencies than incorrect trials in every Exposure Time.
It was difficult to fathom why the saccade parameters for correct and incorrect trials were not significantly different given that they were different for horizontal VSST. As was the explanation for reduced Response Accuracy, perhaps there is no trained behaviour associated with vertical saccades even when differentiating correct and incorrect strategies. In terms of speed and accuracy trade-off, it is more confusing because even at larger Exposure Times when participants had enough time to be accurate, no optimal strategy was observed. Therefore, participants in the study scanned the display in exactly the same way and this almost randomly produced correct and incorrect responses. At no point during the vertical VSST was there evidence to suggest that making more frequent saccades caused a perceptual disadvantage.
Chapter 7  Search Strategies in Elite and Non-Elite Footballers

7.1  Introduction

The ability to quickly and accurately perceive stimuli in a complex sports environment is an essential requirement of skilled performance (Williams et al., 1993a). The universal approach to studying skilled performance in athletes was to compare behaviour between elite and non-elite athletes of the same sport. In this chapter, Australian Rules football players were chosen because of the sports visually demanding nature including the high-speed ball movement and the complexity of their environment during game situations. It was expected that elite footballers would demonstrate the same findings as those originally determined by Morgan (1999) using the non-sports specific task used in Chapters 2-6. Those findings established that faster and larger saccades and to a limited extent more frequent saccades were demonstrated by the elite footballers compared to their non-elite counterparts. Significant differences were observed in Saccade Amplitude and Mean Peak Saccade Velocities between elite and non-elite footballers at all Exposure Times greater than 350 ms. The tendency for elite footballers to make larger saccades during visual search was evident from the Saccade Amplitude frequency distribution revealing non-elite footballers had a peak frequency component around 8° whilst elite footballers had a very even spread between 10 and 15°.

Another study performed by Morgan (1999) found elite netballers demonstrated faster, larger and more frequent saccades during generalised search behaviour than elite swimmers and cyclists. With the addition of the elite soccer and football players data, three elite groups who participate in a visually demanding sport exhibited different visual search behaviour to athletes from non-visually demanding sports. Morgan (1999) concluded that it was extremely unlikely that three groups of elite sportspeople who participate in visually demanding sports would make perceptually counter-productive eye movements. Therefore, it was hypothesised that elite footballers would exhibit saccadic eye movement behaviour that would be best suited to the rapid detection of visual stimuli and that this behaviour would differ to non-elite footballers as previously observed.
7.2 Method

7.2.1 Participants

Eighteen male Australian Rules Football players were recruited for this experiment with seven (Age: \( M = 20.4 \) years, \( SD = 2.2 \) years) classified as elite based on their current participation in the Australian Football League (AFL), whilst another eleven (Age: \( M = 25.1 \) years, \( SD = 2.3 \) years) were classified as non-elite based on their participation in local club-level or amateur competitions. Six of the seven elite AFL footballers reported 10+ years of experience playing football whilst the seventh had between 4-6 years experience. Four of the eleven non-elite footballers reported having 10+ years of experience playing football, two had 7-9 years experience, one had 4-6 years experience and the remaining four had only 1-year experience. All non-elite footballers were friends of the researcher or University students whom volunteered. The elite players were recruited from the Hawthorn Football Club but were not volunteers. One elite AFL player exhibited a red-green colour deficiency but all other participants did not exhibit any indication of colour blindness. Two non-elite footballers had suffered a partially detached retina, although both suggested they were now recovered from this injury. Those participants that wore corrective lenses (prescription glasses or contact lenses) were asked to do so during this task. The elite footballers static visual acuity was better (Left: \( M = -0.04, SD = 0.09 \); Right: \( M = 0.02. SD = 0.07 \)) than the non-elite footballers (Left: \( M = 0.00, SD = 0.12 \); Right: \( M = 0.11. SD = 0.30 \)) with correction.

7.2.2 Procedure

The protocol and equipment outlined in Chapter 2 were used in this study. Participants provided informed consent (see Appendix D), performed the pre-test battery, then completed the horizontal EOG Amplitude Calibration Routine, horizontal VSST, and then repeated the horizontal calibration routine again. The vertical EOG Amplitude Calibration Routine was then conducted, followed by the vertical VSST and then the vertical calibration routine for a second time. The duration of the horizontal and vertical recordings was approximately 10 minutes. The tests were conducted during daylight hours and participants had not consumed caffeine, alcohol or nicotine within 2 hours of
participating in the study. Once again, as per the experimental results in Chapter 4, the lights were dimmed to 25 Lux.

The EOG amplitude calibration routine was used in the same way as Chapter 5 and 6 to calibrate raw serial values into degrees of visual angle. The $r^2$ values determined for each participant following completion of the horizontal EOG amplitude calibration routine were averaged for both Skill Levels and found to be similar (Elite: $M = 0.963$, $SD = 0.032$, $n = 7$; Non-elite: $M = 0.964$, $SD = 0.022$, $n = 11$). The $r^2$ values for the vertical EOG amplitude calibration routine were smaller (Elite: $M = 0.887$, $SD = 0.045$, $n = 7$; Non-elite: $M = 0.910$, $SD = 0.042$, $n = 11$) but not dissimilar between Skill Level even after non-linear trendlines were applied and the same technique to exclude eyelid artefact was used.

7.3 Results

7.3.1 Horizontal Eye Movement Data

The raw data for elite and non-elite footballers were processed using the saccade detection and evaluation software described in Chapter 3. A total of 945 saccades were detected in the 504 horizontal VSST trials performed by seven elite footballers. In contrast, eleven non-elite footballers executed 1507 saccades from the 792 horizontal VSST trials. Main Sequence relationships were calculated for both groups to ascertain whether the data was within the normal range. Peak Saccade Velocity and integer values of Saccade Amplitude were plotted for all horizontal VSST saccades across Skill Level. The results of this plot are shown in Figure 7.3.1a.
CHAPTER 7 SEARCH STRATEGIES IN ELITE AND NON-ELITE FOOTBALLERS

Figure 7.3.1a: Horizontal Main Sequence: Saccade amplitude versus peak saccade velocity for elite and non-elite footballers. Peak saccade velocity is shown on the y-axis and saccade amplitude on the x-axis. The data-points for non-elite footballers are displayed in blue (n = 1507) and elite footballers are displayed in red (n = 945). The logarithmic trendlines for both groups virtually overlap. Standard error bars are displayed for peak velocities at integer values of saccade amplitude.

The Main Sequence logarithmic relationship between velocity and amplitude exist for both groups of footballers. The trendlines overlap to the point that there is almost no difference between them. Variation around the trendline was quite minor for both groups as evidenced by the coefficient of determination values (Elite: $r^2 = 0.9385$, n = 55; Non-elite: $r^2 = 0.8987$, n = 54). When the entire number of saccades is plotted (see Appendix G9) the trendline for elite footballers dips slightly below that of their non-elite counterparts. The increased variation within each sample is due to the increased number of data points included in the regression.

Integer values of Saccade Amplitude were plotted against Saccade Duration for all horizontal VSST trials across Skill Level. This can be viewed in Figure 7.3.1b. The observed trendlines are almost identical and contain a great deal of overlap. The $r^2$ values are very high for both trendlines as well (Elite: $r^2 = 0.9614$, p < 0.001, n = 55; Non-elite: $r^2 = 0.9739$, p < 0.001, n = 54). When all saccades are plotted (see Appendix G10), the variations are increased but are still very high and significant (Elite: $r^2 = 0.871$, p < 0.001, n = 945; Non-elite: $r^2 = 0.7904$, p < 0.001, n = 1507).
Non-elite Footballers
\[ y = 1.5594x + 24.089 \]
\[ R^2 = 0.9739 \]
\( n = 54 \)

Elite Footballers
\[ y = 1.519x + 26.526 \]
\[ R^2 = 0.9614 \]
\( n = 55 \)

Figure 7.3.1b: Horizontal Main Sequence: Saccade amplitude versus saccade duration for elite and non-elite footballers. Saccade duration is shown on the y-axis and saccade amplitude on the x-axis. The data-points for non-elite footballers are displayed in blue (n=1507) and elite footballers are displayed in red (n=945).

Again the trendlines in Figure 7.3.1b almost overlap identically although previous literature suggested that non-elite footballers and soccer players would have much steeper gradient with similar intercepts (Morgan, 1999). All values are within the normal ranges (Becker, 1989; Garbutt et al., 2001).

The frequency distribution was plotted for integer values of Saccade Amplitude and shown in Figure 7.3.1c for both elite and non-elite footballers. Both plots were skewed to the left with the frequency peak for elite footballers between 14° and 17° (\( M = 19.85°, \text{SD} = 11.44°, \text{Range} = 5.11° \) to 59.57°) whilst it was more precisely on 14° for non-elite footballers (\( M = 18.65°, \text{SD} = 9.10°, \text{Range} = 5.03° \) to 65.61°). Surprisingly the 50th percentiles (Elite: 16.43° vs. Non-elite: 16.74°) were similar although the graph depicts the elite group as having a narrower high-frequency band. The 85th percentile was much higher for the elite group (Elite: 30.13° vs. Non-elite: 26.28°) because a greater number of saccades were made at the larger end of the distribution. The narrower high-frequency band for elite footballers around the inter-target step-sizes of 14° probably suggest their saccades were generally more accurate than the broader range exhibited by non-elite footballers although no statistic was calculated to confirm this.
7.3.2 Horizontal Task Parameters

*Response Accuracy* was calculated for both *Skill Levels* at each *Exposure Time* and displayed in Figure 7.3.2a as the percentage of correct trials.

*Figure 7.3.2a: Response accuracy for horizontal VSST for elite and non-elite footballers.* Percentage of correct responses is plotted as the mean total for seven elite and eleven non-elite footballers as a function of exposure time.
A two-way between groups analysis of variance was conducted to explore the impact of Skill Level and Exposure Time on Response Accuracy. The interaction effect between these two variables on Response Accuracy was not significant \([F(5,1284) = 0.916, p = 0.470]\) as was the main effect for Skill Level \([F(1,1284) = 0.945, p = 0.331]\). The main effect for Exposure Time was significant \([F(5,1284) = 30.449, p < 0.001]\) suggesting the task becomes more difficult as Exposure Time decreases regardless of Skill Level. The results of these two groups were reasonably close to the normal population sample observed in Chapter 5 (Figure 5.3.2a). The lowest percentage correct for both groups was observed at the 200 ms Exposure Time (Elite = 33.33; Non-elite = 30.30) and the highest percentage correct was observed at the 1000 ms Exposure Time (Elite = 82.14; Non-elite = 78.79). Only at the longest Exposure Times (800 and 1000 ms) were values observed that were substantially higher than those observed for the normal population, however they were not significantly different between Skill Level \((p > 0.3)\).

### 7.3.3 Horizontal Saccade Parameters

The approach to the analysis in Chapter 5 and 6 was also adopted here. Saccade parameters were determined from the 72 individual trials performed per horizontal VSST. Each trial was treated as a separate case. As with Chapter 5 and 6, any post-hoc t-tests needed to be significant to the 0.009 level due to the Bonferroni adjustment to account for type 2 errors.

#### 7.3.3i Horizontal Mean Saccade Rate

Mean Saccade Rate per second was calculated for each Exposure Time across Skill Level (this replaced Response Accuracy from Chapter 5 and 6). The horizontal VSST results are plotted in Figure 7.3.3i for elite and non-elite footballers.
Figure 7.3.3i: Horizontal saccade rate per second for elite and non-elite footballers. Saccade rate was standardised for each exposure time to saccade rate per second and determined for correct and incorrect trials. Standard Error bars are displayed.

A two-way between groups ANOVA was conducted to explore the impact of Skill Level and Exposure Time on Saccade Rate per second. The main effect for Skill Level was not significant \(F(1,1284) = 2.253, p = 0.134\), although the main effect for Exposure Time was \(F(5,1284) = 267.626, p < 0.001\). The interaction between these two variables approached significance \(F(5,1284) = 2.194, p = 0.053\) although it is unclear as to why considering there is no visible trend and there are a number of inconsistencies present. For this reason, post-hoc t-tests were conducted which were of exploratory nature. However, only at the 650 ms Exposure Time was a significant difference observed, and this difference was unexpected given that non-elite footballers generated more frequent saccades at this Exposure Time.

Table 7.3.3i
Post-hoc t-test scores for Horizontal Saccade Rate per second by Exposure Time and Skill Level

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>df</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>214</td>
<td>214</td>
<td>214</td>
<td>214</td>
<td>214</td>
<td>214</td>
<td>214</td>
</tr>
<tr>
<td>t-value</td>
<td>-1.352</td>
<td>-0.177</td>
<td>-0.912</td>
<td>-2.936</td>
<td>1.764</td>
<td>0.525</td>
<td></td>
</tr>
<tr>
<td>significance</td>
<td>0.178</td>
<td>0.860</td>
<td>0.363</td>
<td><strong>0.004</strong></td>
<td>0.079</td>
<td>0.600</td>
<td></td>
</tr>
</tbody>
</table>

Green = Significant to 0.009
7.3.3ii Horizontal Saccade Amplitude

Cumulative Saccade Amplitude and Mean Saccade Amplitude were calculated per trial across both Skill Levels for each Exposure Time. The results are shown in Figure 7.3.3ii.

![Horizontal saccade amplitude for elite and non-elite footballers.](image)

A two-way between groups ANOVA was conducted to explore the impact of Skill Level and Exposure Time on Cumulative Saccade Amplitude. The main effect for Skill Level was not significant [$F(1, 1055) = 0.516$, $p = 0.473$], although the main effect for
Exposure Time was \[ F(5,1055) = 402.541, p < 0.001 \]. The graph clearly shows that as Exposure Time reduces, so too does the entire visual angle scanned. The interaction between these two variables was significant \[ F(5,1055) = 6.378, p < 0.001 \]. It is unclear as to why this was significant because there is no consistent trend displayed in the graph. In fact only during the two longest Exposure Times is there a considerable difference between elite and non-elite footballers with the elite group scanning more of the display. Post-hoc t-tests (see Table 7.3.3ii) revealed that this was only significant to the 0.009 level for the 800 ms Exposure Time.

Another two-way between groups ANOVA was conducted to investigate how Mean Saccade Amplitude changed as a function of Skill Level and Exposure Time. The main effect for Skill Level was not significant \[ F(1,1055) = 0.122, p = 0.726 \], although the main effect for Exposure Time was \[ F(5,1055) = 9.536, p < 0.001 \]. The interaction between these two variables was not significant \[ F(5,1055) = 1.297, p = 0.263 \]. Although non-significant, Morgan (1999) found some very large differences existed between skilled groups on this particular variable at the 500 to 1000 ms Exposure Times. Post-hoc t-tests were conducted to determine if any comparable trends were present. Table 7.3.3ii shows the t-tests for Saccade Amplitude and reveals that only at the 800 ms Exposure Time was a significant result obtained.

Table 7.3.3ii

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>Cumulative Saccade Amplitude</th>
<th>Mean Saccade Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>t = -0.899, p = 0.383</td>
<td>t = -0.899, p = 0.383</td>
</tr>
<tr>
<td>350</td>
<td>t = -0.489, p = 0.626</td>
<td>t = -0.087, p = 0.930</td>
</tr>
<tr>
<td>500</td>
<td>t = -0.930, p = 0.354</td>
<td>t = 0.311, p = 0.756</td>
</tr>
<tr>
<td>650</td>
<td>t = -1.658, p = 0.099</td>
<td>t = 1.321, p = 0.188</td>
</tr>
<tr>
<td>800</td>
<td>t = 4.309, p &lt; 0.001</td>
<td>t = 3.230, p = 0.001</td>
</tr>
<tr>
<td>1000</td>
<td>t = 2.374, p = 0.126</td>
<td>t = 1.535, p = 0.126</td>
</tr>
</tbody>
</table>

Red = Significant to less than 0.001, Green = Significant to 0.009
7.3.3iii Horizontal Peak Saccade Velocity

Cumulative Peak Saccade Velocity and Mean Peak Saccade Velocity were plotted against Skill Level for each Exposure Time. The results are shown in Figure 7.3.3iii.

Figure 7.3.3iii: Horizontal peak saccade velocity for elite and non-elite footballers. The peak velocity for all saccades per trial was combined (top) to demonstrate total peak velocity exhibited per trial. The peak saccade velocity (bottom) for all saccades per trial was averaged to account for saccade rate. Both graphs show correct and incorrect trials across all exposure times. Standard Error bars are displayed.

Visual inspection of the Cumulative Peak Saccade Velocity graph showed a rise in velocity from smaller Exposure Times to larger Exposure Times which was significantly different \[ F(5,1055) = 467.675, \ p < 0.001 \]. A two-way between groups ANOVA found
the main effect for *Skill Level* was not significant \[F(1,1055) = 1.495, p = 0.222\], but surprisingly the interaction between these two variables was significant \[F(5,1055) = 4.165, p < 0.001\]. *Post-hoc* t-tests (see Table 7.3.3iii) were conducted and revealed that the only significant difference was at the 650 ms *Exposure Time* where non-elite footballers unexpectedly had higher *Cumulative Peak Velocity*.

A two-way between groups ANOVA was conducted to explore the impact of *Skill Level* and *Exposure Time* on *Mean Peak Saccade Velocity*. The main effect for *Skill Level* was significant \[F(1,1055) = 4.430, p = 0.036\] showing that generally non-elite players made faster saccades than elite players. This was intriguing because it was hypothesised that elite players would have faster peak velocities based on the findings of Morgan (1999). The main effect for *Exposure Time* was significant \[F(5,1055) = 4.491, p < 0.001\] although the interaction between these two variables was not significant \[F(5,1055) = 0.564, p = 0.728\]. On the basis that there was an expectation to see elite footballers execute faster saccades, *post-hoc* t-tests were conducted and are displayed in Table 7.3.3iii although no significant results were obtained.

**Table 7.3.3iii**

Post-hoc t-test scores for Horizontal Peak Saccade Velocity by Exposure Time and Skill Level

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
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<tbody>
<tr>
<td>df</td>
<td>15</td>
<td>187</td>
<td>213</td>
<td>214</td>
<td>212</td>
<td>214</td>
</tr>
<tr>
<td>Cumulative Peak Saccade Velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>-1.047</td>
<td>-1.689</td>
<td>-1.665</td>
<td>-3.901</td>
<td>1.768</td>
<td>0.266</td>
</tr>
<tr>
<td>p</td>
<td>0.312</td>
<td>0.093</td>
<td>0.097</td>
<td>&lt; 0.001</td>
<td>0.079</td>
<td>0.791</td>
</tr>
<tr>
<td>Mean Peak Saccade Velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>-1.047</td>
<td>-1.205</td>
<td>-1.518</td>
<td>-1.909</td>
<td>-0.034</td>
<td>-0.841</td>
</tr>
<tr>
<td>p</td>
<td>0.312</td>
<td>0.230</td>
<td>0.131</td>
<td>0.058</td>
<td>0.973</td>
<td>0.402</td>
</tr>
</tbody>
</table>

*Red* = Significant to less than 0.001
7.3.3iv  **Horizontal Saccade Latency**

*Saccade Latency* was calculated for 1067 trials out of a total 1296 trials that had at least one saccade detected. *Saccade Latency* was then plotted for each *Skill Level* across all *Exposure Times*. The results are shown in Figure 7.3.3iv. The figure shows that *Saccade Latency* generally decreases as *Exposure Time* decreases, but this was more readily observed by the non-elite group.

![Figure 7.3.3iv: Horizontal saccade latency for elite and non-elite footballers.](image)

A two-way between groups ANOVA was conducted to explore the impact of *Skill Level* and *Exposure Time* on *Saccade Latency*. The main effect for *Skill Level* was not significant \[F(1,1055) = 0.002, \ p = 0.966\], although the main effect for *Exposure Time* was \[F(5,1055) = 16.396, \ p < 0.001\]. The interaction between these two variables was significant \[F(5,1055) = 2.991, \ p = 0.011\] but again it is unclear why as there does not appear to be a consistent trend. *Post-hoc* t-tests revealed elite footballers reacted significantly slower than non-elite footballers at the 500 ms *Exposure Time* (see Table 7.3.3iv) which was unexpected as there is no perceptual benefit to be gained by reacting slower to the task.
Table 7.3.3iv
Post-hoc t-test scores for Horizontal Saccade Latency by Exposure Time and Skill Level

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>df</th>
<th>t-value</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>15</td>
<td>-1.265</td>
<td>0.225</td>
</tr>
<tr>
<td>350</td>
<td>187</td>
<td>1.802</td>
<td>0.073</td>
</tr>
<tr>
<td>500</td>
<td>213</td>
<td>2.945</td>
<td>0.004</td>
</tr>
<tr>
<td>650</td>
<td>214</td>
<td>2.132</td>
<td>0.034</td>
</tr>
<tr>
<td>800</td>
<td>212</td>
<td>-1.066</td>
<td>0.287</td>
</tr>
<tr>
<td>1000</td>
<td>214</td>
<td>-0.596</td>
<td>0.552</td>
</tr>
</tbody>
</table>

Green = Significant to 0.009

There were no consistent trends through the entire horizontal VSST trials for Saccade Rate, Amplitude, Velocity and Latency, which challenged the findings of Morgan (1999). However, the Main Sequence trendlines for both elite and non-elite footballers were overlapping confirming that the values fell within the range observed from the normal population.

### 7.3.4 Vertical Eye Movement Data

The Main Sequence relationships were calculated and displayed in Figure 7.3.4a for Peak Velocity and integer values of Saccade Amplitude.
The vertical *Main Sequence* for footballers revealed a logarithmic relationship for both *Skill Levels*. The coefficient of determination was considerably lower than the same relationship from the normal population for horizontal and vertical saccades (see Figure 5.3.1a & 6.3.1a) as well as horizontal saccades in the same sample (see Figure 7.3.1a). The relationship between *Peak Saccade Velocity* and *Saccade Amplitude* was still reasonably high for both footballer groups (Elite: $r^2 = 0.8562$, $n = 54$; Non-elite: $r^2 = 0.8928$, $n = 56$) and was higher than when all vertical saccades were plotted (see Appendix G11). Visual inspection of Figure 7.3.4a clearly shows greater variance at earlier than usual amplitudes in the graph at around $27^\circ$ for elite footballers and around $31^\circ$ for non-elite footballers as demonstrated by the larger standard error bars. It was also quite noticeable that the trendline for non-elite footballers was higher than that of the elite footballers implying elite footballers moved their eyes more slowly for amplitudes of the same size. A comparison to normal vertical saccade data (Figure 6.3.1a) shows that the elite footballer’s trendline saturates at very similar velocities to the normal population and that the non-elite footballers were abnormally faster.

*Main Sequence* plot of *Saccade Duration* and integer values of *Saccade Amplitude* is displayed in Figure 7.3.4b.

![Figure 7.3.4b: Vertical Main Sequence: Saccade amplitude versus saccade duration for elite and non-elite footballers. The data-points for non-elite footballers are displayed in blue ($n=1302$) and elite footballers are displayed in red ($n=851$). Standard error bars are displayed for saccade duration.](image-url)

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As the amplitude-velocity-duration relationship of saccades are inter-related according to the Main Sequence (Bahill et al., 1975a), there was no surprise that non-elite footballers showed durations shorter than those of the elite group. In fact, when compared to other normal data within these VSST experiments it is evident that the non-elite group has abnormally short durations. The slope of the equations for both non-elite (1.2984) and elite (1.4478) footballers are lower than reported normal levels of 1.5-3 ms/deg (Becker, 1989; Garbutt et al., 2001) although the intercepts for both equations are between the accepted range of 20-30. The relationship is both high and significant for both Skill Levels and integer values of Saccade Amplitude (Elite: $r^2 = 0.8203$, $p < 0.001$, $n = 54$; Non-elite: $r^2 = 0.8972$, $p < 0.001$, $n = 56$) (see Appendix G12 for all values) and again an increase in the variance is evident for elite footballers at $27^\circ$ and around $31^\circ$ for non-elite footballers.

The frequency distribution for vertical saccades was very similar for both elite and non-elite footballers and was illustrated in Figure 7.3.4c. As with the frequency distribution of vertical Saccade Amplitudes from the normal population (see Figure 6.3.1c), a dual peak existed for both Skill Levels at amplitudes of approximately $5^\circ$ and between 15-18$^\circ$.

![Figure 7.3.4c: Vertical saccade amplitude frequency distribution for elite and non-elite footballers.](image)
The data-points for non-elite footballers are displayed in blue ($n=1507$) and elite footballers are displayed in red ($n=945$).
Once again, both plots were skewed to the left with the mean amplitude lower for elite footballers \( (M = 17.63°, \text{SD} = 10.26°, \text{Range} = 5.00° \text{ to } 73.79°) \) than non-elite footballers \( (M = 19.57°, \text{SD} = 10.36°, \text{Range} = 5.00° \text{ to } 70.33°) \). Elite footballers also had consistently lower Saccade Amplitudes for the 50th percentile (Elite: 15.70° vs. Non-elite: 18.33°) and 85th percentile (Elite: 25.60° vs. Non-elite: 29.38°). The distribution for elite footballers showed a very narrow band of highly frequent Saccade Amplitudes which non-elite footballers did not replicate. As with the other horizontal and vertical VSST results, the Saccade Amplitude generated within these trials was well above those performed under natural viewing conditions (Bahill, Adler & Stark, 1975). The Saccade Amplitude frequency distribution of all VSST trials (Chapter 5-7) indicated a shift towards larger saccades than those of Morgan (1999).

### 7.3.5 Vertical Task Parameters

Response Accuracy was plotted for the vertical VSST trials and grouped according to Skill Level and Exposure Time (see Figure 7.3.5a). The lowest percentage correct for both groups was observed at the 200 ms Exposure Time (Elite = 27.38; Non-elite = 32.58) and the highest percentage correct was observed at the 1000 ms Exposure Time (Elite = 76.19; Non-elite = 62.88).

![Figure 7.3.5a: Response accuracy for vertical VSST.](image)

Response accuracy results in 7 elite (n = 504) and 11 non-elite (n = 792) footballers across the six exposure times. Response accuracy increases as a function of exposure time.
A two-way between groups ANOVA was conducted to explore the impact of Skill Level and Exposure Time on Response Accuracy. The main effect for Skill Level was not significant [$F(1,1284) = 0.993, \ p = 0.319$], although the main effect for Exposure Time was [$F(5,1284) = 19.097, \ p < 0.001$] which was also consistent across all VSST experiments suggesting response accuracy was always higher at longer Exposure Times. The interaction between these two variables was not significant [$F(5,1284) = 1.276, \ p = 0.272$]. Visual inspection suggested that at the longest Exposure Times (800 and 1000 ms) there was a substantially higher response accuracy for elite footballers although this did not prove significantly different (800 ms: $p = 0.166$ & 1000 ms: $p = 0.041$).

### 7.3.6 Vertical Saccade Parameters

The same dependent variables were calculated for the vertical VSST as the horizontal VSST. The dependent variables were divided by Exposure Time (200, 350, 500, 650, 800 and 1000 ms) and Skill Level (elite and non-elite). A total of 1296 trials were recorded, 504 from elite footballers and 792 from non-elite footballers.

#### 7.3.6i Vertical Mean Saccade Rate

Saccade Rate per second was plotted in Figure 7.3.6i for both Skill Levels at each Exposure Time. The graph showed no differences in the data between elite and non-elite footballers although Mean Saccade Rate increased slightly as Exposure Time increased.

![Figure 7.3.6i: Vertical saccade rate per second for elite and non-elite footballers.](image)

Saccade rate was standardised for each exposure time to saccade rate per second and determined for elite and non-elite footballers. Standard error bars are displayed for mean saccade rate at each exposure time.
A two-way between groups ANOVA was conducted to explore the impact of Skill Level and Exposure Time on Saccade Rate per second. The main effect for Skill Level was not significant \( F(1, 1284) = 0.657, p = 0.418 \) which confirms a visual scan of the data that all means were similar for both skill groups at most Exposure Times. The main effect for Exposure Time was significant \( F(5, 1284) = 168.063, p < 0.001 \) suggesting saccades were more frequent at longer Exposure Times. The interaction between these two variables was not significant \( F(5, 1284) = 1.180, p = 0.317 \). Post-hoc t-tests were conducted on the results to explore any relationships that exist in trials at individual Exposure Times. These t-tests are displayed in Table 7.3.6i. As the table reveals, there were no significant values further confirming that there was no difference in vertical Saccade Rate between elite and non-elite footballers at any Exposure Time.

Table 7.3.6i
Post-hoc t-test scores for Vertical Saccade Rate by Exposure Time and Skill Level

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>df</th>
<th>t-value</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>214</td>
<td>0.073</td>
<td>0.942</td>
</tr>
<tr>
<td>350</td>
<td>214</td>
<td>-1.251</td>
<td>0.212</td>
</tr>
<tr>
<td>500</td>
<td>214</td>
<td>1.092</td>
<td>0.276</td>
</tr>
<tr>
<td>650</td>
<td>214</td>
<td>1.535</td>
<td>0.126</td>
</tr>
<tr>
<td>800</td>
<td>214</td>
<td>0.607</td>
<td>0.545</td>
</tr>
<tr>
<td>1000</td>
<td>214</td>
<td>-0.130</td>
<td>0.897</td>
</tr>
</tbody>
</table>

### 7.3.6ii Vertical Saccade Amplitude

Cumulative and Mean Saccade Amplitude were plotted in Figure 7.3.6ii for both Skill Levels at each Exposure Time. Visual inspection of the graph shows that Cumulative Saccade Amplitude increases as a function of Exposure Time \( F(5, 1023) = 124.407, p < 0.001 \) but appears unrelated to Skill Level \( F(1, 1023) = 0.633, p = 0.426 \). The interaction between these two variables was not significant \( F(5, 1023) = 1.036, p = 0.395 \).

A more surprising result was that Mean Saccade Amplitude was higher for non-elite footballers at almost all Exposure Times except 200 ms, although the main effect was not significant \( F(1, 1023) = 2.771, p = 0.096 \). Additionally, the main effect for Exposure Time was not significant \( F(5, 1023) = 1.868, p = 0.097 \) as was the interaction effect \( F(5, 1023) = 1.441, p = 0.207 \).
Figure 7.3.6ii: Vertical saccade amplitude for elite and non-elite footballers. The amplitude for all saccades per trial was combined (top) to demonstrate total amplitude covered per trial. The mean saccade amplitude (bottom) was calculated as the mean amplitude made for all saccades in an individual trial. Standard error bars are displayed for saccade amplitude.

Post-hoc t-tests were conducted on the data (see Table 7.3.6ii) but only revealed one significant difference in Cumulative Saccade Amplitude at the 350 ms exposure time. However, the post-hoc t-tests did confirm to some extent that non-elite footballers had larger Mean Saccade Amplitude than elite footballers between the 350 – 800 ms Exposure Times. Only two of these Exposure Times were significant to the 0.009 level, however the 500 ms (p = 0.015) and 800 ms (p = 0.023) both approached significance.
Table 7.3.6ii

Post-hoc t-test scores for Vertical Saccade Amplitude by Exposure Time and Skill Level

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>df</th>
<th>Cumulative Saccade Amplitude</th>
<th>Mean Saccade Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>t = 1.169</td>
<td>t = 1.169</td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>p = 0.276</td>
<td>p = 0.276</td>
</tr>
<tr>
<td>350</td>
<td>180</td>
<td>t = -3.129</td>
<td>t = -3.829</td>
</tr>
<tr>
<td>500</td>
<td>205</td>
<td>t = -0.861</td>
<td>t = -2.463</td>
</tr>
<tr>
<td>650</td>
<td>210</td>
<td>t = -0.028</td>
<td>t = -2.740</td>
</tr>
<tr>
<td>800</td>
<td>210</td>
<td>t = -0.687</td>
<td>t = -2.291</td>
</tr>
<tr>
<td>1000</td>
<td>210</td>
<td>t = -2.104</td>
<td>t = -1.349</td>
</tr>
</tbody>
</table>

Red = Significant to less than 0.001, Green = Significant to 0.009

7.3.6iii Vertical Peak Saccade Velocity

Cumulative and Mean Peak Saccade Velocity were calculated across Skill Levels at each Exposure Time and plotted in Figure 7.3.6iii. Visual inspection of the graph suggested that there were very similar results to Saccade Amplitude. Cumulative Peak Saccade Velocity rises steadily at each Exposure Time which is significant \( F(5,1023) = 127.638, p < 0.001 \) however Skill Level does not appear to be different at any Exposure Time except the 1000 ms which may be why this main effect was not significant \( F(1,1023) = 1.406, p = 0.236 \). There was no significant interaction between these two independent variables and Cumulative Peak Saccade Velocity \( F(5,1023) = 1.708, p = 0.130 \).

As with vertical Saccade Amplitude, Mean Peak Saccade Velocity showed that faster saccades were being performed by the non-elite footballers during the vertical VSST. A two-way between groups ANOVA was conducted to explore the impact of Skill Level and Exposure Time on Cumulative Peak Saccade Velocity. The main effect for Skill Level \( F(1,1023) = 8.821, p = 0.003 \) and Exposure Time were both significant \( F(5,1023) = 2.277, p = 0.045 \). The interaction between these two variables was not significant \( F(5,1023) = 0.484, p = 0.788 \).
Figure 7.3.6iii: Vertical peak saccade velocity for elite and non-elite footballers. The peak velocity for all saccades per trial was combined (top) to demonstrate total peak velocity covered per trial. The peak saccade velocity (bottom) for all saccades per trial was averaged to account for saccade rate. Standard error bars are displayed for peak saccade velocity.

*Post-hoc* t-tests were still used to investigate individual differences at some exposure times (see Table 7.3.6iii) but were unable to find any differences in *Cumulative Peak Saccade Velocity*. However, significant differences were found for *Mean Peak Saccade Amplitude* at all *Exposure Times* above 200 ms. In all of these trials, non-elite footballers generated faster saccades. Only at the 1000 ms *Exposure Time* was *Cumulative Peak Saccade Velocity* significantly higher for non-elite footballers.
Table 7.3.6iii
Post-hoc t-test scores for Vertical Peak Saccade Velocity by Exposure Time and Skill Level

<table>
<thead>
<tr>
<th>Exposure Times</th>
<th>200</th>
<th>350</th>
<th>500</th>
<th>650</th>
<th>800</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>8</td>
<td>180</td>
<td>205</td>
<td>210</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>Cumulative Peak Saccade Velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>0.205</td>
<td>-2.196</td>
<td>-0.825</td>
<td>0.190</td>
<td>-1.005</td>
<td>-2.795</td>
</tr>
<tr>
<td>p</td>
<td>0.843</td>
<td>0.029</td>
<td>0.411</td>
<td>0.849</td>
<td>0.316</td>
<td>0.006</td>
</tr>
<tr>
<td>Mean Peak Saccade Velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>0.205</td>
<td>-3.326</td>
<td>-3.226</td>
<td>-3.294</td>
<td>-2.953</td>
<td>-3.324</td>
</tr>
<tr>
<td>p</td>
<td>0.843</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.004</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Red = Significant to less than 0.001, Green = Significant to 0.009

7.3.6iv Vertical Saccade Latency

Of the 1296 trials performed, there were 1035 trials in which at least one saccade was detected. Saccade Latency was determined from these 1035 trials and then plotted for Skill Level at each Exposure Time in Figure 7.3.6iv. As with earlier Saccade Latency results, all anticipation saccades were removed from the data.

![Figure 7.3.6iv: Vertical saccade latency for elite and non-elite footballers.](image)

The time taken to initiate the first saccade was measured in each individual trial (trials without a saccade were excluded). Standard error bars are displayed for saccade latency across both skill levels at each exposure time.
A two-way between groups ANOVA was conducted to explore the impact of Skill Level and Exposure Time on Cumulative Peak Saccade Velocity. The main effect for Skill Level was not significant \( F(1,1023) = 0.154, p = 0.695 \), although the main effect for Exposure Time was \( F(5,1023) = 10.842, p < 0.001 \). The interaction between these two variables was not significant \( F(5,1023) = 0.519, p = 0.762 \). Although a trend was evident showing a slower Saccade Latency for elite footballers than non-elite footballers, the difference was not significant. As opposed to Saccade Rate, Amplitude and Peak Velocity that historically has shown differences, Saccade Latency has never proven to differ between elite and non-elite footballers and therefore there was no reason to conduct post-hoc t-tests and almost certainly violate a type 2 error.

7.4 Discussion

In visually demanding sports, it was assumed that elite players would possess the overall capacity to rapidly acquire visual information more than the non-elite players (Williams et al., 1993a). Using a non-sports specific visual search task, Morgan (1999) found that elite football and soccer players execute faster and larger but not necessarily more frequent saccades. This visual search behaviour appeared to be perceptually advantageous even though larger saccades were generated and it is known that saccadic suppression increases in proportion to the magnitude of the saccade (Ridder & Tomlinson, 1997). The current experiments were expected to verify these horizontal visual search findings although the vertical visual search analysis was completely exploratory.

Firstly, the elite and non-elite groups both demonstrated the Main Sequence relationship from their horizontal and vertical saccades respectively for velocity and duration as a function of amplitude. However, the vertical Main Sequence relationship revealed that the eleven non-elite footballers possessed abnormally fast saccades as well as durations that were abnormally short according to previous research (Becker, 1989; Garbutt et al., 2001). This result was unexpected, as there does not appear to be any perceptual benefit in executing slower and longer saccades, especially by an elite sports group who were expected to demonstrate optimal search strategies. In this case, elite footballers took longer to scan the entire display and in turn exposed them to longer periods of visual suppression, which would surely not be considered optimal.
The horizontal *Saccade Amplitude* frequency distributions revealed that elite footballers generated a narrower range of amplitudes compared to non-elite players. The horizontal data for both skilled groups showed that the highest frequencies were recorded around the 14° to 17° range, which implies that saccades between the inter-target step-sizes were reasonably accurate. The vertical frequency distribution also confirmed that dual peaks were evident at 5° and 14°-17° which is consistent with the 32 normal participants in chapter 6 (see Figure 6.3.1c). As stated then, the dual peak may occur because of small overshoot followed by corrective saccades. The distribution was also skewed to the left, as it has in all VSST trials (Chapter 5 and 6). However, not one distribution conforms to previous research estimating that 86% of naturally occurring saccades were equal to or less than 15° (Bahill, Adler & Stark, 1975). The horizontal VSST data actually showed that the 85th percentile was 30° for elite footballers and 26° for non-elite footballers. The 85th percentile for vertical saccades was 26° for elite footballers and 29° for non-elite footballers. This is almost twice as large as the earlier work on naturally occurring saccades (Bahill, Adler & Stark, 1975). Therefore, the VSST must induce *Saccade Amplitudes* that are larger than what would naturally be expected to occur. The generation of larger saccades is likely the product of having such large inter-target step-sizes as opposed to being the natural characteristic of horizontal or vertical visual search tuned through playing football. Whether the use of such large inter-target step sizes accentuated any results or equates to any perceptual advantage is still unclear (Morgan, 1999).

Performance in terms of *Response Accuracy* showed that both elite and non-elite groups responded more accurately the longer the stimuli were exposed for. However, this did not translate to either skilled group out-performing the other during the horizontal or vertical VSST. Both groups performed equally well on this non-sports specific task contrasting earlier results which showed reduced error by elite footballers at *Exposures Times* between 350 ms and 800 ms (Morgan, 1999). The results in Chapter 7 are consistent with other research which suggested that observed differences are more readily observed when the task becomes sports specific (Abernethy *et al*., 1994; Williams, 2000).
CHAPTER 7  SEARCH STRATEGIES IN ELITE AND NON-ELITE FOOTBALLERS

The saccadic behaviour of elite footballers in the horizontal VSST did not show significantly different results than non-elite footballers relating to speed, size, frequency and latency. A number of differences were expected but it was not obvious why this did not eventuate. A potential reason why these differences were not observed could stem from the participant sample tested. The average age of the elite footballers was 20 whilst the non-elite footballers averaged 25 years of age. It is entirely possible that they had not acquired the perceptually beneficial visual search behaviour acquired through elite sports training. However, the elite footballers had on average been playing football for many more years than their older non-elite counterparts so if there were differences learned through sports training then it should have been already acquired considering the number of years of football experience these participants had. However, it may only be through elite sports training that task specific skills are acquired, which is why there was no difference between the visual search of both skill groups. It would be advantageous in future experiments to age-match and experience-match the footballers.

Although horizontal saccades proved non-significant, vertical saccades revealed that between 350 and 650 ms that non-elite footballers made larger saccades. Vertical Mean Peak Saccade Velocity showed significant differences at all Exposure Times above 200 ms. These differences are also very difficult to interpret. Perhaps elite sportsmen knew that making slower and smaller vertical saccades was somehow more perceptually benefiting than making larger and faster vertical saccades. There was thought to be some benefit to making eyes movements with these characteristics because elite footballers responded correctly to more trials, especially at the 800 and 1000 ms Exposure Times. However, the percentage of correct responses (Figure 7.3.5a) was not significantly different at these and other Exposure Times, so this ruled out any superior performance. However, the saccade behaviour is significantly different so there must be some benefit to performing saccades in this way, otherwise elite footballers would not make them. At no point in time did the visual search behaviour of either skill group demonstrate a distinct disadvantage from performing more saccades.
Chapter 8 Discussion

The experiments conducted in this thesis were designed to investigate the dynamic components of saccadic eye movements in the acquisition of visual information. The experiments were modelled on the recent work of Morgan (1999) who designed a protocol for testing and evaluating performance and saccadic behaviour on a multiple eye movement visual search task. This novel approach addressed the perceptual consequences of executing multiple saccades during visual search. The following discussion focuses on the decisions made throughout this thesis which may have impacted the results either positively or negatively.

8.1 Review of Methodology

The use of EOG for the acquisition of saccadic eye movement data in these experiments was considered extremely adequate. It was simple to use and easy to apply, was non-invasive to the participant, and did not require lengthy calibration procedures whilst the participants were present at the laboratory. Post-recording session the data were calibrated to an extremely high level of accuracy using linear equations for the horizontal saccade data (mean $r^2 = 0.975$, $n = 33$) and a combination of linear and cubic equations for vertical saccade data (mean $r^2 = 0.922$, $n = 32$). The nature of the task meant detection of small saccades less than $5^\circ$ was not required even though the 10 bit processor was easily capable of resolving movements less than $1^\circ$ after calibration. The temporal resolution of 480 Hz was more than ample for the current experiments but could be improved upon considering further technological advancements. However, EOG alone was unable to confirm whether peak velocities above 1000°/s and amplitudes greater than 60° were accurate recordings or erroneous data. A complimentary system would have achieved this as well as eliminate the need to subjectively identify the presence of blinks in a trial. A multiple recording system using a video-based device with adequate temporal resolution as well as EOG would have complimented the current procedure quite well.

The saccade detection and evaluation algorithm was based on 40 years of previous research giving it a very sound base. The decision to use the 100°/s velocity threshold, $5^\circ$ amplitude threshold, and 12 ms duration threshold was considered very conservative.
The effect this had on the data was to slightly underestimate the amplitude, duration and frequency of saccades. Both peak velocity and latency of saccades were unaffected by this decision. Being a conservative estimate of saccade initiation and termination, it increased the likelihood that any deflections conforming to the criteria were in fact saccades. The underestimation appeared to have little effect on the data because in all participant groups the *Main Sequence* relationships were within normal limits.

In contrast to the previous method of Morgan (1999), an individual amplitude calibration was used per participant. This was considered more effective given that the variance for an individual calibration ($r^2 = 0.95$ to $0.98$; Figure 4.3a) was always much lower than when calibration values from all participants were combined ($r^2 = 0.81$ to $0.86$; Figure 4.3b) regardless of the illuminance level used. An amplitude calibrated from group data varied 10% more than amplitude calibrated from individual data making the decision to calibrate individually an obvious one.

Previous literature had already forewarned that turning the lights off during or prior to testing would cause a reduction in the corneo-retinal potential affecting all subsequent values recorded (Hickson, 1983; Gonshor & Malcolm, 1971) including a reduction in amplitude and a slowing of the velocity (Riggs *et al.*, 1974; Becker & Fuchs, 1969). This criticism could be levelled at Morgan (1999) because participants went from a normally lit room to complete darkness during the test. This criticism does not diminish Morgan’s findings because the methodology was consistent and there appeared to be no sign of saccade velocity slowing in the *Main Sequence* relationships, although it was difficult to assess this retrospectively. Morgan’s (1999) method did maximise the contrast between background illuminance levels so any variation to his methodology would have to account for this also. In Chapter 4, this was addressed by having participants go from a normally lit room to a variety of illuminance levels ranging from complete darkness to no change. Surprisingly, when the illuminance level was dimmed to 25 Lux, the *Saccade Amplitude* varied the least (mean $r^2 = 0.979$) rather than when the lighting remained unchanged (mean $r^2 = 0.976$) which differed from Jackson (1979). As there was less amplitude variance using the dimmer illuminance level rather than the unchanged illuminance level over the 10-minutes, then the *Main Sequence* dictated that there was also very little change in velocity and certainly no slowing. Therefore, an
illuminance level of 25 Lux provided the most reliable signal and allowed the contrast between room illuminance and LED luminance to remain favourably high.

The VSST proved to be quite adequate for observing a wide range of performance. Results suggested the task was highly demanding because at no point was 100% success observed during any Exposure Time or as a factor of the Number of Targets. The Response Accuracy varied for normal participants between 33.3% and 70.2% for horizontal VSST and 32.3% and 60.4% for vertical VSST clearly indicating the vertical task was more difficult. If a learning effect existed, then vertical VSST results would have been superior. As this was not the case, one may assume there were no learning effects for the task. Future tests should counterbalance the order of horizontal and vertical trials however; this study could not because it was not known whether the testing sequence in some way influenced the findings of Morgan (1999). A fatigue related component to the task may explain the poorer vertical VSST performance but as time on task never exceeded 10 minutes and the Main Sequence relationship was always observed (Peak Saccade Velocity actually increased for larger vertical saccades) another explanation must be suggested. Perhaps if the ratio of display dimensions to the limit of the human visual field were similar, then Response Accuracy may have been more comparable. As it stood, the horizontal VSST tested 28% of the horizontal visual field (56°/200°) whilst the vertical VSST tested 43% of the vertical visual field (56°/130°). A reduction in vertical display dimensions would have very likely improved vertical task performance, however it remains to be seen whether this would have produced a subsequent difference in successful or unsuccessful vertical visual search strategies.

Two decisions were made which may have inadvertently caused inaccuracies in some of the dependent variables. Firstly, the inclusion of vertical trials which had eyelid artefact objectively identified may have caused some inaccuracies. As Figure 6.2.4 showed, even when the eyelid artefact was excluded, the saccades which remained included appeared to be larger and potentially faster than what they actually were. There is no way of knowing whether the deflections which remained included were accurate, so a more conservative approach might have been to exclude the entire trial rather than the deflection caused by the eyelid artefact. The second variable affected by exclusion criteria was Saccade Latency. When an anticipatory saccade was excluded, it often caused a longer than usual delay until the second saccade was detected. Again, a more
suitable approach may have been the exclusion of the trial. The exclusion of trials containing eyelid artefact or anticipatory saccades was not performed because of the reduction in saccade numbers or trials that this might have caused.

8.2 Review of Visual Search Strategy

The only previous study of this kind found faster, longer and more frequent eye movements were associated with the successful identification of all target letters in the horizontal VSST for Exposure Times between 500-800 ms (Morgan, 1999). Successful trials by a sample of the normal population in this horizontal VSST were characterised by more frequent saccades (Figure 5.3.3i), greater cumulative visual angle covered (Figure 5.3.3ii) and faster cumulative velocity (Figure 5.3.3iii) for Exposure Times between 650-1000 ms. Only the cumulative variables for amplitude and velocity were significant as opposed to the mean variables for amplitude and velocity. There was little evidence to suggest that task performance was impeded by generating more frequent, larger or faster saccades. In fact, when there was sufficient time to make several saccades there was a clear perceptual advantage associated with their frequent execution. During shorter Exposure Times, there was no distinct advantage associated with specific saccadic behaviour.

Quite unexpectedly, there was no distinction between successful and unsuccessful trials completed during vertical VSST at all Exposure Times. This clearly identifies a difference in the generation of vertical and horizontal saccades during visual search. Based on the percentage of correct trials for horizontal (Figure 5.3.2a) and vertical (Figure 6.3.2a) VSST, it was clear that the vertical VSST task was more difficult, and the largest differences in accuracy were observed at Exposure Times from 650-1000 ms. The horizontal and vertical VSST had similar accuracies at Exposure Times less than 650 ms.

However, under all conditions, generation of saccadic eye movements did not cause any perceptual disadvantage. This is in contrast to single eye movement studies that demonstrate clear association with errors when making saccades (Morgan, 1999). Morgan (1999) believed participants may intuitively reduce Saccade Rate during tasks for which saccadic suppression might be a significant factor. In relation to performing
the vertical VSST, perhaps generating high numbers of saccades may be inappropriate and that Saccade Rate was reduced intuitively. An equally suitable explanation is that horizontal scanning of the environment is more refined through greater exposure and practice than our vertical scanning particularly via tasks such as reading.

8.3 Review of Visual Search Strategy in Footballers

Elite and non-elite footballers did not demonstrate any significantly different trends regarding the generation of horizontal saccades, challenging the results of Morgan (1999). However, it was remarkable that elite footballers generated smaller (Figure 7.3.6ii) and slower (Figure 7.3.6iii) vertical saccades across almost all Exposure Times above 200 ms. Although their general saccadic eye movement behaviour was different during these trials, the Response Accuracy was not different so there was no disadvantage in generating saccades in this way. However, producing smaller and slower saccades may be an indication of a more efficient visual search strategy by spending longer at fixation, although most studies would suggest otherwise (Williams & Davids, 1998; Williams, 2000).

It was not readily obvious why the sample of elite footballers tested in this thesis did not replicate the results of Morgan (1999). Firstly, the elite footballers recruited for these experiments were considerably younger than the non-elite counterparts, so although they were now playing for an elite club, they had not been doing so for very long and therefore may not have acquired the perceptually benefiting visual search behaviour potentially acquired through training. This comes down to a fundamental question regarding whether visual search behaviour is innate or learned. If the elite footballers possessed superior innate visual search capabilities, then it should have been evident during the horizontal VSST, regardless of their age. However, if this study were repeated, the footballers should be age matched to control for this confounding variable. Furthermore, the seven elite players generally had more years of football playing experience over their non-elite rivals, so if superior visual search behaviour was learned; it would also have been evident during the VSST and should have shown differences either way.
Another explanation for why there was no difference between elite and non-elite footballers was that the task was not sports specific so it may not reflect visual search strategies of footballers during competitive situations. However, the same protocol was used by Morgan (1999) who did observe different visual search strategies across skill level, so this should have also been reflected in the chapter 7 results. Current sports-specific studies involve elite players viewing filmed sequences of game play and anticipating the result of the play (Abernethy et al., 1994; Williams & Davids, 1998; Williams, 2000). Elite players may have used many visual cues or alternatively very few visual cues to successfully anticipate the result. However, there is no way of knowing in these sports-specific situations whether the correct response was from an efficient visual search strategy or an inefficient one that was somehow successful. Therefore, the sports specific components had to be nullified in order examine the visual search behaviour in a standard task.

Due to the task being non-sports specific meant the combination of saccades performed may not resemble those observed during play. Levy-Schoen et al. (1974) showed that tasks involving multiple saccades and multiple fixations produce a strategy in combination, rather than a sequence of successively initiated responses. This moves the task further away from a realistic setting of successive saccades in a sporting environment, with the next saccade based on the previous fixation. In an unpredictable environment, a combination of multiple pre-programmed saccades would not be generated because the results of each fixation would dictate the next saccade. It is very difficult to overcome the nature of making a combination of saccades in a controlled visual search environment and forcing a sequence of successively initiated responses. If this were addressed, the entire nature of the task and experimental objectives would alter considerably but would be worth considering for the design of future experiments.

### 8.4 Application of the Results

The nature of the VSST task meant that its application back to real world scenarios was limited. Firstly, the task used a static array when most real world situations consist of a dynamic environment (Viviani, 1990). Secondly, visual scanning involves both head and eye movement in combination. Unfortunately, recording by EOG does not allow accurate spatial resolution without the head remaining stationary so this alone could
make the examination of such a large display unnatural. The results from Figures 5.3.1c, 6.3.1c, 7.3.1c, 7.3.4c supported this supposition because *Saccade Amplitudes* were often larger in this VSST than those performed under natural viewing conditions (Bahill, Adler & Stark, 1975).

However, Morgan (1999) never designed the task to be readily applicable to the real world nor one that was sports specific. Nonetheless, he did create a task where elite athletes from a number of sports (AFL, soccer, netball) scanned differently to non-elite athletes or athletes from a non-continuous ball sports backgrounds. Unfortunately, the results of Chapter 7 were unable to reproduce these findings in the horizontal visual field but were able to identify scanning differences in the vertical visual field. If the results were consistent with Morgan (1999) then the task could be applied as a sports screening tool but this regrettably was not the case. Nevertheless, the disparity in findings between Morgan (1999) and Chapter 7 relating to horizontal visual search strategies warrants further investigation.

Although the practical significance of the VSST was limited, the theoretical implications were considerable. For the second time, the exploratory research provided evidence confirming multiple eye movements were not perceptually counterproductive during visual search. Therefore, it is unclear what role saccadic suppression plays during visual search compared to single eye movement studies and hence there is a clear need to extend these findings and further develop the visual search task.

### 8.5 Conclusion

In conclusion, these experiments produced two major findings relating to the acquisition of visual information during visual search tasks. The first confirmed via these experiments that there was no perceptual disadvantage to generating saccadic eye movements during any VSST. The second major finding was the inability to observe differences in elite and non-elite footballers during horizontal visual search on a non-sports specific task. However, vertical visual search poses some interesting avenues for future research, especially since it was considered a much more demanding physical action potentially arising from our inefficient and under-practised vertical search behaviours.


25 July 2002

Dr John Patterson & Mr Robert Chapman  
School of Biophysical Sciences & Electrical Engineering (H31)  
Swinburne University of Technology  
John St  
Hawthorn, 3122

Dear Dr Patterson & Mr Chapman

Re: Investigating the effects of varying illuminance levels on the corneo-fundal potential (2002/13)

The Joint School of Biophysical Sciences & Electrical Engineering and Brain Sciences Institute Human Research Ethics Subcommittee has now considered your application for ethical clearance and now has pleasure in advising you that your application has been approved for 1 year.

Will you please inform the Committee of your progress at the end of 12 months or at the conclusion of the project. Continuation will be required for projects extending further than 12 months.

Yours faithfully

[Signature]

Prof Con Stough  
Chair BSEE/BSI Human Research Ethics Sub-Committee  
cc: Dr M Schier  
Dr S Morgan
SWINBURNE UNIVERSITY OF TECHNOLOGY
HUMAN RESEARCH ETHICS COMMITTEE
FORM OF DISCLOSURE AND INFORMED CONSENT

PROJECT TITLE STUDY 1
Investigating the effects of varying illuminance levels on the corneo-retinal potential.

INVESTIGATORS:
Investigator: Robert Chapman
Supervisor: Dr. John Patterson
Co-Supervisor: Dr. Mark Schier
Dr. Stuart Morgan

EXPLANATION OF PROJECT:
The purpose of this study is to investigate what effect varying room lighting (illuminance) levels have on the potential difference between the front and back of the eyeball (corneo-retinal potential).

In the first testing session, three tests will be employed to assess certain characteristics of the participant's vision. These three tests are the Dominant Eye Test, Visual Acuity Test, and Ishihara Colour Blindness Test. The dominant eye test is a standard test designed to demonstrate which eye is the stronger of the two. The LogMAR Visual Acuity test is designed to assess participant's ability to discriminate fine detail. It entails reading progressively smaller lines from a chart at a distance of 3 meters. The Ishihara colour blindness test was designed to identify colour deficiencies from participants. It entails observing 24 circular shapes with a number or line extending through the circle. Participants are asked to describe what they observe. These tests should take approximately 15 minutes to perform.

The main visual test is the Multiple Eye Movement Task. In this task participants are connected to an Electro-oculogram (EOG) via 3 disposable recording electrodes, which are attached to specific sites around the eyes for recording horizontal eye movements. Participants are then asked to watch a display board containing numerous alphanumeric displays and identify a specific target letter. The test only requires the recording of normal signals (no stimulation is used). This task should take approximately 25 minutes to perform.

On the day of testing participants will be required to avoid consuming caffeinated products (including tea, coffee, soft drink, chocolates etc.), alcohol, and nicotine two hours prior to and throughout the recording period.

HAZARDS OR DISCOMFORT:
The study requires the placement of three electrodes on the participant's face for EOG recordings. This standard procedure may be considered initially uncomfortable to participant's who have not observed or experienced EOG testing before.
SWINBURNE UNIVERSITY OF TECHNOLOGY
HUMAN RESEARCH ETHICS COMMITTEE
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TIME ALLOCATION:
Participants are asked to attend five testing sessions. The sessions need to take place on five different days at approximately the same time of the day, and during daylight hours. The experiment will take approximately 35 minutes for the first session to complete and 20 minutes for the remaining four sessions. Total experimental time will be approximately 2 hours. All sessions will be held at Swinburne University of Technology (Hawthorn Campus), Applied Science Building in the Sensory Neuroscience Laboratory Room AS420.

POTENTIAL BENEFITS FOR INDIVIDUAL AND SOCIETY:
Your willingness to participate will help provide important information concerning how oculomotor characteristics are affected by light level. Therefore your participation is greatly appreciated.

WITHDRAWING CONSENT:
Your participation in this study is voluntary, and you are free to withdraw at any time should you desire without any adverse consequences.

QUESTIONS ABOUT THE PROCEDURE:
Should you have any questions or require any additional information please do not hesitate to ask. This project is being supervised by Dr. John Patterson who can be contacted at Swinburne University of Technology on (03) 9214 8862 between the hours of 9am – 5pm.

PRIVACY PROTECTION
The names of all participants will be assigned a code and all data will be logged in reference to that code only. Records listing names and codes of participants will be kept locked in separate locations with access to the codes restricted to investigators only. At the completion of the study all identifiable data will be destroyed. The results will be submitted for publication following the completion of the study. At no time will participants be identified through the publication. If you would like to read a copy of the published work please ask me for a copy.

COMPLAINT PROCEDURE
In the event that there is a complaint about how you have been treated during the study or a query that the senior investigator has been unable to satisfy please write to:

The Chair
Human Research Ethics Committee
Swinburne University of Technology
PO Box 218
HAWTHORN, VIC. 3122
Phone: (03) 9214 5223
SWINBURNE UNIVERSITY OF TECHNOLOGY
HUMAN RESEARCH ETHICS COMMITTEE
FORM OF DISCLOSURE AND INFORMED CONSENT

 AGREEMENT

Participant’s Code Number: ............................................ (Experimenter use only)

Project Title: Study 1
Investigating the effect of varying illuminance levels on the corneo-retinal potential.

I ....................................................... have read and understood the information sheet titled “Investigating the effects of varying illuminance levels on the corneo-retinal potential”. Any questions I have asked have been answered to my satisfaction.

I agree to participate in this activity, realising that I may withdraw at any time, free of any adverse consequence.

I agree that research data collected for the study may be published or provided to other researchers on the condition that anonymity is preserved and that I cannot be identified.

NAME OF PARTICIPANT: .................................................................................................

SIGNATURE........................................................................DATE..............................

NAME OF INVESTIGATOR: Robert Chapman

SIGNATURE........................................................................DATE..............................
SWINBURNE UNIVERSITY OF TECHNOLOGY
HUMAN RESEARCH ETHICS COMMITTEE
FORM OF DISCLOSURE AND INFORMED CONSENT

PROJECT TITLE STUDY 2
Investigating oculomotor components of horizontal and vertical saccades during visual search tasks.

INVESTIGATORS:
Investigator: Robert Chapman
Supervisor: Dr. John Patterson
Co-Supervisor: Dr. Mark Schier
Dr. Stuart Morgan

EXPLANATION OF PROJECT:
The purpose of this study is to investigate oculomotor components of horizontal and vertical saccades during visual search tasks.

Initially, three tests will be employed as standard preliminary tests to assess certain characteristics of the participant’s eyes. These three tests are the Dominant Eye Test, Visual Acuity Test, and Ishihara Colour Blindness Test. The dominant eye test is a standard test designed to demonstrate which eye is the stronger of the two. The LogMAR Visual Acuity test is designed to assess participant’s ability to discriminate fine detail. It entails reading progressively smaller lines from a chart at a distance of 3 meters. The Ishihara colour blindness test was designed to identify colour deficiencies from participants. It entails observing 24 circular shapes with a number or line extending through the circle. Participants are asked to describe what they observe. These tests should take approximately 15 minutes to perform.

The main visual test is the Multiple Eye Movement Task. In this task participants are connected to an Electro-oculogram (EOG) via 5 disposable recording electrodes, which are attached to specific sites around the eyes for recording horizontal and vertical eye movements. Participants are then asked to watch a display board containing numerous alphanumeric displays and identify a specific target letter. The test only requires the recording of normal signals (no stimulation used). This task should take approximately 30 minutes to perform.

On the day of testing participants will be required to avoid consuming caffeinated products (including tea, coffee, soft drink, chocolates etc.), alcohol, and nicotine two hours prior to and throughout the recording period.

HAZARDS OR DISCOMFORT:
The study requires the placement of five electrodes on the participants face for EOG recordings. This standard procedure may be considered initially uncomfortable to participant’s who have not observed or experienced EOG testing before.
TIME ALLOCATION:
Participants are asked to attend one testing session. The experiment will take approximately 45 minutes to complete. All sessions will be held at Swinburne University of Technology (Hawthorn Campus), Applied Science Building in the Sensory Neuroscience Laboratory Room AS420.

POTENTIAL BENEFITS FOR INDIVIDUAL AND SOCIETY:
Your willingness to participate will help provide important information concerning how oculomotor characteristics enable improved performance in visual search tasks. Participants also receive feedback for performance on visual acuity in the right and left eye, as well as colour blindness. Therefore your participation is greatly appreciated.

WITHDRAWING CONSENT:
Your participation in this study is voluntary, and you are free to withdraw at any time should you desire without any adverse consequences.

QUESTIONS ABOUT THE PROCEDURE:
Should you have any questions or require any additional information please do not hesitate to ask. This project is being supervised by Dr. John Patterson who can be contacted at Swinburne University of Technology on (03) 9214 8862 between the hours of 9am – 5pm.

PRIVACY PROTECTION
The names of all participants will be assigned a code and all data will be logged in reference to that code only. Records listing names and codes of participants will be kept locked in separate locations with access to the codes restricted to investigators only. At the completion of the study all identifiable data will be destroyed. The results will be submitted for publication following the completion of the study. At no time will participants be identified through the publication. If you would like to read a copy of the published work please ask me for a copy.

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HUMAN RESEARCH ETHICS COMMITTEE
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AGREEMENT

Participant’s Code Number: ........................................... (Experimenter use only)

Project Title: Study 2
Investigating oculomotor components of horizontal and vertical saccades during visual search tasks.

I ..................................................... have read and understood the information sheet titled “Investigating oculomotor components of horizontal and vertical saccades during visual search tasks”. Any questions I have asked have been answered to my satisfaction.

I agree to participate in this activity, realising that I may withdraw at any time, free of any adverse consequence.

I agree that research data collected for the study may be published or provided to other researchers on the condition that anonymity is preserved and that I cannot be identified.

NAME OF PARTICIPANT:........................................................................................................

SIGNATURE..........................................................................................................DATE........................................

NAME OF PRINCIPAL INVESTIGATOR: Robert Chapman

SIGNATURE..........................................................................................................DATE........................................
SWINBURNE UNIVERSITY OF TECHNOLOGY
HUMAN RESEARCH ETHICS COMMITTEE
FORM OF DISCLOSURE AND INFORMED CONSENT

PROJECT TITLE STUDY 3
Investigating oculomotor components of horizontal and vertical saccades of elite and non-elite Australian Rules football players during visual search tasks.

INVESTIGATORS:
Investigator: Robert Chapman
Supervisor: Dr. John Patterson
Co-Supervisor: Dr. Mark Schier
Dr. Stuart Morgan

EXPLANATION OF PROJECT:
The purpose of this study is to investigate oculomotor components of horizontal and vertical saccades of elite and non-elite Australian Rules football players during visual search tasks.

Initially, three tests will be employed as standard preliminary tests to assess certain characteristics of the participant’s eyes. These three tests are the Dominant Eye Test, Visual Acuity Test, and Ishihara Colour Blindness Test. The dominant eye test is a standard test designed to demonstrate which eye is the stronger of the two. The LogMAR Visual Acuity test is designed to assess participant’s ability to discriminate fine detail. It entails reading progressively smaller lines from a chart at a distance of 3 meters. The Ishihara colour blindness test was designed to identify colour deficiencies from participants. It entails observing 24 circular shapes with a number or line extending through the circle. Participants are asked to describe what they observe. These tests should take approximately 15 minutes to perform.

The main visual test is the Multiple Eye Movement Task. In this task participants are connected to an Electro-oculogram (EOG) via 5 disposable recording electrodes, which are attached to specific sites around the eyes for recording horizontal and vertical eye movements. Participants are then asked to watch a display board containing numerous alphanumeric displays and identify a specific target letter. The test only requires the recording of normal signals (no stimulation used). This task should take approximately 30 minutes to perform.

The questionnaire is designed to identify how important players and officials rank certain skills/attributes according to player size, or player position. All participants in this study who play Australian Rules football will be asked to fill in a four-page questionnaire. This questionnaire should take approximately 10 minutes to complete.

On the day of testing participants will be required to avoid consuming caffeinated products (including tea, coffee, soft drink, chocolates etc.), alcohol, and nicotine two hours prior to and throughout the recording period.

HAZARDS OR DISCOMFORT:
The study requires the placement of five electrodes on the participants face for EOG recordings. This standard procedure may be considered initially uncomfortable to participant’s who have not observed or experienced EOG testing before.
TIME ALLOCATION:
Participants are asked to attend one testing session. The experiment will take approximately 45 minutes to complete. All sessions will be held at Swinburne University of Technology (Hawthorn Campus), Applied Science Building in the Sensory Neuroscience Laboratory Room AS420.

POTENTIAL BENEFITS FOR INDIVIDUAL AND SOCIETY:
Your willingness to participate will help provide important information concerning how oculomotor characteristics enable improved performance in visual search tasks. Participants also receive feedback via performance on the visual acuity test, as well as colour blindness test. If the participant wishes, it is possible to keep track of their individual result and compare it to either group result (AFL or VAFA). Player’s participation is greatly appreciated.

WITHDRAWING CONSENT:
Your participation in this study is voluntary, and you are free to withdraw at any time should you desire without any adverse consequences.

QUESTIONS ABOUT THE PROCEDURE:
Should you have any questions or require any additional information please do not hesitate to ask. This project is being supervised by Dr. John Patterson who can be contacted at Swinburne University of Technology on (03) 9214 8862 between the hours of 9am – 5pm.

PRIVACY PROTECTION
The names of all participants will be assigned a code and all data will be logged in reference to that code only. Records listing names and codes of participants will be kept locked in separate locations with access to the codes restricted to investigators only. At the completion of the study all identifiable data will be destroyed. The results will be submitted for publication following the completion of the study. At no time will participants be identified through the publication. If you would like to read a copy of the published work please ask me for a copy.

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HUMAN RESEARCH ETHICS COMMITTEE
FORM OF DISCLOSURE AND INFORMED CONSENT

AGREEMENT

Participant’s Code Number: ........................................... (Experimenter use only)

Project Title: Study 3
Investigating oculomotor components of horizontal and vertical saccades of elite and non-elite Australian Rules football players during visual search tasks.

I ....................................................... have read and understood the information sheet titled “Investigating oculomotor components of horizontal and vertical saccades of elite and non-elite Australian Rules football players during visual search tasks”. Any questions I have asked have been answered to my satisfaction.

I agree to participate in this activity, realising that I may withdraw at any time, free of any adverse consequence.

I agree that research data collected for the study may be published or provided to other researchers on the condition that anonymity is preserved and that I cannot be identified.

NAME OF PARTICIPANT: ..................................................................................

SIGNATURE.............................................DATE.................................

NAME OF PRINCIPAL INVESTIGATOR: Robert Chapman

SIGNATURE.............................................DATE.................................

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The following text is the actual verbal instructions given to participants prior to performing the horizontal EOG amplitude calibration routine.

**EOG Amplitude Calibration Routine Verbal Instructions to Participants**

“This task is a simple task designed to allow me to calibrate the equipment. To perform it correctly I will ask you at the beginning to look at the middle segment of the most central LED display. This will be the only LED segment illuminated. It will remain on for 1½ seconds and then the entire display will change to the numbers ‘1’, ‘2’, ‘3’, ‘4’ and ‘5’. When this occurs you have to look from farthest left LED display to farthest right LED display within 3 seconds but pause on each LED display for approximately half a second. For example, when the LED displays change to the numbers 1 to 5, move your eyes to the farthest left LED display showing ‘1’ and fixate on this for approximately half a second before moving your eyes rightwards to the LED display showing ‘2’. Again fixate on this display for approximately half a second before moving your eyes rightwards to the next display where you will fixate again for half a second. Repeat this process with the fourth and fifth LED display. If you time your eye movements correctly, you will be able to fixate on the fifth LED display for half a second before the mask appears. The mask illuminates all the displays (or changes them to the number ‘8’ or letter ‘B’). This indicates the end of one trial.”

“At the end of each trial you will need to press a button on the hand-held responder before it progresses to the next trial. It does not matter which button you press. This is to allow you to self-pace the trial. Only press a button when you are ready to begin the next trial. There will be six trials in each calibration routine.”

“At all times you must keep your head still and only move your eyes to focus on the LED displays. Try to avoid coughing or sneezing and blinking during the trial as best you can. If you need to cough, sneeze or blink, try to wait until all displays are illuminated with the number ‘8’ (or letter ‘B’) because we do not record the signal at this point.”
“If you find focusing on the numbers difficult from such close distance, then only focus on the middle segment of each LED display but ensure you move your eyes from farthest left to farthest right in the correct order. This order never changes.”

“Do you have any questions about the task? If not we will do some practice runs to get you familiar with the timing of the presentation sequence”.

[At this point the participant practices the routine until they are comfortable with the task and I am confident they are performing the task as per the instructions].

**Visual Search Strategy Task Routine Verbal Instructions to Participants**

“In this next task you need to scan the five targets (LED displays), whilst keeping your head still, and try to identify how many times the letter ‘E’ appears. There are other letters which might appear; ‘F’, ‘S’, ‘L’ and ‘B’ and these are designed to distract you. It is important to only respond with how many ‘E’ s were definitely seen. For example, if you’re unsure whether you saw 1 or 2, then respond with 1 because that’s all you definitely saw.”

“Unlike the previous calibration task, you don’t have to focus on the middle segment to begin with. For example, you could focus on the farthest left display and then quickly scan rightwards. Or you could begin focusing on the farthest right display and then quickly scan leftwards. Alternatively you could begin focusing on the display second from the left, use your peripheral vision to scan the most leftward display and then quickly scan rightwards. And vice versa, you could begin focusing on the display second from the right, use your peripheral vision to scan the most rightwards display and then quickly scan leftwards. Otherwise you can use a strategy of your own. There is no right or wrong way to scan the displays so it is totally up to you. However, the letters will only be displayed for a limited amount of time, so it important to choose quickly.”

“At the end of each trial, a visual mask will appear, as it did in the Calibration Routine. The mask illuminates all the displays (or changes them to the number ‘8’). This indicates the end of each trial and signifies the time that you respond.”
“The task is self paced so you control how long the task will go for. Just remember that once you press the button that the next trial will begin immediately.”

“Try to avoid coughing or sneezing or blinking during the time that the letters are presented otherwise you may miss seeing the targets. If you need to cough, sneeze or blink, try to wait until all displays are illuminated because we do not record the signal at this point.”

“Do you have any questions about the task? If not we will do some practice runs to get you familiar with the timing of the presentation sequence”.

[At this point the participant practices the routine until they are comfortable with the task and I am confident they are performing the task as per the instructions].
Option Explicit
Public Sub ProcessAllFilesInDirectory()

Dim i As Long

Application.ScreenUpdating = False

With Application.FileSearch
  .NewSearch
  .LookIn = "C:\Robert\Study 2 Normal Population\Subject 1 Robert Chapman Mon 1439 28-10-02\Sub1 Horizontal\Modified Files"
  .SearchSubFolders = False
  .Filename = "*.mod"
  .FileType = msoFileTypeExcelWorkbooks
  If .Execute() > 0 Then
    For i = 1 To .FoundFiles.Count
      Workbooks.OpenText Filename:=.FoundFiles(i), Origin:=xlWindows, StartRow:=1, DataType:=xlFixedWidth, FieldInfo:=Array(Array(0, 1), Array(15, 1))
      Columns("A:A").Select
      Selection.Copy
      Windows("Confirmer.xls").Activate
      Sheets(Sheets.Count + 1 - i).Select ' Selects sheets in order from right hand side (Trial1 then Trial2, 3, 4, ...)
      Columns("B:B").Select
      ActiveSheet.Paste
      With Selection.Interior 'This little procedure keeps the cells green
        .ColorIndex = 4
        .Pattern = xlSolid
      End With
      Sheets(Sheets.Count + 1 - i).Name = TruncatedFileName(NoExtFileName(.FoundFiles(i)))
    Next i
    Else
      MsgBox "There are no files found"
    End If
  End With
End Sub

Sub Generate_SACCADEINFO() 'Generates saccadic eye movement information

Dim ColC, ColD, ColE, ColF, ColH, ColI, ColJ, ColK, ColL, ColM, ColN, ColO
Dim DataRow, TableRow, StimEndRow, SerValEnd, PeakVel, Velocity, PreviousVelocity
Dim TempSum, Count, AveValue, Saccade_Starts, Saccade_Ends, StartAmp, EndAmp, Amplitude

ColC = 3 'Column C filled with the amplitude (altered via calibr. eqn. from raw data)
ColD = 4 'Column D filled with velocity values (diff b/w amp/sampling rate)
ColE = 5 'Column E filled with acceleration values (diff b/w velocity/sampling rate)
ColF = 6 'Column F assigned saccade membership of 0 or 10 depending on criterion
ColH = 8 'Column H places saccade first data point in table of results
ColI = 9 'Column I places saccade last data point in table of results
ColJ = 10 'Column J places saccade duration in table of results
ColK = 11 'Column K places the start of the Amplitude in table of results
ColL = 12 'Column L places the end of the Amplitude in table of results
ColM = 13 'Column M calculates (StartAmp - EndAmp = Amplitude)
ColN = 14 'Column N places the Peak Velocity from ColD in table of results
ColO = 15 'Column O places average saccadic velocity values in table of results
DataRow = 721 'Datapoint at which the stimulus is timelocked to begin
TableRow = 23 'Saccadic values are placed in a table beginning row 23
StimEndRow = 8 'Row 8 which contains the Stimulus End Row number in it
TempSum = 0 'Addition of values within the cell if criteria is met
Count = 1 'Counts the number of cells in which criteria is met

SerValEnd = ActiveSheet.Cells(StimEndRow, ColM)

Do While DataRow <= SerValEnd 'Datapoint 1200 is 2.5sec after routine starts (Pre-stim + stim)
    Do While ActiveSheet.Cells(DataRow, ColF) = 0 And DataRow <= SerValEnd
        DataRow = DataRow + 1 'Skips through each datapoint that has sacc. mem. of 0
    Loop
    Saccade_Starts = DataRow
    Count = 0
    PeakVel = 0
    Velocity = 0
    PreviousVelocity = 0

    'At this point Sacc. mem. does not equal zero and the saccade has begun
    Do While ActiveSheet.Cells(DataRow, ColF) = 10 And DataRow <= SerValEnd
        TempSum = TempSum + ActiveSheet.Cells(DataRow, ColD) 'Temporarily adds the velocity
    Loop
    Velocity = ActiveSheet.Cells(DataRow, ColD) 'Initial velocity value
    PreviousVelocity = ActiveSheet.Cells(DataRow - 1, ColD) 'Previous velocity value
    If PeakVel < Velocity = True Then 'Clause: if PeakVel is ever < Vel then leave it
        If Velocity >= PreviousVelocity = True Then 'If vel > than prev velocity
            PeakVel = Velocity '..then Peak Velocity becomes greater val (velocity)
        Else: PeakVel = PreviousVelocity 'or PeakVel remains previous val (Prev.Vel.)
    End If
    Count = Count + 1
    DataRow = DataRow + 1
    StartAmp = ActiveSheet.Cells(Saccade_Starts, ColC)
    Saccade_Ends = Saccade_Starts + Count
    EndAmp = ActiveSheet.Cells(Saccade_Ends, ColC)
    Amplitude = StartAmp - EndAmp
    Amplitude = Abs(Amplitude)
    Loop

    'Now calc AveValue of the Saccade Velocity (ColD) whilst saccade exists
    If Count = 0 Then
    ElseIf Count > 0 Then
        AveValue = TempSum / Count
    End If

    'Now place all the important values into areas on the Active Worksheet
    If Count > 6 And Amplitude > 5 Then 'Threshold set by Behrens and Weiss (1992) pg 890
        'at 12ms and Minimum Amplitude of Saccade must be 5 degrees
        ActiveSheet.Cells(TableRow, ColH) = Saccade_Starts
        ActiveSheet.Cells(TableRow, ColI) = Saccade_Starts + Count
        ActiveSheet.Cells(TableRow, ColJ) = DataRow - Saccade_Starts
        ActiveSheet.Cells(TableRow, ColK) = StartAmp
        ActiveSheet.Cells(TableRow, ColL) = EndAmp
        ActiveSheet.Cells(TableRow, ColM) = Amplitude
        ActiveSheet.Cells(TableRow, ColN) = PeakVel
        ActiveSheet.Cells(TableRow, ColO) = AveValue
        TableRow = TableRow + 1
    End If
AveValue = 0
TempSum = 0
DataRow = DataRow + 1
Loop
End Sub

Function TruncatedFileName(ByVal strInputString As String)
'Calculate position and length of the filename substring by searching for
'the first occurrence of "/" from the right hand side of full path - hence instrREV
'This function returns only the name of the file, NOT the path + name.
' --- Later learned that the CommonDialog.FileTitle property returns this
' --- however, it does not work for multi-file names.
Dim TotLength
Dim PositionOfSubString

TotLength = Len(strInputString)
PositionOfSubString = InStr(ReverseString(strInputString), "/") - 1

If InStr(ReverseString(strInputString), "/") <> 0 Then
    TruncatedFileName = Right(strInputString, PositionOfSubString)
Else:
    TruncatedFileName = strInputString
End If
End Function

Function ReverseString(strInputString) As String ' for any format of string
' *** FULLY WORKING FUNCTION ***
' This function simply returns the same string as strInputString,
' but with each character in reverse order within the string
Dim TotLength As Integer
Dim strTEMP As String
Dim i As Integer

TotLength = Len(strInputString)
strTEMP = ""
For i = 0 To (TotLength - 1)
    strTEMP = strTEMP & Mid(strInputString, (TotLength - i), 1)
Next i

ReverseString = strTEMP
End Function

Function NoExtFileName(strInputString)
'Returns the full path (if present) and file name WITHOUT the file extension
'note: the '-1' ensures that even the '.' is removed from file name
'If Len(strInputString) > 3 Then _

Dim TotLength
Dim PositionOfExtension

TotLength = Len(strInputString)
PositionOfExtension = InStr(ReverseString(strInputString), ".")
NoExtFileName = Left(strInputString, (TotLength - PositionOfExtension))
End Function
Figure Appendix G1: Main Sequence: Saccade amplitude versus peak saccade velocity for all horizontal data. Peak velocity increases linearly with amplitude for saccades less than 20° as depicted by the red trendline. Peak velocity increases logarithmically with amplitude for all saccade amplitudes as depicted by the black trendline.

Figure Appendix G2: Main Sequence: Saccade amplitude versus saccade duration for all horizontal data. Duration increases linearly with amplitude.
Figure Appendix G3: Saccade rate versus mean peak saccade velocity for all horizontal data. The spread of values is so great for each saccade rate (saccades per trial) that it is difficult to assess any relationship. This is reflected by the coefficient of determination ($r^2 = 0.002$) which suggests there is great variance and the linear trendline which is virtually flat.

Figure Appendix G4: Saccade rate versus mean peak saccade velocity for all horizontal data. The spread of values is so great for each saccade rate (saccades per second) that it is difficult to assess any relationship. This is reflected by the linear or logarithmic coefficient of determination (linear: $r^2 = 0.001$; logarithmic: $r^2 = 0.020$) again suggesting there is a huge amount of variance.
Figure Appendix G5: Main Sequence: Saccade amplitude versus peak saccade velocity for all vertical data. Peak velocity increases logarithmically with amplitude.

Figure Appendix G6: Main Sequence: Saccade amplitude versus saccade duration for all vertical data. Duration increases linearly with amplitude.
Figure Appendix G7: Saccade rate versus mean peak saccade velocity for all vertical data. The spread of values is so great for each saccade rate (saccades per trial) that it is difficult to assess any relationship. This is reflected by the coefficient of determination ($r^2 = 0.027$) which suggests there is great variance and the linear trendline which is virtually flat.

Figure Appendix G8: Saccade rate versus mean peak saccade velocity for all vertical data. The spread of values is so great for each saccade rate (saccades per second) that it is difficult to assess any relationship. This is reflected by the linear and logarithmic coefficient of determination (linear: $r^2 = 0.038$; logarithmic: $r^2 = 0.038$) again suggesting there is a huge amount of variance.
Figure Appendix G9: Horizontal Main Sequence: Saccade amplitude versus peak saccade velocity for footballers. Peak velocity increases logarithmically with amplitude for saccades in both elite (red data points) and non-elite footballers (blue data points). The trendline for elite footballers is slightly lower than non-elite footballers. The coefficient of determination for elite footballers is higher ($r^2 = 0.7757$, $n = 945$) than non-elite footballers ($r^2 = 0.6837$, $n = 1507$).

Figure Appendix G10: Horizontal Main Sequence: Saccade amplitude versus saccade duration for footballers. Duration increases linearly with amplitude for both elite (red data points) and non-elite footballers (blue data points). The coefficient of determination for elite footballers is higher ($r^2 = 0.871$, $n = 945$) than non-elite footballers ($r^2 = 0.7904$, $n = 1507$).
Figure Appendix G11: Vertical Main Sequence: Saccade amplitude versus peak saccade velocity for footballers. Peak velocity increases logarithmically with amplitude for saccades in both elite (red data points) and non-elite footballers (blue data points). Both the trendline and coefficient of determination for elite footballers ($r^2 = 0.731$, $n = 851$) is slightly lower than non-elite footballers ($r^2 = 0.7356$, $n = 1302$).

Figure Appendix G12: Vertical Main Sequence: Saccade amplitude versus saccade duration for footballers. Duration increases linearly with amplitude for both elite (red data points) and non-elite footballers (blue data points). The coefficient of determination for elite footballers is higher ($r^2 = 0.703$, $n = 851$) than non-elite footballers ($r^2 = 0.6774$, $n = 1302$).