A Study of Saccade Dynamics and Adaptation in Athletes and Non Athletes

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis including any required final revisions, as accepted by my examiners.

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Abstract

Purpose: The aim of the study was to delineate differences in saccade characteristics between a population of athletes and non athletes. Aspects specifically investigated were latency, accuracy, peak velocity, and gain adaptation of saccades using both increasing and decreasing paradigms.

Methods: A sample of 28 athletes (varsity badminton and squash players) and 18 non athletes (< 3 hour/week in sports) were studied. Eye movements were recorded at 120Hz using a video based eye tracker (ELMAR 2020). Each subject participated in 2 sessions on separate days. Baseline saccade responses to dot stimuli were measured in both sessions (stimulus size: 5-25 deg). The first session involved a gain decreasing paradigm, induced by displacing the stimulus backwards by 3 degrees from the initial target step (12 deg) for 500 trials. In the 2nd session a gain increase was induced by displacing the stimuli by 3 degrees in the forward direction. The latency and accuracy were calculated from the baseline. The asymptotic peak velocity was calculated from the main sequence (amplitude vs. peak velocity). The amplitude gains, calculated from the adaptation phase, were averaged for every 100 saccade responses. The averaged gains were normalized with respect to the baseline, fitted with a 3rd order polynomial, and differentiated to obtain the rate of change. Differences between the groups were compared using a regression analysis.

Results: There were no significant differences in latency, accuracy, and asymptotic peak velocity between athletes and non athletes. No significant differences were seen between the two groups in the magnitude of saccadic adaptation, both for decreasing (- 15% in both groups) and increasing (athletes + 7% and non athletes + 5%) paradigms. However, athletes showed a significantly faster rate of adaptation for the gain increasing paradigm ($F = 17.96[3,6]$; $p = 0.002$). A significant difference was not observed in the rate of adaptation for the gain decreasing adaptation ($F = 0.856[3,6]$; $p = 0.512$).

Conclusions: The study showed that the athletes do not respond better in terms of reaction time or accuracy of saccades. The significant difference in the rate of change of adaptation between the groups shows that online modification of saccades in the positive direction, although not greater in magnitude, occurs quicker in athletes than non athletes.

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Dedication

This thesis is dedicated to my loving parents and brothers whose constant support helped me in this endeavor.

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1 Introduction

1.1 Vision in Sports

Sports, in the course of civilization, have evolved to be a crucial part of our daily life style. Sports have achieved importance not only as recreational entertainment for amateurs but also as professional events involving huge economic funds and manpower. The Olympic Games, conducted once in every four years, are one of the many events which involve global participation. Strengths and weaknesses are proven by athletes in their respective fields during such major events. Researchers have given their inputs by studying human physiological systems under various domains such as sports sciences, sports medicine and biomedical engineering. Physiological and behavioral motor scientists have attempted to delineate how physiological systems work and how to maintain and improve the efficacy of these systems. Research in this field is usually quite difficult on account of the complexity of most sports tasks and the difficulty in replicating a field situation in a laboratory environment.

The development of a sport starts as "play", such as when a child is playing with a toy. Eventually, when two or more people take part and have a goal to achieve, it becomes a "game" and at a much more competitive level, the game becomes a "sport".[1] The development of skill in a sport is an ongoing process which is time dependant and requires human physiological systems to be functioning efficiently. Vision, proprioception, hearing, kinesthetic information and the manual motor apparatus all have their own role to play in sports, in time appropriate sequences.[2-8] The role designated for vision may vary from one sport to another. Vision is useful in gathering information from the environment and acts as the basis for the execution of appropriate motor tasks. Vision is a combination of sight and information processing. Images of objects of interest are acquired on the retina from the environment. Sensory commands pertaining to these images travel down the optic tract towards the brain where they are processed to give meaning to the task at hand.

Sports tasks such as catching a ball, returning a serve (as in tennis, badminton and squash) require short latency information processing of vision. On account of the requirement of rapid information processing in such tasks, sports are considered very demanding and complex with respect to vision.

Eye factors affecting sports performance have been studied since the 1930's.[9,10] With increased interest and ongoing research[11-16] in sports, there was a need for a new discipline to focus on diagnosing, prescribing and enhancing the visual skills of athletes. Accordingly, the American Optometric Association formed a Sports Vision Section in collaboration with the United States Olympic committee in 1978.

Many sport scientists have assumed that athletes have superior skills. The superiority in skills was attributed to the superiority of the physiological systems of the athletes.[17] The visual system was also found to be superior in a few studies.[18-20] Are athletes different in terms of their visual capacity? Aspects of vision such as acuity, depth perception, eye movements and contrast sensitivity are areas of study which will be reviewed.

1.1.1 Visual acuity:

Visual acuity is defined as the resolving power of the eye. It might appear logical to assume that visual acuity has considerable importance in sports performance. However, since many professional athletes with less than 6/6 visual acuity have performed well in sports, the effect of this aspect of vision on performance in sports has been brought to question.[11,13,14] Applegate[21] shows that decreases in visual acuity over the range of 6/6 to 6/75 resulting from defocus do not affect shooting performance in basketball. Screening studies of static visual acuity are found to be poorly correlated with sports performance.[12,22] Dynamic Visual Acuity (DVA) is visual acuity measured when there is relative motion between the subject and the test object. Since most sports involve motion of the object of interest, such as in baseball, basketball and badminton, dynamic visual acuity should have a greater impact on sports performance. The data of Beals et al.[12] and Morris and Kreighbaum[15] from samples of field shooters and basketball players, respectively, shows a correlation between DVA and sports. Rouse et al.[23] found a statistically significant difference in DVA between college baseball players and controls, with a difference of almost 13 deg/sec favoring the athletes. The studies by Ishigaki and Miyao[24] and Melcher and Lund[25] show similar results, with athletes having superior resolution at higher target velocities.

1.1.2 Contrast sensitivity:

Studies by Coffey and Reichow[26] and Hoffman et al.[27] found that athletes have higher contrast sensitivity than age matched controls, using Visitech charts and Arden grating plates respectively. However, Hitzeman and Beckerman[18] have questioned the validity of these results on methodological grounds. Laby et al.[28] show that athletes have superior contrast sensitivity when tested with contrast gratings using 3 and 6 cycles per degree (cpd). Their study used two eyes from the same subject as independent samples for statistical purposes, and hence the results obtained are questionable.

1.1.3 Visual fields:

Hobson[29] and Olson[30] have noted larger visual fields in athletes participating in basketball, baseball, football and rugby, compared to non athletes, as cited by Gregg[17] in his book on Vision and Sports. Berg and Killian[31] measured the size of the visual field using manual kinetic perimetry and found that female collegiate softball players have larger visual fields compared to female non athletes.

1.1.4 Depth perception:

Bannister and Blackburn[9] found lower stereoscopic thresholds in a group of Rugby players, compared to non athletes. When comparing major and minor league baseball players, Laby et al.[28] found significant differences in stereopsis using random dots and contour stimuli for both timing and distance factors. Olson[30], Montebello[32] and Ridini[33] also report lower stereoscopic thresholds when testing athletes, while Clark and Warren[10], Dickinson[34] and Shick[35] report the contrary. Regan[36] and Regan and Grey[37] report that estimating the time to collision with an object is an important factor in making judgments in ball games, in addition to stereopsis and depth perception.

1.1.5 Eye Movements:

Five basic types of eye movements have been described in the literature.[38] These eye movement types can be grouped into two major subsystems of the ocular motor system namely gaze shifting and gaze holding. Saccades are fast refixatory movements which are useful in scanning the visual scene, fixating from one object to another and reading text. Pursuit movements are used to track or follow the object of interest, primarily slowly moving objects. Saccade and pursuit movements are conjugate movements as the eyes move in the same direction. Vergence eye movements align the eyes so that both eyes fixate on an object. Vergence eye movements are disconjugate movements as the eyes move in opposite directions.

These eye movements comprise the gaze shifting mechanisms. Vestibulo-ocular reflex (VOR) eye movements compensate for head movements and help to stabilize the image motion of stationary objects due to the rotation or translation of the head or body. The Optokinetic system supplements the VOR in the case of full field image motion across the retina. The VOR and Optokinetic systems constitute the gaze holding machinery. All of these eye movements play a considerable role in sports performance.

1.2 Saccades

Saccades are the fastest eye movements generated by the human ocular motor system. The eyes are anatomically placed in the primary or straight ahead position in the orbit, and with the appearance of visual stimulus the eyes move to a new position. The presence of the fovea on the primate retina necessitates the need for these movements so as to appropriately place images on or near this region of highest acuity. Saccades include (a) changes of fixation which help to redirect the gaze from one point to another, (b) rapid eye movements (REM) occurring during sleep, and (c) the quick phases of optokinetic nystagmus. Included in (a) are both voluntary and reflexive saccades. Voluntary saccades are saccades made as part of purposeful behavior. Reflexive saccades are saccades made to novel stimulus which occur unexpectedly in the environment. My discussion will be focusing on voluntary and reflexive saccades.

1.2.1 Characteristics of saccades

Saccades made to visible targets are usually generated by the ocular motor system within approximately 200 milliseconds. The time taken to generate a saccadic response following the start of stimulus is referred to as the saccadic latency (Figure 1a). The time taken from eye movement initiation to the completion is called the duration of the saccade. The duration of the saccade is linearly correlated with the size of saccade.

Saccadic accuracy refers to the correctness of the saccadic response. An accurate saccade occurs when the eye moves from an initial starting position towards the target and stops exactly at the target. Such saccades are known as normometric saccades. Saccadic accuracy is usually measured in terms of saccadic gain which is the ratio of the size of saccade to the size of stimulus (Figure 1b). Saccades which undershoot the final target position are referred to as hypometric saccades. Saccades which overshoot the final target position are referred to as hypermetric saccades.

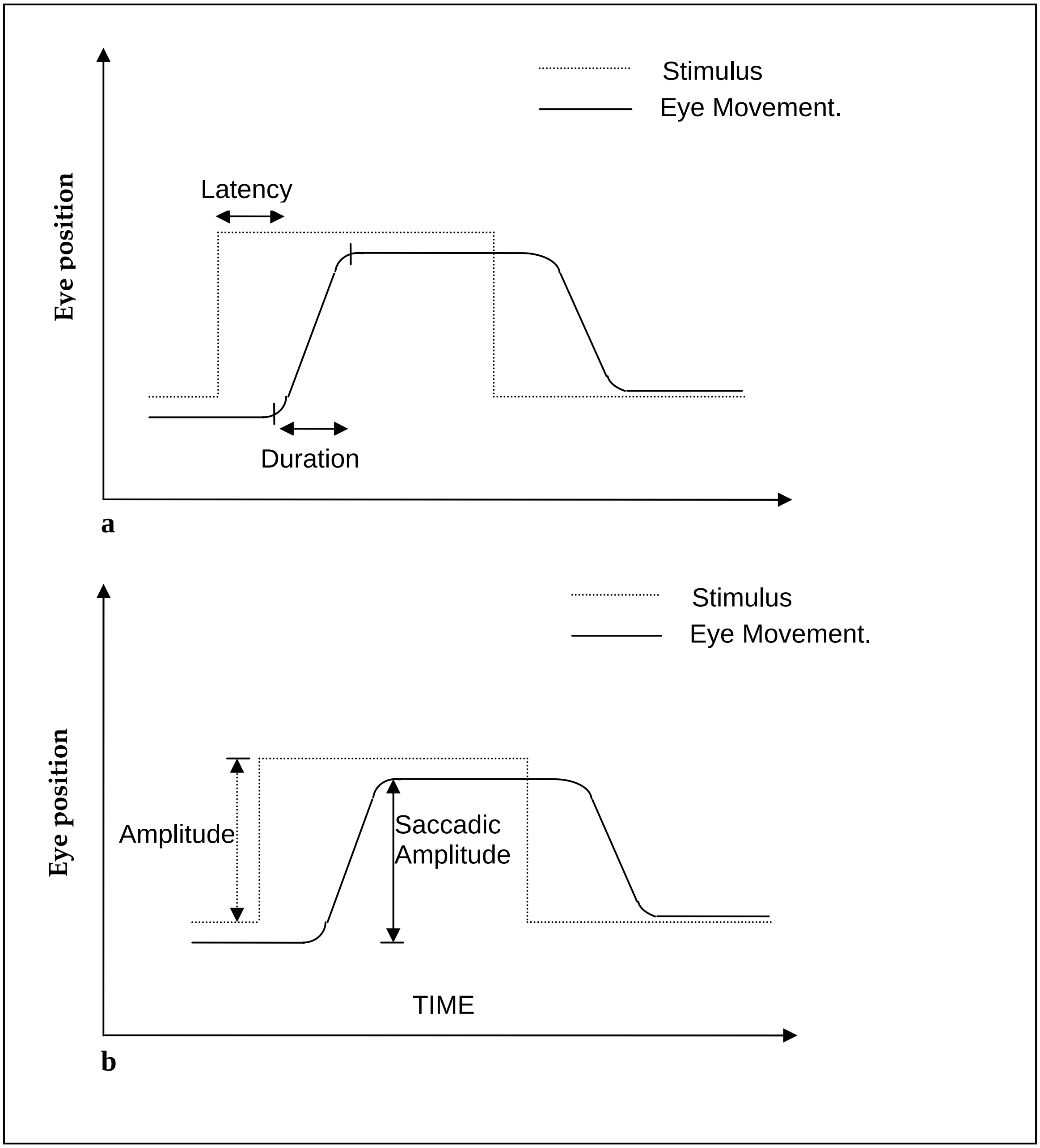

Figure 1. The figure on the top (a) depicts the latency and duration of a saccade response to a stimulus. The figure at the bottom (b) depicts the accuracy of the saccade response; the amplitudes of the saccade and the stimulus are shown.

$$Latency = Start\ time\ of\ \ saccade - Start\ time\ of\ \ stimulus$$

$$Gain = \frac{Saccade\ \ Amplitude}{Stimulus\ \ Amplitude}$$

1.2.1.1 Amplitude/Peak velocity relationship

Saccadic velocity varies as a function of saccadic amplitude. For ranges of amplitudes up to 15 degrees, the relationship between amplitude and peak velocity appears linear. However, for larger amplitudes the peak velocity saturates. The overall relationship is best described by the exponential equation

Vp = Vpmax * [1- exp (K *A)] as suggested by Bahill et al.[38]

Vp is the peak velocity. Vpmax is the asymptotic peak velocity. A refers to the amplitude and K is a constant, equal to the slope at the origin (Figure 2).

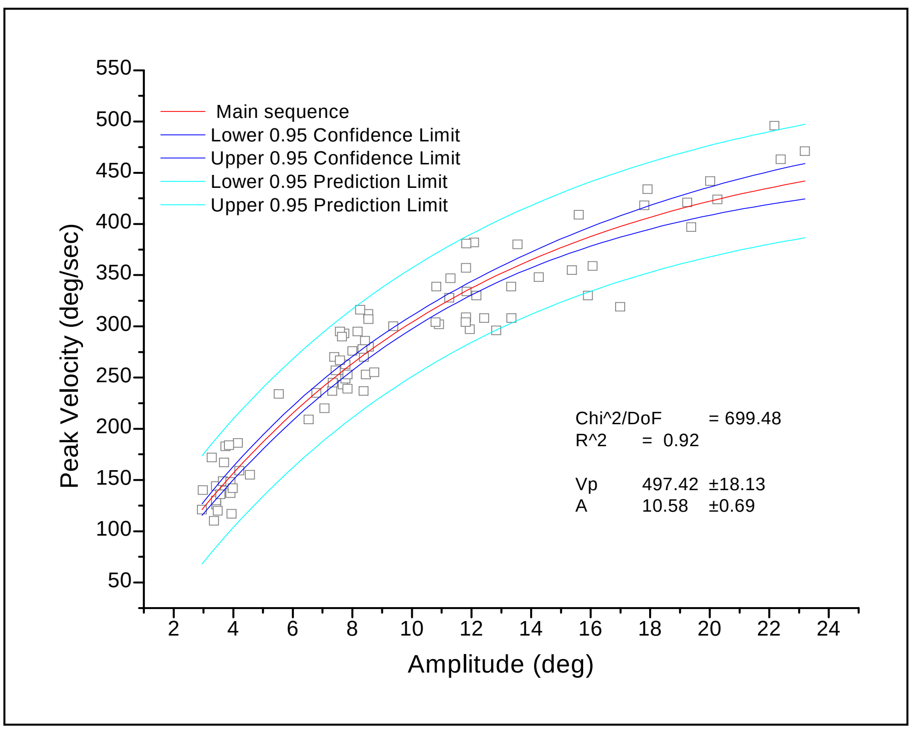

Figure 2: Example of a main sequence: Plot of peak velocity versus amplitude. Data points in the figure are saccades from both eyes of one subject (WS). The plot shows the curve of the equation Vp = Vpmax * [1- exp (K*A)], Vp is the peak velocity, Vpmax is the asymptotic peak velocity, A is the amplitude and K is the slope at the origin.
Also plotted are the 95 % confidence and prediction bands.

This is called the main sequence. The time to reach the peak velocity varies as a function of the amplitude. This is best described by a skewness ratio which refers to the time taken to reach peak velocity divided by the total duration. The skewness ratio is approximately 0.5 for small saccades and 0.2 for larger saccades.

1.2.2 Ballistic nature of saccades

The saccadic system is very fast, with brief responses that lead one to think that the system is ballistic in nature. Westheimer's[39] experiments on saccades led to proposals of sampled data system wherein preprogrammed responses are generated based on initial information. Further research shows that saccades can be modified in mid-flight such as in the case of an oblique saccade, generated when two stimuli are presented in different directions on the same plane.[40] This suggests that feed back mechanisms help to vary characteristics such as latency, accuracy and the peak velocity of saccades.

1.2.3 Neurophysiology of saccades

Sensory information about target location, target size and color etc., reaches the visual cortex from the retina via neurons that stimulate specific regions. This is referred to as place coded information, as specific neurons correspond to particular sensory stimuli. The sensory information is transferred to the motor network, which generate appropriate movement, based on the frequency and duration of neuronal discharge. This is referred to as temporal coding.[41] The neural generation of saccades involves transformation of place coded retinal information to temporally coded motor information. The amplitude of saccadic movement depends on the discharge frequency and duration from the ocular motoneurons.[42]

At the final level, a burst or pulse innervation is produced in the ocular motoneurons (IIIrd, IVth and VIth nerves). This phasic pulse creates enough force to overcome the orbital viscous drag, and hence moves the eye to a new position. Following this, innervation of the ocular motoneurons and associated agonistic extra ocular muscles changes to a new tonic level. This change in tonic level, called the step, helps to hold the eye at the new position against elastic orbital forces. The transition between pulse and step is not abrupt, but rather a slow process, hence called a glide. These innervational changes thus make the saccade an outcome of pulse-glide-step.[43,44]

The horizontal components of saccades originate in the pons and the medulla. The excitory burst cells (EBN) present in the posterior pontine reticular formation (PPRF) project to the ipsilateral motoneurons and generate the neuronal phasic pulse. The inhibitory burst neurons (IBN) in this site connect monosynaptically to the contralateral motoneurons, which project to the antagonistic muscles. Neurons in the prepositus hypoglossus (PPH) and the vestibular nuclei generate the step resulting in tonic elevation. These neurons are responsible for gaze holding and act as the neural integrator. The EBN and IBN are active only during the saccade. During fixation they are deactivated by the omnipause neurons in the pontine nucleus raphe interpositus which discharge continuously, except during a saccade.[43,44]

Connections higher up in the brain, such as in the superior colliculus (SC), provide input to the pontine and midbrain regions. The SC consists of dorsal and ventral layers. The dorsal layers are functionally sensory in nature. The ventral parts of the SC are functionally motor. The SC has a rostral fixation zone which has connections with the pontine omnipause neurons. Larger amplitude saccades originate near the caudal region and smaller amplitude saccades originate nearer to the rostral fixation zone. The SC has isoamplitude (saccades of same size) lines running medial to lateral and isodirectional (saccades of same direction) lines running anterior to posterior. Stimulation along these lines produces saccades of specific size and direction in an all or none fashion. Saccades with upward components occur with more medial stimulation and saccades with downward components occur with more lateral stimulation. The SC is deemed responsible for saccade initiation and direction.[45] The SC is also suggested to have a role in transformation of place to motor maps.[46,47]

The cerebellum has an important role in governing the accuracy of the saccade. The fastigial nucleus of the cerebellum has connections with the EBN and IBN of the pontine reticular formation and the dorsal vermis of the cerebellum. The discharge activity of the neurons in these sites progresses with the saccade and stop during saccade landing. The peak frequency and duration of the discharges of these neurons are altered to maintain accuracy.[48] In this way the accuracy of saccades is governed by the cerebellum. A spread of neuronal discharge during the saccade across the fastigial nucleus suggests that this portion is also responsible for the transformation of place to motor maps.[49]

The cortex, mainly the frontal eye fields, supplementary eye fields, dorsolateral prefrontal cortex and posterior parietal cortex have connections either directly or indirectly via the superior colliculus and cerebellum to the brain stem saccade generator (posterior pontine reticular formation). [44,50,51]

1.3 Saccadic Adaptation

The accuracy of saccades is maintained continuously either by feed back mechanisms operating with each saccade generation or by a calibrative mechanism. The short duration and rapidity of saccades make online correction of saccadic accuracy difficult. The presence of a calibration system helps to maintain the accuracy by altering the system parameters accordingly. These mechanisms[52-59] have been known to exist for almost half a century[60,61]. Kommerrell et al.[60] reports that in patients with abducens nerve palsy, saccades which are initially hypometric in the paretic eye become normal. Occlusion of the non paretic eye causes altered signals to reach the ocular motor system. The altered signals require the system to recalibrate in order to produce an appropriate motor response. The recalibrated system has normometric saccades in the paretic eye and overshooting saccades in the non paretic eye. Experiments to study adaptation have also been conducted on animals. Surgically weakening or tenectomising the extra ocular muscle[54,58,62,63] initially leads to saccades that undershoot the desired target position, but within a few days, the saccades become normometric. In these experiments, adaptation of the saccades takes from a few days to a couple of weeks. This mode of adaptation is referred to as "Long term saccadic adaptation".

An alternative experimental paradigm, to study the adaptation of saccades, has been devised by McLaughlin[61]. In the laboratory, saccades are usually produced as a response to step displacements of the target. When two successive step stimuli are provided as a stimulus for saccades they are referred to as "double step stimuli".[39] McLaughlin[61] altered this paradigm so that the second step occurs during the course of the eye movement and by an amount which cannot be perceived by the visual system. Since the final or second target position is altered, either in the same direction as the saccade or in the opposite direction, an error signal is generated resulting in a final outcome of dysmetria (inaccurate saccade). These error signals, if consistent, lead to adaptation. Of further concern is whether the adaptation is an outcome of gain change or a sensory remapping. If the adaptation is due to sensory remapping, the adapted saccades will have the same dynamics as a normal saccade of similar amplitude. A change in force magnitudes, between the normal and adapted saccades, suggests that adaptation is not the result of sensory remapping.[64] Three paradigms, devised to change the gain of the saccadic system by producing positional error, are outlined below.

1.3.1 Gain decreasing paradigm

To decrease the gain of saccades, the position of the final target stimulus has to be moved back by an adequate magnitude (i.e. opposite to the direction of the progressed saccade). This change in the final target position, after the start of eye movement, causes the progressed saccade to overshoot, and hence to maintain accuracy, the gain of the system is decreased. Recalibration of gain is achieved in humans by providing repeated error signals in saccades. The number of saccades required range from 5 to 200. In monkeys, usually 500 saccades or more are required for recalibration.[52,65-67]

1.3.2 Gain increasing paradigm

To increase the gain of saccades, the position of the final target stimulus has to be moved forward by an adequate magnitude (i.e. in the direction of the progressed saccade). This change in the final target position, after the start of eye movement, causes the progressed saccade to undershoot, and hence, to maintain accuracy, the gain of the system is increased. Similar to the gain decreasing paradigm, repeated error signals are required to achieve recalibration of gain. A higher number of saccades are required to achieve recalibration by this paradigm, than in the gain decreasing paradigm, for both humans and monkeys. [52,65,68]

The above mentioned methods are referred to as conventional adaptation in the literature.

1.3.3 Deubel paradigm

This is a variation of the gain increasing and decreasing paradigms.[52,56] In this method the final target position of the first target step is the starting position for the next saccade. This method allows adaptation to preclude position specific learning.

Saccadic adaptation experiments reveal that there is a higher adaptive change when the system is provided with a negative positional error (gain decreasing paradigm) than a positive positional error (gain increasing paradigm).[52,67,68] The inability of the ocular motor system to tolerate an overshooting of the target could be the reason for this difference in the adaptive mechanism. This could be because the system will have to produce a corrective saccade in the opposite direction if an overshoot has to be corrected.[69,70] In normal circumstances the eye tends to undershoot the target position.[71]

Studies dealing with the specificity and transfer of adapted saccades have shown that adapted saccades are direction and amplitude specific. This means that, if a single rightward saccade is adapted it transfers fully to only that particular size saccade, in the same direction.[52,65,72] This is called vector specific adaptation. Eye position signals originating from different vertical positions result in similar amounts of adaptation, which indicates that irrespective of different orbital positions, saccades of the same vector adapt similarly.[73,74]

Error signals cueing saccadic adaptation are suggested to be the result of error at the end of each saccade.[55,75] The retinal error after a saccade is produced seems to trigger the process of saccadic adaptation. Corrective saccades are saccades which correct the error following inaccurate saccades. These corrective saccades were thought to provide signals to regulate the adaptation process.[69,70] Noto and Robinson[55] and Wallman and Fuchs[75] evaluated this concept, by using a paradigm which eliminates corrective saccades, and found that adaptation occurs in spite of the absence of corrective saccades. The amount of adaptation achieved is similar to the adaptation achieved using a conventional method. These results suggest that visual error, which is the difference in eye position from the fovea following a saccade, can be thought of as the signal that drives the saccadic adaptation process.

1.4 Role of eye movements in various sporting tasks

Researchers in the field of sports have given considerable attention to the role of eye movements in sports. Tasks such as tracking a ball, visual search strategies, fixation and gaze allocation in game situations and anticipatory cue usage have been looked at. The studies encompass sports such as baseball (tracking and fixation allocation)[76-78], cricket (tracking)[79,80], table tennis (fixation allocation and gaze stabilization)[81], tennis (search strategy and anticipatory cue usage)[82], squash (anticipatory cue usage)[83-86], boxing (fixation allocation)[87], golf (gaze allocation)[88,89] and basketball (gaze allocation in basketball shooting)[90-92]. Some of these studies are able to delineate expert/novice differences.[93] The visual system utilizes techniques that maximize efficiency in game situations. For example, Kato and Fukida[78], in their analysis of visual search strategies used in baseball batting, found that expert batters fixate on a small localized area on the pitchers bowling arm where as the novices have a widespread area of fixation. The duration of fixation was also seen to be longer for experts than novices.

1.5 Eye movement parameters in athletes: Are they different? A review of the literature

A series of sports vision tests are used to evaluate the performance of athletes in visuo-motor tasks.[22] The motility of the eye, specifically saccades at distant targets, is tested by using the King Devick Demonstration and Test II form transparencies. The form contains numbers, lines and arrows. For the purpose of testing saccadic eye movements, the lines and arrows are eliminated. Forms are projected to a distance of 10 feet, using an overhead projector. The subjects are asked to read out the numbers from top left to right bottom as quickly and accurately as possible and the time taken are recorded to 1/10 of a second, using a stop watch. Christenson and Winkelstein[22] in their comparison of the mean scores for athletes and non athletes (sample of 54 athletes and 54 non athletes) show statistically significant differences in saccadic eye movement speed, with athletes being faster than non athletes. This type of testing has disadvantages such as the lack of non random positioning of the stimulus, the use of verbalization for testing eye movements and a greater chance of familiarity. The greatest drawback is that the majority of the recorded time is spent fixating and not making saccades. Hence, when both the saccades and fixations are combined as a single unit of measurement it is difficult to say whether the saccade is faster or the fixation durations are shorter. The athletes' better test performance, could well have been due to their having shorter fixation durations rather than "faster saccades".

A study by Williams and Helfrich[94], investigating whether the speed of eye movements is related to batting scores in baseball, shows that subjects with greater saccadic eye movement speed have better batting scores. Saccadic eye movement speed is estimated using a Reading Eye II test in this study. The requirements of the test are to move the eyes quickly between two dots that are 4 inches apart. The average number of saccadic eye movements in two 10 sec periods is recorded electronically. It should be noted that even though pursuit is usually analyzed in baseball studies, in this case they analyzed saccades, based on the notion that at speeds greater than 40 degrees per second it is saccades that are required for information pick up. A one way ANOVA indicates a significant difference between fast, moderate and slow eye movement groups. In this study the measurement is a combination of saccades and fixations. Since the total time is the only measurement, it is impossible to separate the saccades and fixations.

Comparison of ocular motilities and batting averages in thirty six Little Leaguers aged 10 to 12 show a significant correlation (+ 0.44;$p < 0.01$) between saccade quality and batting averages.[95] Saccade and pursuit quality in this study have been estimated subjectively and scaled.

Griffiths[96] uses a new method for testing eye movement speed. The test is known as Dynamic fixation. Subjects are required to change fixation from a card at 1m to a near card at 20 cm and read out the letters on both the cards, in a specified pattern, as fast as they can. The cards are positioned in such a way that subjects can see the distant letters through the middle of the near card. The letters are arranged in a circular pattern on the cards. The subjects start from the top letter on the near card.

The group that Griffiths[96] used in his study are athletes who took part in dynamic sports (track and field athletes) and archers in the same age group. His findings show that track and field athletes perform fastest on the test, and their eye movement speeds are significantly different from those of the archers. The differences observed between the groups might be due to the fact that archers consistently fixate on the centre of the target whereas track and field athletes are used to sudden changes in target location in the environment. The differences observed between the groups point to the environmental influences in generating physiological responses.

A study by Hughes et al.[97] compares the saccadic latencies of expert, intermediate and novice table tennis players (total sample of 83 subjects) using a two channel projection tachistoscope. The stimulus presentation onset is hand triggered by the subject. The mean saccadic latencies are 208 msec, 209 msec and 221 msec for the expert, intermediate and novice table tennis players respectively. No statistical differences are found between the groups. Since, the stimulus presentation is non random (always 15 degrees to the right or left) and hand triggered, it generates certain amount of premotor organization.

In a recent study Lenoir et al.[98], compares the performance of athletes and controls in both prosaccade and antisaccade tasks. The study aims to investigate the latency of these eye movements. The sample includes 18 athletes and 20 controls and eye movements are recorded using an infra-red oculographic technique (250 Hz sampling). Upon comparison, no significant difference in latency is seen in the prosaccade (saccade made in the direction of the stimulus) task. A significant difference is seen in the latency of antisaccades (saccade elicited in a direction opposite to that of the stimulus) between athletes and non athletes. The athletes show shorter antisaccade latencies than non athletes. These differences in latency are attributed to cognitive learning, similar to that used in sporting situations (suppression of reflex saccades towards opponents' movements), leading to improved reaction times for athletes in generating antisaccades. Moreover, the variability of the latency for both the prosaccades and antisaccades are lower in the athletes showing an increase in consistency with skill acquisition. It should be noted that the overall latencies of the prosaccades are also shorter for the sports group though not statistically significant. No comparisons of saccadic accuracy have been made in this study.

A review of literature in sports sciences shows that adequate measures of eye movement dynamics have not been obtained in athletes, specifically for saccades. Most of the data from studies of athletes' eye movement performance are from screening situations that lack critical information about the dynamic aspects of saccades. For example, Lenoir et al.[98] have been able to measure eye movements accurately but they only looked at the latency of the responses. Hence, this research is formulated to investigate the dynamic properties of saccades in athletes in comparison to a non athlete group. In addition to the baseline parameters of eye movements, a study of the adaptive properties of saccades between athletes and non athletes would help to understand the differences in their responses to online visual error (error generated during the course of an eye movement).

2 Purpose of this Research

Saccade dynamics have been effectively studied in both humans and monkeys and properties of the saccadic system are quite well known. The environmental effects on the saccadic system are not yet clear. There is a paucity of data as to whether athletes differ from non athletes in the dynamic aspects of saccades. Hence, the purpose of my research was to investigate the differences in the dynamic properties of saccades (latency, accuracy and peak velocity) between athletes and non athletes. I also studied parameters of saccadic adaptation (magnitude and rate of change) during gain increasing (positive visual error) and gain decreasing paradigms (negative visual error) between athletes and non athletes. This research provides valuable information as to how environmental influences, in this case participation in sports, affect the dynamic properties of saccades.

3 Methods

3.1 ELMAR Eye tracker: Model 2020 - binocular system

The apparatus used to measure eye movements was a video based eye tracking system. The system includes a light weight headset (200 grams), which is adjustable to fit comfortably on the participant's head. Infra red light emitting diodes (LED's) located on the head set illuminate each eye. The irradiance is less than 0.5MW/cm^2. The light from the LED's is reflected by a "hot mirror" to the subject's eye, back to the hot mirror, to the mirrors on the headset, and finally captured by CCD cameras which are located on the head set. The system uses corneal reflection (first order Purkinje images from the anterior surface of the cornea) and dark pupil tracking (Figure 3). The relative distance from the pupil center to the nearest corneal reflection is used to calculate the degrees of eye rotation.

The system records both horizontal and vertical eye movements binocularly with a resolution of ± 0.1 deg for a linear range of at least ± 30 deg in the horizontal, and at least ± 25 deg in the vertical meridian. The system samples at a frequency of 120Hz, providing an eye position signal every 8 msec. DiScenna et al.[99] compared the ELMAR eye tracker with the Magnetic search coil (most reliable method of eye tracking)[100-102] and found the video eye tracker (ELMAR) to be robust in measuring eye movements and to have a reasonable resolution and sampling rate.

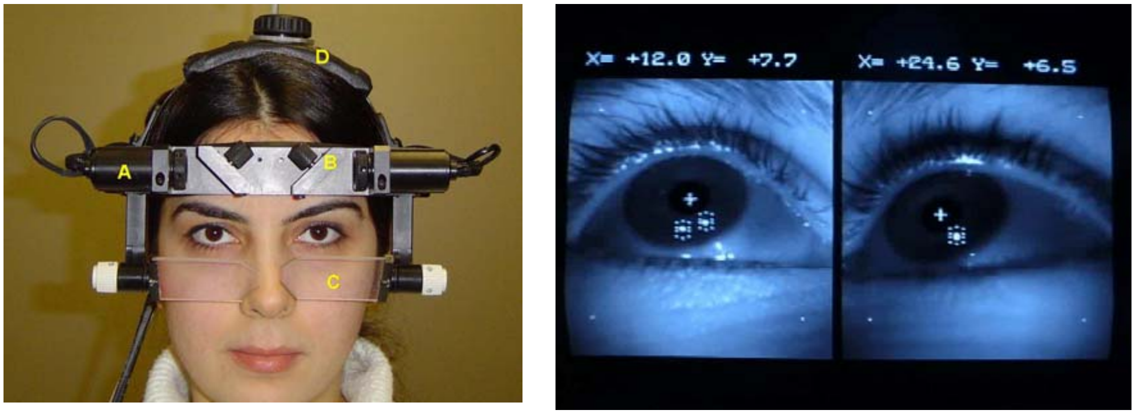

Figure 3. Photograph on the left shows a subject wearing the binocular ELMAR eye tracker. The parts of the eye tracker seen are; "A": CCD camera, "B": mirrors, "C": hot mirror that reflects infra red light, "D": adjustable head set. On the left is a picture showing the pupillary marker (cross) and the Purkinje images (square grids) on the cornea.

The ELMAR eye tracker also includes a stimulus generator, a monitor which displays eye position, and an analysis system. The information from the video, generated from the CCD cameras, is digitized and converted to eye position (deg) as a function of time.

3.2 Stimulus generation

The stimulus was generated using software provided by the manufacturer of the ELMAR eye tracker. To provide a single step stimulus for generating a saccade, two spatial positions were required. By specifying each spatial position and the duration at each position, adequate saccade stimuli were generated. The stimuli were projected on to a screen or monitor as small white squares on a black background. Sequences of random spatial positions were specified to provide adequate saccade stimuli as per the task. In our experiments we generated only horizontal saccadic stimuli.

3.2.1 Baseline saccade stimuli

The stimulus for saccade generation was a small square target. A series of random positions within a range of ± 13 degrees, were presented with unpredictable timing (i.e. duration in each position between 1 to 1.5 seconds) and separated by 5 deg, 10 deg, 15 deg, 20 deg or 25 deg. A total of 45 random saccadic stimuli were generated by this method. The stimulus included approximately equal numbers of leftward and rightward saccades.

3.2.2 Baseline adaptation saccade stimuli

The stimuli used for determining the baseline adaptation were also small square targets. The spatial positions were specified such that all rightward saccade stimuli were of the same amplitude, 12 degrees. Following this stimulus presentation, the stimulus was set to move to any random spatial position. This spatial location served as the starting position for the next 12 degree rightward saccade. The targets were set to appear for a duration of 1 to 1.5 seconds. The horizontal range was limited to ± 13 degrees. A total of 100 saccade stimuli were generated within this range.

3.2.3 Adaptation phase stimuli

Stimuli in the adaptation phase were similar to the baseline adaptation stimuli. All the rightward stimuli were 12 degrees originating from random positions. An intrasaccadic target jump of 3 degrees occurred once the eye movement reached a velocity of + 40 deg/sec. This jump occurred only for rightward saccades. The magnitude of the target jump was determined empirically (Appendix One). A total of 500 saccades were generated, separated into 5 equal blocks of 100. The intra-saccade jump specification was different for the gain increasing and the gain decreasing paradigms. For the gain increasing paradigm the target jump of 3 degree was in the same direction as the progressed saccade (positive visual error). This makes the total amplitudes 15 degrees for rightward saccades during the adaptation phase. For the gain decreasing paradigm the intra saccadic target jump was in the direction opposite to that of the progressed saccade (i.e. to the left and hence negative visual error). This makes the total amplitude 9 degrees during the adaptation phase (Figure 4).

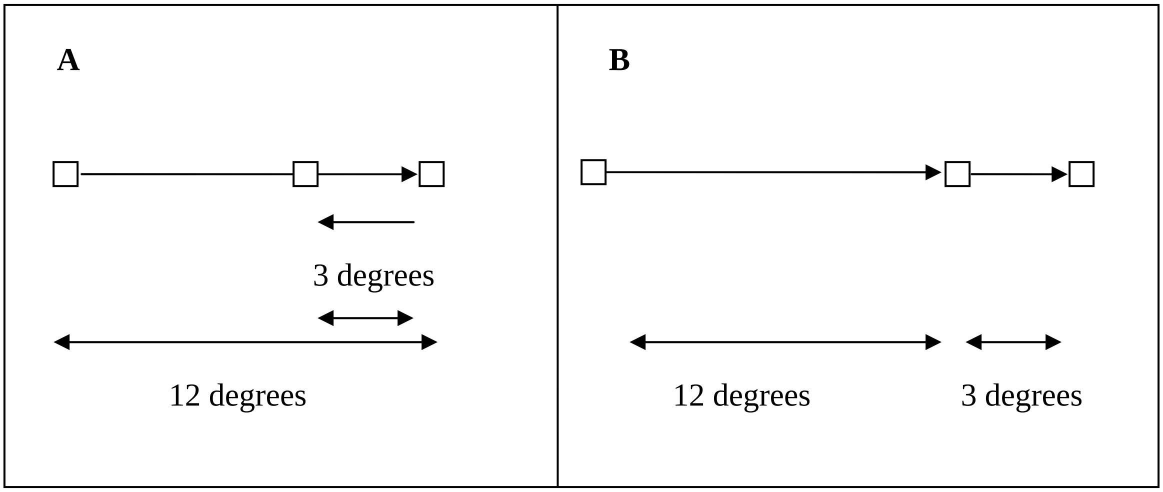

Figure 4. The squares represent the dot stimuli. The directions of the single head arrows represent the direction of movement of the targets in the adaptation phases. The intrasaccadic jump occurs once the eye movement reaches a velocity of + 40 deg/sec. A) schematic of the gain decreasing paradigm B) schematic of gain increasing paradigm.

3.2.4 Recovery adaptation stimuli

Stimuli in the recovery adaptation trial were the same as the baseline adaptation stimuli. A total of 100 saccades were generated.

3.2.5 Recovery saccade stimuli

The stimuli were the same as those for the baseline saccade stimuli.

3.3 Design of the study

The sample to be studied included a population of athletes (N = 28) and non athletes (N = 18). Each subject was required to take part in two sessions on separate days. These sessions were separated by one week. Each session took approximately 40 to 50 minutes. The researchers were not masked at any point in the study. It is impossible to judge the outcome of the study from raw eye movement data measures at any stage in the study.

The study involved human participants and hence approval for the study was obtained from the Office of Research Ethics at the University of Waterloo. Informed consent was obtained from all the participants. An honorarium of $40 was paid to the participants.

3.3.1 Subject recruitment

The participants were recruited by means of posters distributed within the university. Coaches of the university varsity badminton team were contacted and asked to inform team members about the study.

3.3.1.1 Inclusion criteria for athlete group

- Athletes belonging to varsity badminton and squash team were recruited based on the following criterion.
- Age range: 18 to 30 years
- Must have been on the varsity team for more than a year.
- Should have played the sport for a minimum of 5 years.
- Should take part in the sport for more than 6 hours per week.

3.3.1.2 Inclusion criteria for the non athlete group

- Age range: 18 to 30 years

- Should not have participated in racquet sport at any professional or varsity level.
- Other recreational sport for less than 3 hours per week.

3.3.1.3 Exclusion criteria

- Ocular deviation or any known binocular vision anomaly that may disrupt binocular viewing.
- Distance refractive error of greater than ± 5.00 Diopters.
- Ocular health anomalies.

3.4 The experiment

The subjects were seated on a chair, wearing the headset, so that it fitted comfortably on the head. The monitor (height of viewable area was 30 cms and width was 40 cms) on which the stimulus was projected, was placed at a distance of 85 cms in front of the subject. Accurate stimulus projection on the monitor was confirmed by the experimenter before each session by measuring the length of a known stimulus size projection. Moreover, the monitor was positioned such that the centre of the screen and subjects' midline (the centre between the two eyes) were aligned.

3.4.1 Calibration procedure

Following this initial procedure, the instrument was calibrated. The light levels of the LED's were adjusted so that the pupillary marker and the two corneal reflections were seen clearly on the video monitor. These adjustments were made by adjusting the hot mirrors, the mirrors and the focusing knob on the CCD cameras (Figure 3). The calibration procedure required the subject to look at small squares which appeared at 7 positions across a ± 10 degree range along both the horizontal and vertical meridians. The fixation targets appeared at known positions (equal distances apart) and the corresponding change in distance between the pupillary marker and corneal reflexes for every change in fixation was used to calibrate the instrument. During the calibration procedure the video monitor also showed the changing positions of the reflections and marker and the experimenter noted any unusual changes in the tracking.

3.4.2 Session one

The session included 9 trials of recorded eye movements. Participants were instructed to look at the small square target and only move their eyes, without moving the head.

1) Baseline saccade trial:

The participants were asked to respond to baseline saccade stimuli by following the jumping targets. The random positions of the targets and the unpredictable timing of the jumps helped to reduce anticipatory responses. The saccades originated from random positions and had amplitudes ranging from 5 to 25 degrees.

2) Baseline adaptation trial:

The instructions were the same as those for the baseline saccade trials; to follow the square targets as they came up on the screen, without moving their head. All the saccades had a rightward saccadic amplitude of 12 degrees, originating from random starting positions.

3) Adaptation phase - Gain decreasing paradigm:

Following the baseline trial the adaptation phase trials took place. There were five trials with 100 saccade stimuli in each. Each trial lasted 2 minutes. The break between each trial did not last more than 10 seconds. During the break, participants were asked to keep their eyes closed. In this paradigm, the saccades had a characteristic intrasaccadic jump of 3 degrees *opposite to the direction of the saccade*. The intrasaccadic jump occur once the velocity of the response eye movement reached + 40 deg/sec. The subjects were unable to notice the jump since it occurred during the eye movement. The trials in this phase lasted for a total of 10 minutes. During the entire adaptation phase, the room was kept completely dark to eliminate other visual cues and to avoid distractions. Verbal encouragements to keep at the task were given during the breaks between the trials.

4) Recovery adaptation trial:

Participants were asked to respond to the recovery adaptation stimuli which were the same as the baseline adaptation stimuli, hence did not have intrasaccadic jumps.

All the saccades had a rightward saccadic amplitude of 12 degrees, originating from random starting positions.

5) Recovery saccade trial:

The recovery saccade stimuli were the same as the baseline saccade stimuli. The saccades originated from random positions and had amplitudes ranging from 5 to 25 degrees.

3.4.3 Session two

In order to control for the transfer of adaptation effects from session one (gain decreasing paradigm), session two was conducted one week after the first session. Session two was similar to session one with respect to order and number of trials (Figure 5). However, the adaptation phase was different. In session two, the adaptation phase had a gain increasing adaptation paradigm. In this paradigm the intrasaccadic jump of 3 degrees was *in the direction* of the saccade. Figure 5 shows the order of trials in sessions one and two.

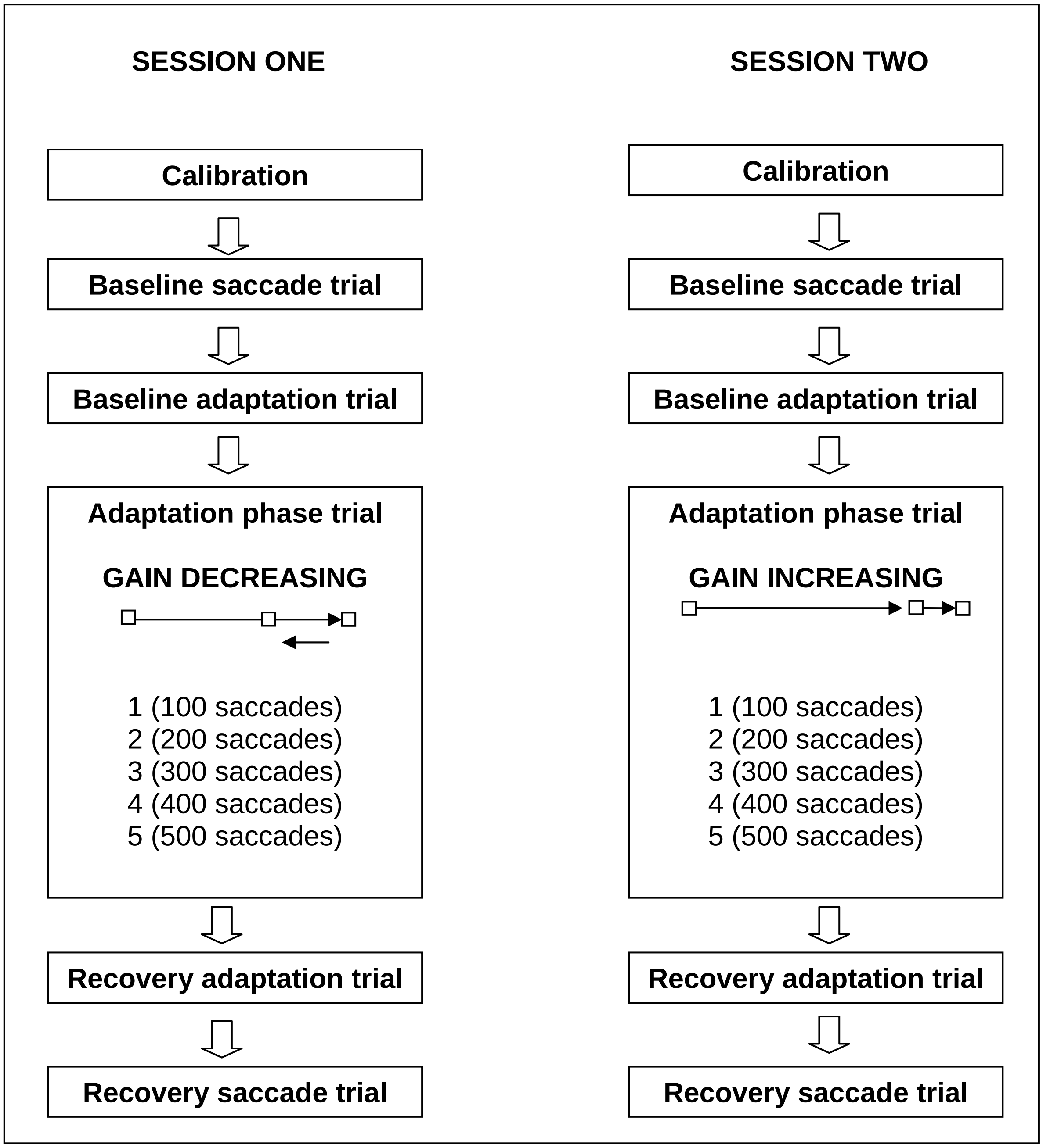

Figure 5. : The flow chart shows the progression of trials during the two experimental sessions. The adaptation phase trials are different in the sessions with respect to the gain decreasing and increasing paradigm. The gain decreasing paradigm had an intrasaccadic jump (following the start of eye movement) in the direction opposite to movement of the saccade. In the gain increasing paradigm, the intra saccadic jump was in the direction of the saccade.

3.5 Data analysis

The eye movement data obtained from the trials were analyzed using custom software ANALYZE II, operated on a Macintosh platform. Before analyzing the data, the stimulus characteristic such as the distance projected (85 cms), screen width (40 cms), and screen height (30 cms) were specified in the software. The data were plotted separately for each eye (Rxp corresponding to right eye position and Lxp for the left eye position). The data were plotted as a graph with eye position on the Y axis, and time on the X axis. The stimulus positions were also plotted along with the eye position data. By inspecting the eye position and stimulus position trace the experimenter removed unwanted eye movements such as those occurring before stimulus onset (anticipatory saccades), late onset saccades (presumably due to attention distractions) and saccades not in the direction of the stimulus. Saccades were detected from eye position signals using a velocity detection criterion. Primary saccades (first saccade with target velocities greater than 40 deg/sec) were marked. Data from both the eyes were marked separately and collapsed together because in the case of conjugate movements (both eyes moving in the same direction), the difference in saccade dynamics is minimal. Some saccades were not recorded accurately by the instrument; these judgments were made by looking at the velocity profile and were deleted accordingly. The start time, end time, duration, amplitude, and peak velocity were outputted from the marked saccades onto a spread sheet and were used for further analysis.

3.5.1 Latency

The time it takes for the initiation of eye movement following the start of the stimulus is the latency. This was calculated by taking the difference between the start of the eye movement and the start of the stimulus.

Latency (msec) = Start of Eye movement (msec) – Start of Stimulus (msec).

The latency information was obtained from the baseline saccade trials and recovery saccade trials in both sessions. The saccades which had latencies above and below two standard deviations of the mean were eliminated as outliers. This usually corresponded to values of less than 100 msec and greater than 400 msec. The latency was compared between athletes and non athletes using a two sample independent t test.

3.5.2 Baseline gain of saccades

The gain refers to the accuracy of the saccades. This was calculated as Eye movement amplitude/Stimulus amplitude. The gains for all amplitudes, in the baseline saccade trial, were averaged for each subject. The saccades which had gains above and below two standard deviations of the mean were eliminated as outliers.

The saccadic gains were then compared between athletes and non athletes using a two sample independent t test.

3.5.3 Main sequence - Amplitude/Peak velocity relationship

The main sequence was plotted for the baseline saccade trial and recovery saccade trial for each subject. The saccadic peak velocity was plotted as a function of amplitude and fitted with an exponential curve $Vp = Vpmax * [1- \exp (K *A)]$.

Vp is the peak velocity. Vpmax is the asymptotic peak velocity. A refers to the amplitude and K is a constant, equal to the slope at the origin. The asymptotic peak velocity (Y max) and the slope at the origin were obtained from the above equation. The mean values for athletes and non athletes were compared using a two sample independent t test.

3.5.4 Gain in adaptation phase

Only rightward saccades were marked for analysis in the adaptation phase. This was done because, during the adaptation phase the intrasaccadic target jumps were present only for rightward saccades. The average gain for the baseline adaptation trial, the adaptation phase trials (5 trials) and the recovery adaptation trial was calculated separately.

Normalization procedure: The average gain of the saccades in each block, was further normalized with respect to the baseline. This was done by dividing the averaged values in the adaptation phases with the average baseline gain. (Employing such a procedure eliminated the baseline variability between subjects.) Gain at baseline is made unity for all the subjects by this procedure.

Two methods of analysis were employed to delineate differences in the adaptation between athletes and non athletes. In the first method, the data of the subjects in the same group (athletes, non athletes) were plotted on a single graph. The normalized gain was plotted on the Y axis. The baseline adaptation trial, the 5 adaptation trials and the recovery adaptation trial were plotted on the X axis. A 3rd order polynomial of the equation, $Y = A + B1*X + B2*X^2 + B3*X^3$ was fit for each of the groups and these were compared to estimate the differences in the magnitude of adaptation. The same analysis procedure was applied to both the gain increasing and gain decreasing paradigms. The 3rd order polynomial curves were differentiated in order to obtain the rate of change of gain for athletes and non athletes for both the gain increasing and decreasing paradigms. Regression analyses were used to compare differences in the rate of change of adaptation between athletes and non athletes.

In the second method, the data of each of the subjects were individually plotted and fitted with the 3rd order polynomial of the equation, $Y = A + B1*X + B2*X^2 + B3*X^3$.

The coefficients from the plots, namely B3, B2 and B1, were averaged across subjects and compared between the two groups. This analysis was applied for both the gain increasing and gain decreasing paradigms.

4 Results

Of the 46 subjects enrolled in the study, 5 subjects did not report for session 2. Hence, data from the remaining 41 subjects (27 athletes and 14 non athletes) were analyzed. However, during session 2 of the baseline saccade trial, the data from 3 subjects could not be analyzed due to poor instrument calibration. Hence, data from only 38 subjects (25 athletes and 13 non athletes) were analyzed for session 2 of the baseline saccade trial. All other trials (session 1 of baseline saccades, gain decreasing, and gain increasing) consisted of 41 subjects.

4.1 Latency: Athletes vs. Non Athletes

The comparison of the latency (start time of saccade – start time of stimulus) between athletes and non athletes showed no significant difference (Figure 6). The athletes had a group mean of 193.33 msec ± 6.72 (SE) and the non athletes had a group mean of 191.46 msec ± 6.81 (SE) in the baseline saccade trial of the first session. Differences in the means upon comparison with a two sample independent t test showed no significant difference ($t = -0.66$; $df = 39$; $p = 0.954$). In the second session, the athlete group had a mean latency of 197.01 msec ± 6.98 (SE) and the non athletes had a group mean of 196.34 msec ± 12.16 (SE). Differences in the means between groups were non significant ($t = -1.87$; $df = 36$; $p = 0.854$).

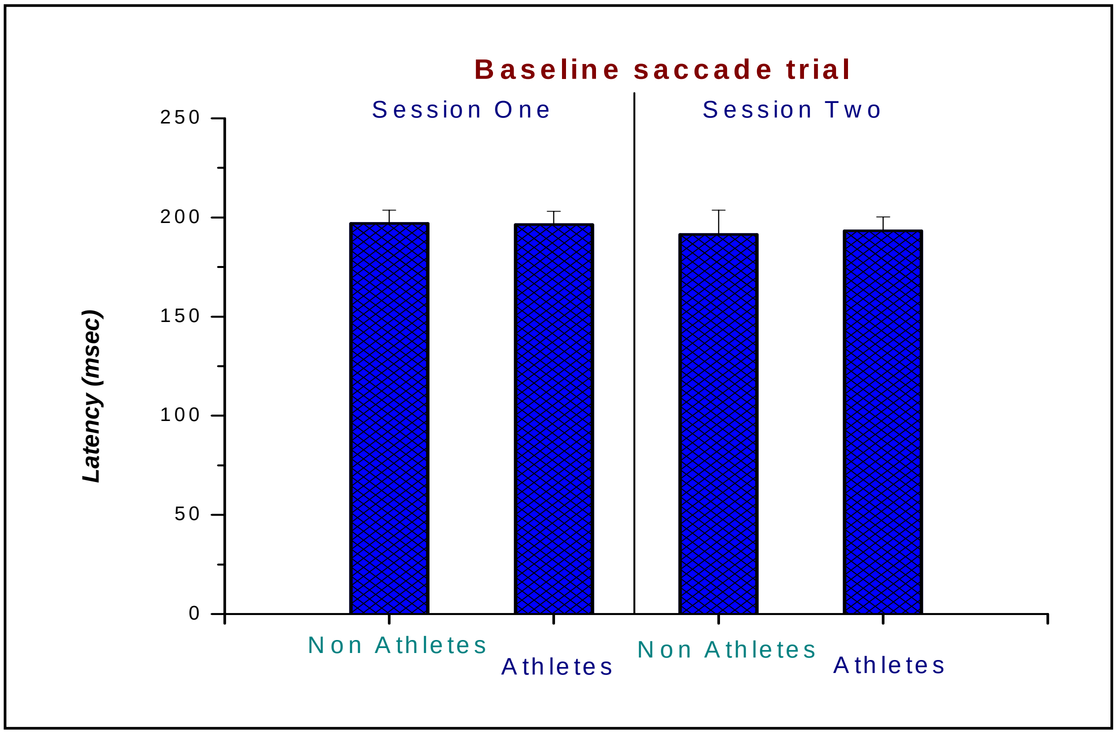

Figure 6. Difference in the mean baseline latency for athletes and non athletes in session one and session two. The error bars represent 1 standard error.

4.2 Accuracy of saccades: Athletes vs. Non Athletes

The accuracy of saccades were compared for athletes and non athletes from the baseline saccade trial of the two sessions. The athletes had a group mean of 0.939 ± 0.02 (SE) and the non athletes had a group mean of 0.972 ± 0.03 (SE) in the baseline saccade trial of the first session. In the second session, athletes had a group mean of 0.904 ± 0.02 (SE) and the non athletes had a group mean of 0.975 ± 0.03 (SE). There was no significant difference in the means of the baseline gains between athletes and non athletes for either session (Figure 7).

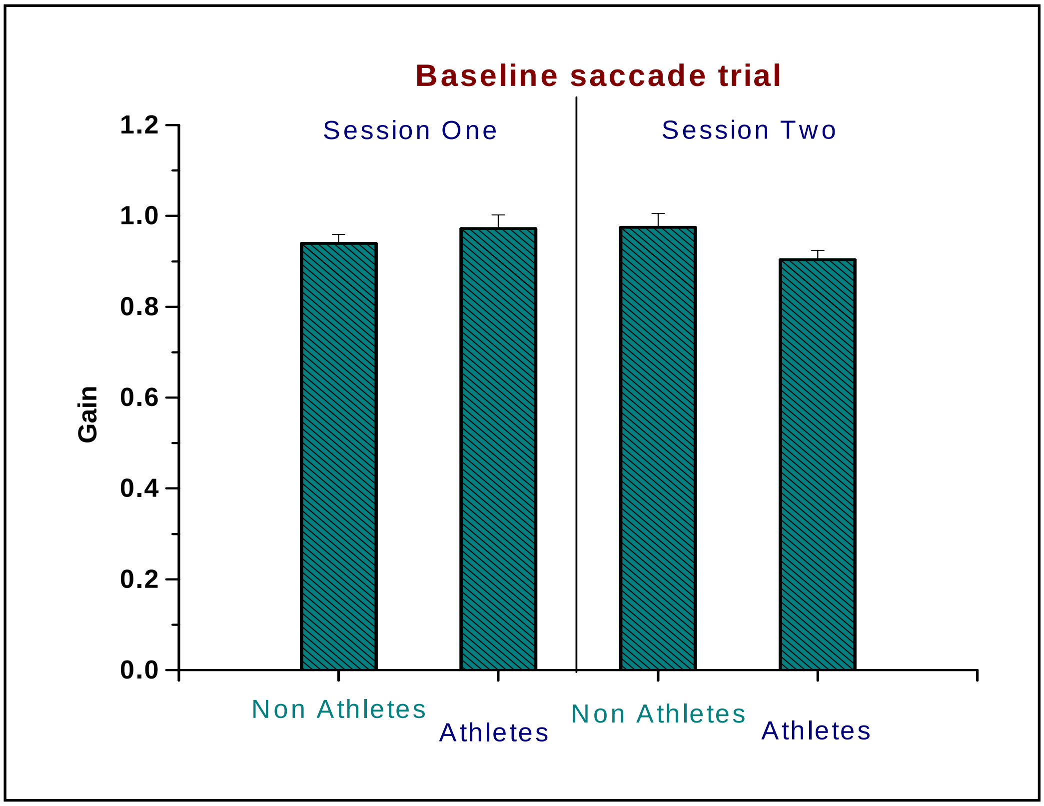

Figure 7. Difference in the mean baseline saccadic accuracy for athletes and non athletes for session one and session two. The error bars represent 1 standard error.

The difference in the means between the groups was compared by a two sample independent t test, for both sessions. For the first session, the mean difference in accuracy was 0.033 ($t = 0.93$; $df = 39$; $p = 0.354$), and for the second session, the mean difference was 0.04 ($t = 1.55$; $df = 36$; $p = 0.120$). Mean differences between the groups failed to achieve statistical significance as seen from the p values being greater than 0.05.

4.3 Results of the main sequence

From the main sequence plots for the baseline saccades, the asymptotic peak velocities (Vmax) and the slopes at the origin (K) were obtained. These values were compared between athletes and non athletes (Figure 8).

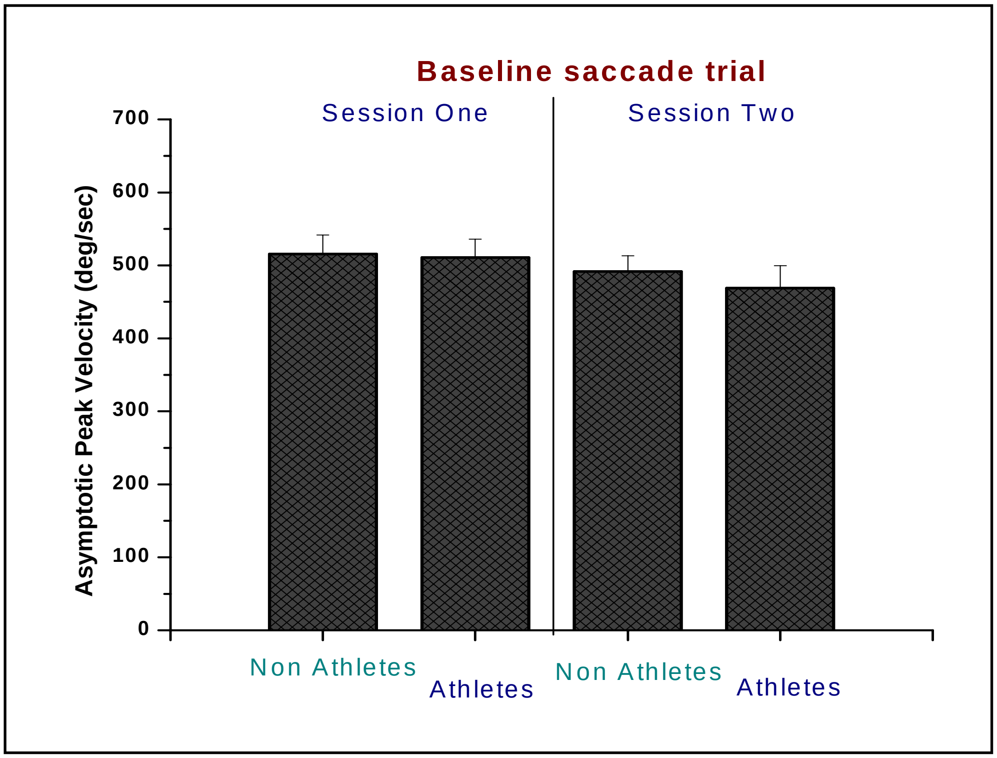

Figure 8. Comparison of the mean saccadic asymptotic peak velocity between athletes and non athletes for both sessions. The error bars represent one standard error. The asymptotic peak velocity was obtained from the average of the main sequence plots which were fitted independently for each subject.

No significant differences in the peak velocity of the saccades were found between the groups, in either session. In the first session, the athletes and non athletes had a mean asymptotic peak velocity of 511.00 ± 24.89 (SE) and 515.61 ± 25.91 (SE) respectively. For the second session, athletes showed a mean value of 468.90 ± 30.64

(SE) and non athletes had a mean value of 491.87 ± 21.38 (SE) for the asymptotic peak velocities. The mean difference between groups in the first session was 4.573 ($t = 0.11$; $df = 39$; $p = 0.908$) and for the second session, the mean difference was 22.97 ($t = 1.66$; $df = 36$; $p = 0.103$).

The slope at origin (K value) of the main sequence plots were also compared between the groups using a two sample independent t test and no statistically significant differences were found (Figure 9). The difference between the mean values for each group in the first session was 0.03 ($t = 0.03$; $df = 39$; $p = 0.972$) and for the second session it was 0.916 ($t = 1.25$; $df = 36$; $p = 0.216$).

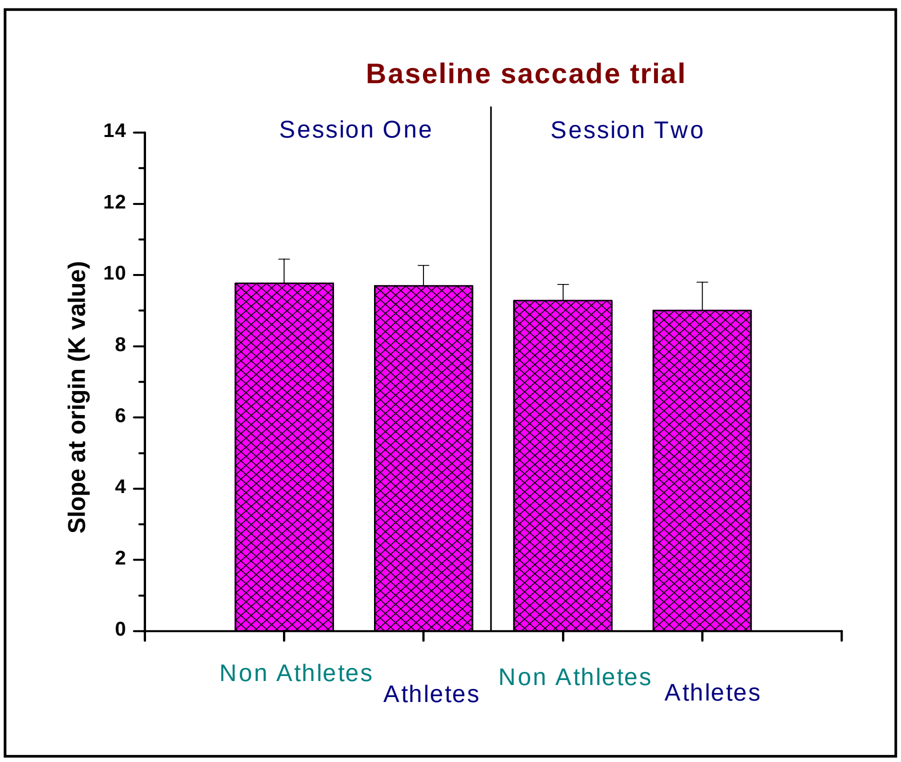

Figure 9. Comparison of the mean slope at origin for the main sequence plots, between athletes and non athletes for both sessions. The error bars represent one standard error.

4.4 Results of the adaptation phase: Gain decreasing adaptation

4.4.1 Magnitude of gain decrease

The results for the magnitude of gain decrease were plotted separately for the athletes and non athletes. A change in gain from baseline was seen for both groups across the adaptation phase of the trials (Figure 10).

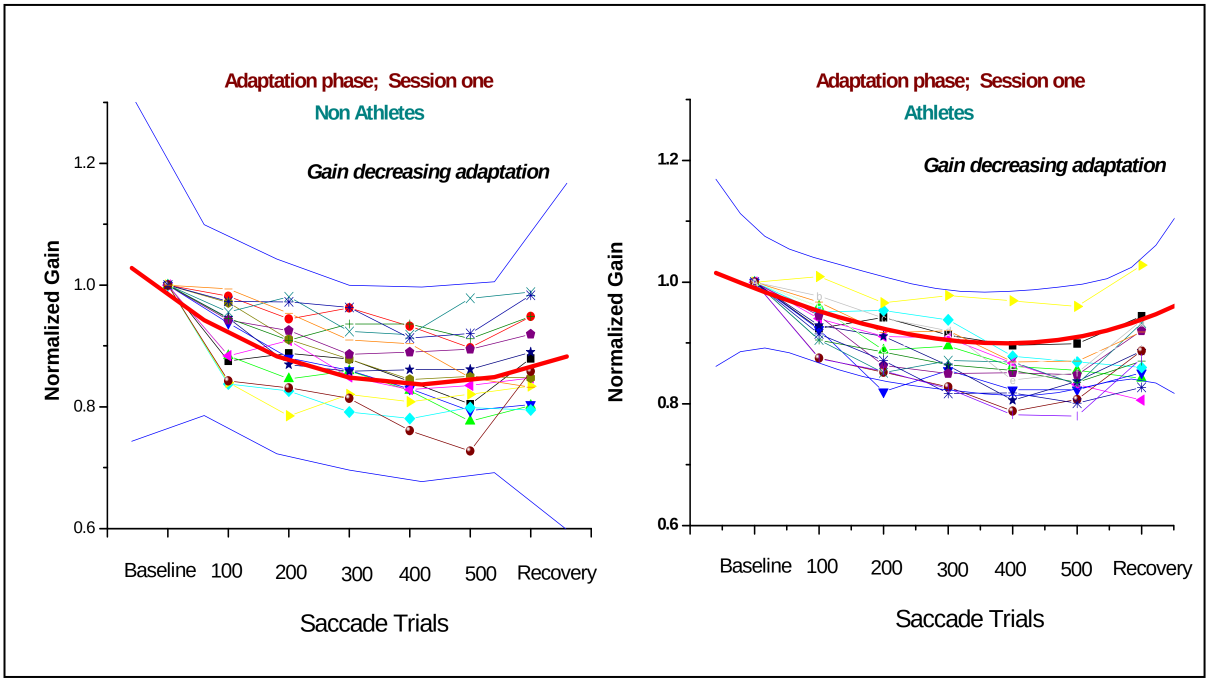

Figure 10. Average gain of saccades for the gain decreasing paradigm. The X axis represents the saccade trials from baseline to recovery. The Y axis represents the normalized gain. The gains are plotted separately for each subject, as seen by the use of different symbols, and joined by lines across the trials. The thick line shows the third order polynomial of the equation
$Y = A + B1*X + B2*X^2 + B3*X^3$ fit from the data. The outer bands are 95% prediction bands.

The figure on the left shows the data of non athletes fitted with;
$Y = 0.98 + (-0.04)*X +0 .002*X^2 + (4.41E-4)*X^3$ [$R^2 = 0.80$].

Figure on the right shows the data for athletes fitted with;
$Y = 1.06 + (-0.08)*X +0 .009*X^2 + (-8.61E-5)*X^3$ [$R^2 = 0.76$]

4.4.1.1 Comparative analysis of the curves and the averaged magnitude of gains

The average magnitude of the normalized gains is shown in Table 1 as well as plotted in Figure 11.

Table 1. The magnitude of averaged normalized saccadic gains from baseline trial to recovery trial for the gain decreasing adaptation paradigm.

Normalized	Non athletes		Athletes	
	Gain (avg)	SE (±)	Gain (avg)	SE (±)
Baseline	1.00		1.00	
100	0.92	0.01	0.92	0.01
200	0.90	0.01	0.89	0.01
300	0.88	0.01	0.88	0.01
400	0.86	0.01	0.85	0.01
500	0.85	0.01	0.85	0.01
Recovery	0.88	0.01	0.89	0.01

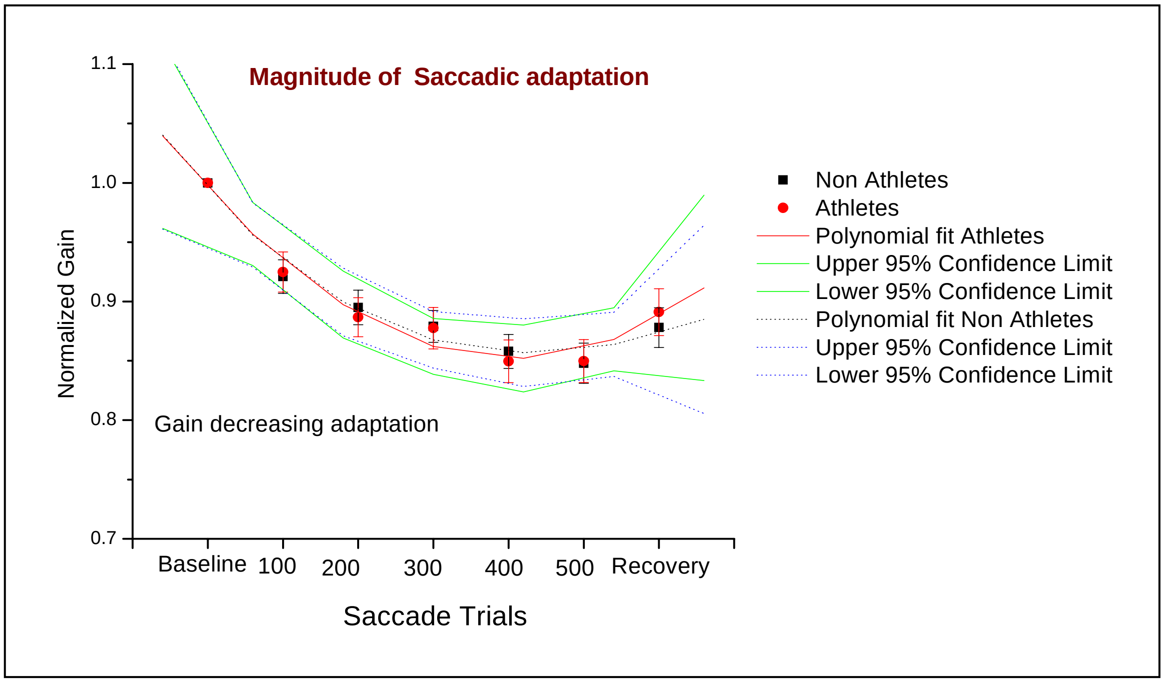

Figure 11. Averaged normalized saccadic gains for both groups fitted separately with the 3rd order polynomial of the equation; $Y = A + B1*X + B2*X^2 + B3*X^3$.
Athletes {$Y = 1.07 + (-0.08)*X + 0.007*X^2 + (9.25E{-}5)*X^3$ [$R^2 = 0.97$]}
Non athletes {$Y = 1.07 + (-0.09)*X + 0.011*X^2 + (-3.33E{-}5)*X^3$ [$R^2 = 0.96$]}. The solid lines represent the curve for the athletes and solid bands represent the 95% confidence intervals. The dotted lines represent the curve for non athletes and corresponding 95% confidence intervals. The error bars represent ± 1 standard error.

A comparison of the magnitude of saccadic adaptation (i.e. the decrease in the gain of saccades) between athletes and non athletes showed that there were no significant differences. The averaged gain of both groups lies within the set 95% confidence limits (Figure 11).

4.4.1.2 Analysis of magnitude using the coefficients of the polynomials

The saccadic adaptation data in the gain decreasing paradigm for each subject was fitted with the polynomial of the equation $Y = A + B1*X + B2*X^2 + B3*X^3$ and each of the coefficients was compared between the groups. The fitting criterion was based on the R^2 values. Fits which had R^2 values less than 0.75 were removed from the comparative analysis. The data of 4 non athletes and 4 athletes were removed. See Tables 2 and 3 for the data of non athletes and the athletes respectively.

Table 2. Coefficients for polynomial fit of the equation, $Y = A + B1*X + B2*X^2 + B3*X^3$ for non athletes.

Non Athletes	A	B1	B2	B3
NA 1	1.062	-0.089	0.009	0.000
NA 2	0.993	0.014	-0.012	0.001
NA 3	1.125	-0.164	0.030	-0.002
NA 4	1.070	-0.077	0.006	0.000
NA 5	1.201	-0.259	0.052	-0.003
NA 6	1.083	-0.109	0.015	-0.001
NA 7	1.246	-0.318	0.070	-0.005
NA 8	1.040	-0.031	-0.006	0.001
NA 9	1.105	-0.116	0.015	0.000
NA 10	1.060	-0.068	0.006	0.000
NA 11	1.073	-0.096	0.000	0.001
NA 12	1.080	-0.102	0.021	-0.001
NA 13	0.954	0.062	-0.027	0.003
NA 14	1.006	0.006	-0.010	0.001

Table 3. Coefficients for polynomial fit of the equation $Y = A + B1*X + B2*X^2 + B3*X^3$ for athletes.

Athletes	A	B1	B2	B3
A1	1.093	-0.047	0.002	0.000
A2	0.997	-0.085	0.012	-0.001
A3	1.184	-0.176	0.030	-0.002
A4	1.041	-0.012	-0.005	0.000
A5	0.806	-0.062	0.011	-0.001
A6	0.982	-0.006	-0.017	0.002
A7	0.919	-0.073	0.003	0.001
A8	1.081	-0.111	0.008	0.001
A9	0.944	-0.101	0.015	-0.001
A10	0.964	-0.108	0.014	0.000
A11	1.113	-0.116	0.013	0.000
A12	1.332	-0.437	0.089	-0.006
A13	0.905	0.002	-0.013	0.002
A14	0.951	-0.078	0.000	0.001
A15	0.951	-0.105	0.010	0.000
A16	1.021	-0.063	0.004	0.000
A17	0.904	0.102	-0.046	0.004
A18	0.940	-0.047	0.000	0.001
A19	1.061	-0.119	0.013	0.000
A20	0.956	0.000	-0.011	0.002
A21	1.096	-0.171	0.039	-0.003
A22	1.171	-0.253	0.054	-0.004
A23	1.198	-0.207	0.040	-0.002

Independent t tests on each of the coefficients for both groups showed statistically insignificant differences (Table 4).

Table 4. Hypothesis testing of the coefficients of the polynomial fit for the groups using independent t tests. Statistically insignificant differences are shown by the p values being greater than 0.05.

	t value	df	p value
B^3	-0.241	35	0.810
B^2	0.071	35	0.943
B^1	0.074	35	0.941

4.5 Results of the adaptation phase: Gain increasing adaptation

4.5.1 Magnitude of gain increase

The results for the magnitude of gain increase were also plotted separately for the athletes and non athletes. A change in gain from baseline was seen for both groups across the adaptation phase of the trials (Figure 12).

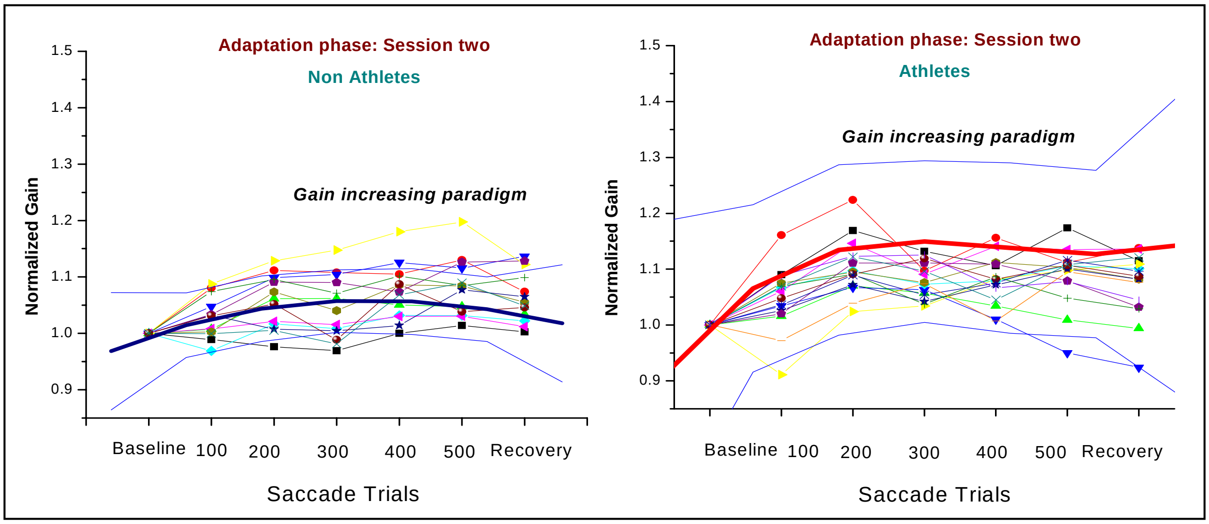

Figure 12. Average gain of saccades for the gain increasing paradigm. The X axis represents the saccade trial from baseline to recovery. The Y axis represents the normalized gain. The gains are plotted separately for each subject as seen by the use of different symbols and joined by lines across the trials. The thick line shows the third order polynomial of the equation $Y = A + B1*X + B2*X^2 + B3*X^3$ fit from the data. The outer bands are the 95% prediction bands.

Figure on the left shows the data of non athletes fitted with;
$$Y = 0.94 + (0.05)*X + (-0.006)*X^2 + (1.35E-4)*X^3 \quad [R^2 = 0.82]$$

Figure on the right shows the data for athletes fitted with;
$$Y = 1.00 + (0.12)*X + (-0.03)*X^2 + (0.002)*X^3 \quad [R^2 = 0.77]$$

4.5.1.1 Comparative analysis of the curves and the averaged magnitude of gains

The average magnitude of the normalized gains is shown in the Table 5 as well as plotted in Figure 13.

Table 5. The magnitude of averaged normalized saccadic gains from baseline to recovery trial for the gain increasing adaptation paradigm.

Normalized	Non athletes		Athletes	
	Gain (avg)	SE (±)	Gain (avg)	SE (±)
Baseline	1.00		1.00	
100	1.02	0.01	1.04	0.01
200	1.05	0.01	1.09	0.01
300	1.04	0.01	1.07	0.01
400	1.06	0.01	1.07	0.01
500	1.07	0.01	1.08	0.01
Recovery	1.06	0.01	1.07	0.01

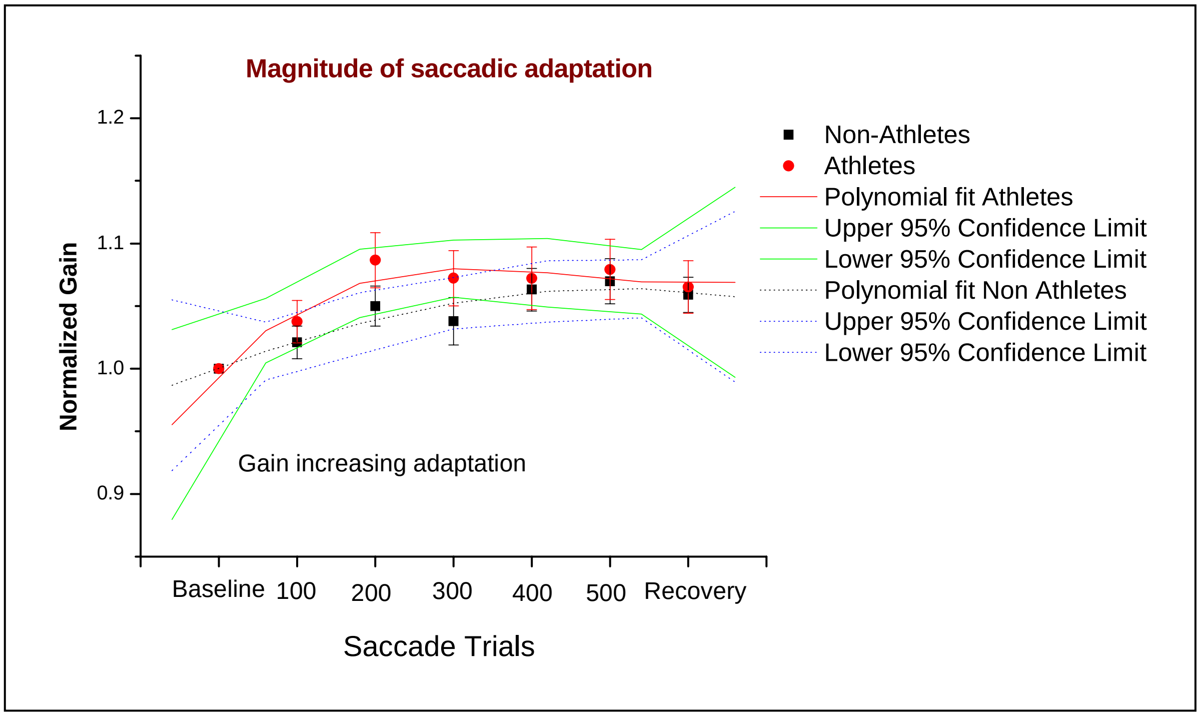

Figure 13. Averaged normalized saccadic gains for both groups fitted separately with the 3rd order polynomial of the equation; $Y = A + B1*X + B2*X^2 + B3*X^3$.
Athletes $\{Y = 0.92 + 0.09*X + (-0.01)*X^2 + (0.001)*X^3 \quad [R^2 = 0.91]\}$
Non athletes $\{Y = 0.97 + 0.02*X + (-0.001)*X^2 + (-7.70E-5)*X^3 \quad [R^2 = 0.90]\}$
The solid lines represent the curve for the athletes and solid bands represent the 95 % confidence intervals. The dotted lines represent the curve for non athletes and corresponding 95 % confidence intervals. The error bars represent ± 1 standard error.

A comparison of the magnitude of saccadic adaptation (i.e. the increase in the saccadic gain) between athletes and non athletes showed that there are no statistically significant differences. The averaged gain of both groups lies within the set 95% confidence limits.

4.5.1.2 Analysis of magnitude using the coefficients of the polynomials

The saccadic adaptation data in the gain increasing paradigm was fitted with the polynomial of the equation $Y = A + B1*X + B2*X^2 + B3*X^3$ and each of the coefficients were compared between the groups. The fitting criterion was based on the R^2 values. Fits which had R^2 values less than 0.75 were eliminated from the comparative analysis. Data of 5 non athletes and 10 athletes were removed based on the above criterion. See Tables 6 and 7 for the data of the non athletes and athletes respectively.

Table 6. Coefficients for polynomial fit of the equation $Y = A + B1*X + B2*X^2 + B3*X^3$ for non athletes.

Non Athletes	A	B1	B2	B3
NA 1	0.909	0.115	-0.019	0.001
NA 2	0.949	0.051	-0.007	0.000
NA 3	0.908	0.106	-0.019	0.001
NA 4	1.027	-0.049	0.018	-0.002
NA 5	1.000	-0.003	0.004	-0.001
NA 6	0.942	0.064	0.002	-0.001
NA 7	0.987	0.002	0.009	-0.001
NA 8	0.915	0.100	-0.020	0.001
NA 9	0.891	0.142	-0.032	0.002

Table 7. Coefficients for polynomial fit of the equation $Y = A + B1*X + B2*X^2 + B3*X^3$ for athletes.

Athletes	A	B1	B2	B3
A 1	0.843	0.197	-0.041	0.003
A 2	0.717	0.379	-0.095	0.007
A 3	0.917	0.094	-0.019	0.001
A 4	0.883	0.140	-0.032	0.002
A 5	0.898	0.134	-0.030	0.002
A 6	0.728	0.305	-0.037	0.001
A 7	0.878	0.147	-0.028	0.002
A 8	1.077	-0.136	0.046	-0.004
A 9	0.921	0.103	-0.018	0.001
A 10	0.965	0.041	-0.005	0.000
A 11	0.926	0.069	-0.003	-0.001
A 12	0.906	0.109	-0.019	0.001
A 13	0.829	0.221	-0.056	0.004
A 14	0.942	0.071	-0.013	0.001
A 15	0.835	0.209	-0.047	0.003
A 16	0.973	0.029	-0.001	0.000
A 17	0.950	0.059	-0.007	0.000
A 18	0.873	0.164	-0.030	0.002

Independent t tests on each of the coefficients for both groups showed statistically insignificant differences. The results are shown in Table 8.

Table 8. Hypothesis testing of the coefficients of the third order polynomial fit for the groups using independent t tests. Statistically insignificant differences are shown by the p values being greater than 0.05.

	t value	df	p value
B^3	-1.479	25	0.151
B^2	1.651	25	0.111
B^1	-1.730	25	0.094

4.6 Rate of change of adaptation: Gain decreasing adaptation

To obtain the rate of change of adaptation, the polynomials fitted to the magnitude of adaptation were differentiated. It has to be noted that the recovery trial following adaptation was removed from this analysis so as to specifically look into the rate of change of adaptation from baseline to the final adapted state. The data for both groups are plotted in Figure 14.

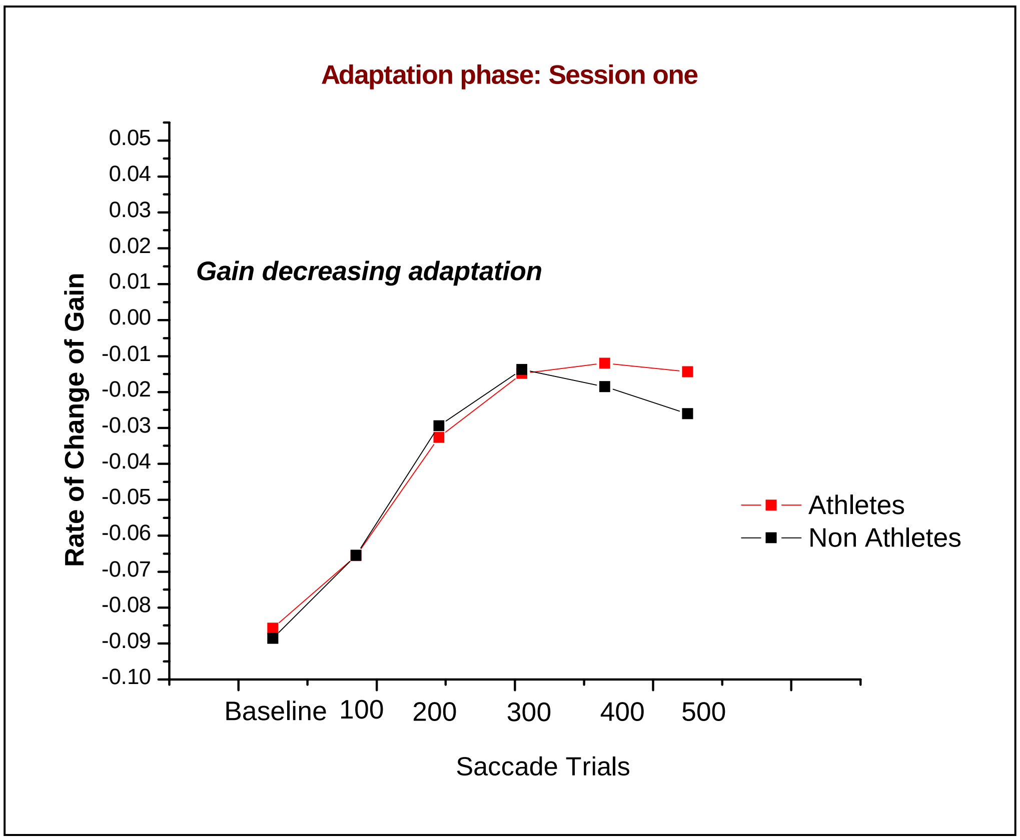

Figure 14. The rate of change of adaptation in the gain decreasing paradigm (Session 1).

4.6.1 Non linear regression analysis

Non linear regression was applied to this data by fitting a second order polynomial of the equation $Y = A + B*X + C*X^2$. Statistical analysis using the F test (Prism, GraphPad Inc., USA) showed that the data points of both groups could be represented by a single non linear curve ($F = 0.856[3,6]$; $p = 0.512$). Thus, the data of athletes and non athletes were not significantly different from each other (Figure 15).

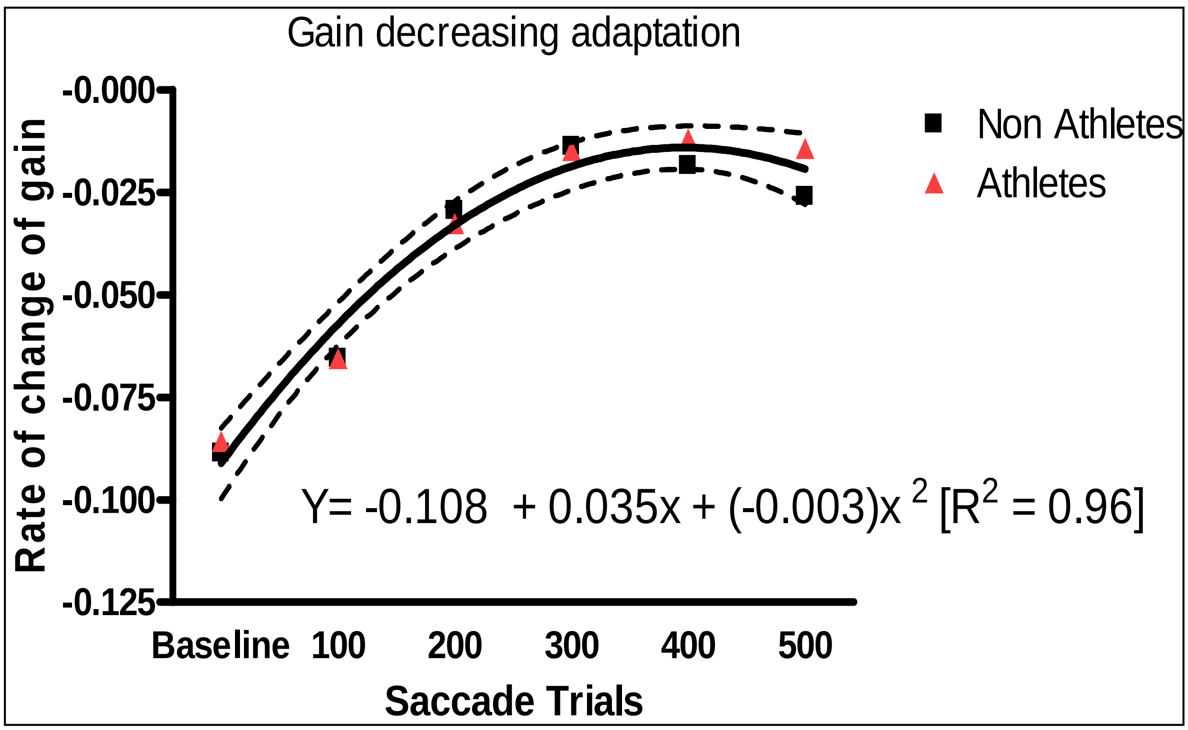

Figure 15. Rate of change of saccadic adaptation of both athletes and non athletes - gain decreasing paradigm. Non linear regression applied to the differentiated curves of both groups. The solid curved line represents the regression.

4.7 Rate of change of adaptation: Gain increasing adaptation

To obtain the rate of change of adaptation the polynomials fitted to the averaged normalized gain (magnitude) were differentiated. The recovery data were removed so as to specifically investigate the rate of adaptation from baseline. The data for both groups are plotted in Figure 16.

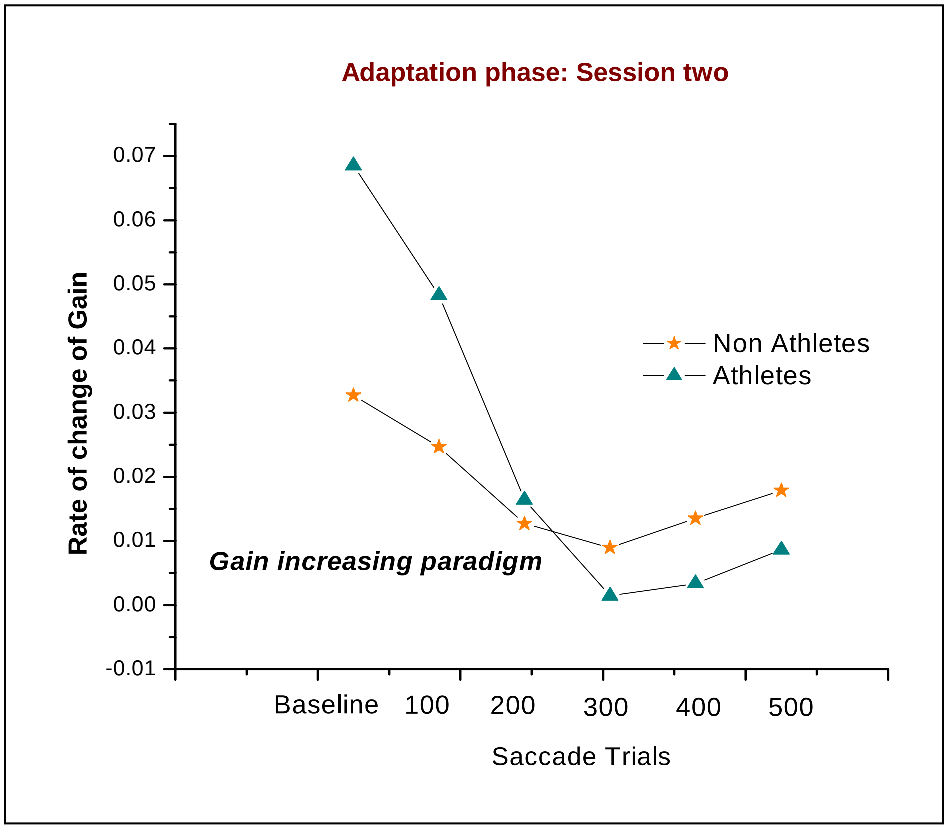

Figure 16. The rate of change of adaptation in the gain increasing paradigm (Session 2).

4.7.1 Non linear regression analysis

To compare differences between the groups a non linear regression analysis was applied. The data were fitted with a second order polynomial of the equation

$Y = A + B^* X + C *X^2$. Statistical analysis using the F test (Prism, GraphPad Inc., USA) showed that the lines were significantly different from each other

($F = 17.96[3,6]$; $p = 0.002$). Athletes initially adapted at a higher rate than the non athletes, in the gain increasing paradigm. After 200 saccade trials the rate decreased below that of non athletes (Figure 17).

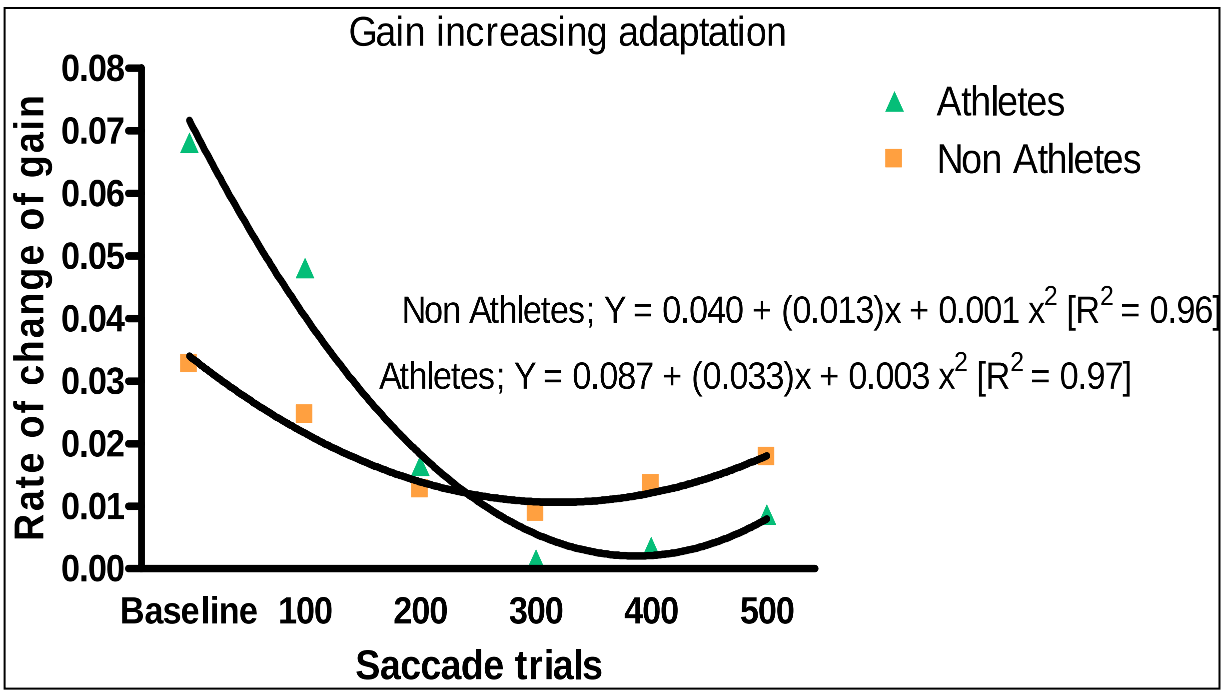

Figure 17. Rate of change of saccadic adaptation of both athletes and non athletes - gain increasing paradigm. Non linear regression applied to the differentiated curves of both groups. The solid curved lines represent the regression. The symbols represent the data points of the differentiated polynomials.

4.8 Recovery from adapted state

4.8.1 Gain decreasing adaptation

In the gain decreasing paradigm, when the recovery trial was included in the analysis, the athletes and non athletes showed a significant difference from each other (F = 5.053[3,7]; p = 0.029). Hence, a single non linear curve does not fit the data points of both groups (Figure 18). The athletes showed a faster recovery from the adapted state. It has to be noted that the recovery from the gain decreasing paradigm is similar to the adaptation in the gain increasing paradigm.

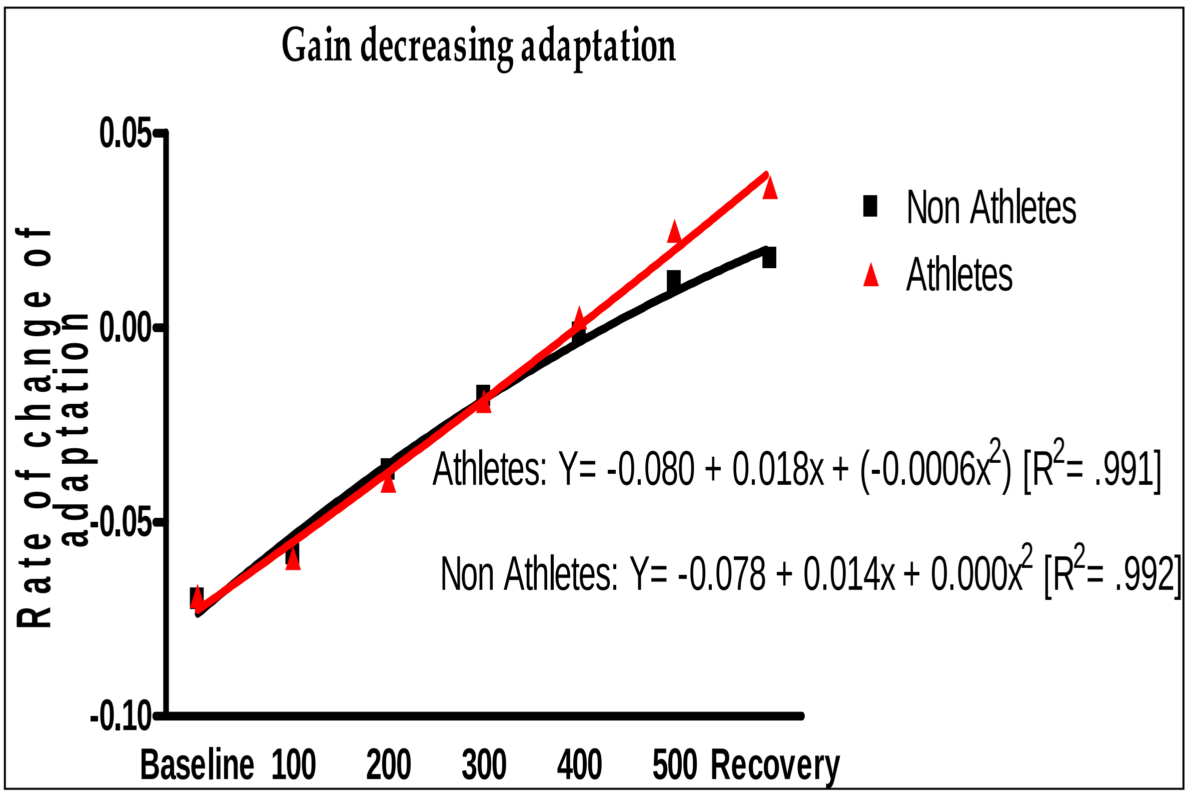

Figure 18. Non linear regression applied to the data of the athletes and non athletes. The recovery trial is included in this analysis.

4.8.2 Gain increasing adaptation

The recovery of adaptation from the gain increased state also showed that athletes were faster to recover from the adapted state. The lines were significantly different from each other (F = 40.56[3,7]; p < 0.000) (Figure 19). The comparison of curves to test recovery from adaptation was limited in the gain increasing adaptation as these curves were significantly different even before including recovery in the analysis.

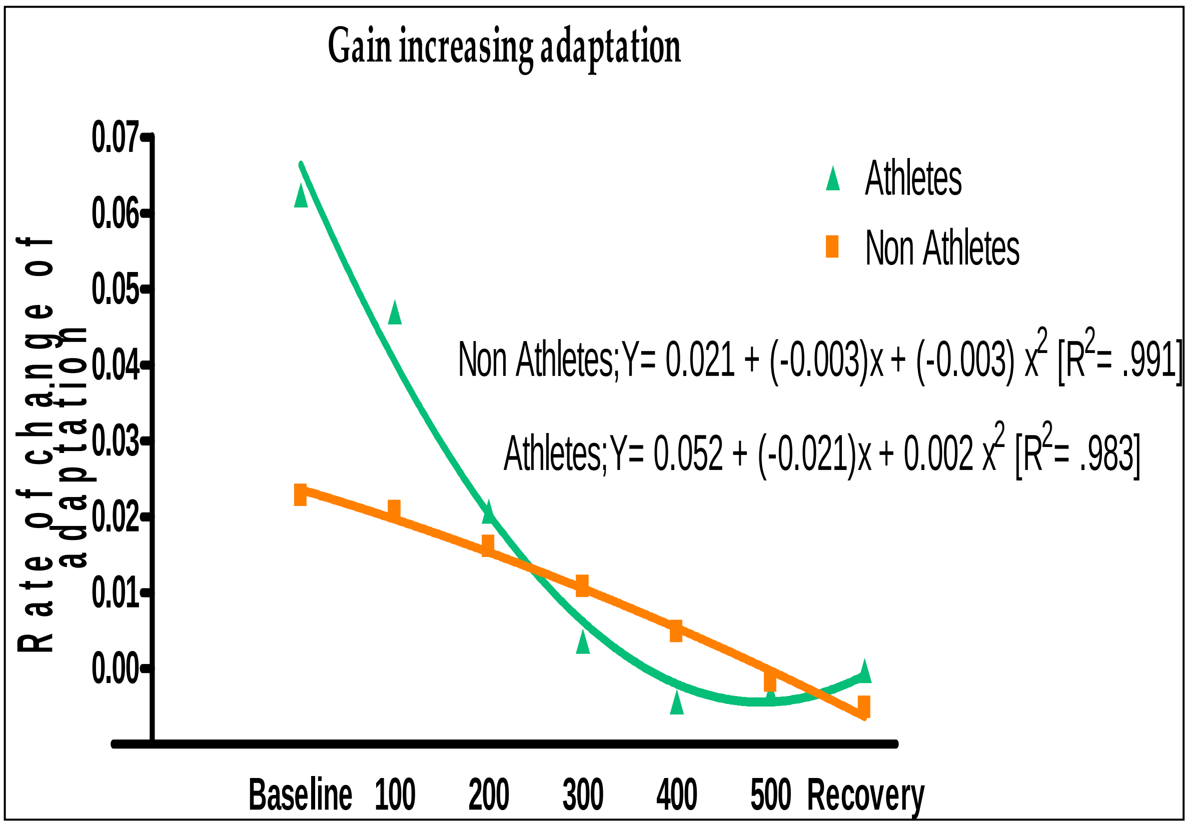

Figure 19. Non linear regression applied to the data of the athletes and non athletes. The recovery trial is included in this analysis.

5 Discussion

5.1 Latency

The latency refers to the time difference following stimulus presentation and when the eye starts to move in a saccade. Latency is a measure of the visuo–motor reaction time. Our results indicate that, in the sample studied, there are no significant differences in this parameter of saccades between the athletes and non athletes. This result concurs with Lenoir[98] and Hughes[97] studies, as no significant differences were observed in the latency of prosaccades in their respective studies. The sample studied by Lenoir[98] included high speed ball game players (tennis, basketball, volleyball, handball and soccer) and our sample had racquet sport players. With respect to the sport, they are all characterized by high velocities and sudden changes in target location to which athletes have to respond. This might explain the similarities observed in the latency values of the athletes, when compared to our study. The control group in their study had a higher latency. Their methodology differed from our study in that they compared a single degree of saccade amplitude (15 degree) in both leftward and rightward direction while our study used saccades of varying amplitudes (5 to 25 degrees). In our study the latencies mentioned are averages for all amplitudes. The effect of amplitude on the latency has been studied and the results are equivocal.[103,104]

Contrary to the result of our study, Di Russo et al.[105] found that the saccadic latency in a sample of elite clay target shooters was significantly different (mean difference of approximately 50 msec; $p < 0.005$) in comparison to non athletes. The mean latencies of close to 300 msec in their study might have arisen due to the use of an overlap paradigm for the "saccade task". Saccade execution using gap and overlap paradigms have been previously studied and saccade execution is found to be slower using an overlap paradigm.[106] The overlap paradigm requires disengagement of the attention from the persisting fixation point before saccade execution. This could explain the latencies of close to 300 msec obtained for their athletes and controls in their study which are much higher in comparison to ours (Table 9).

Table 9. Comparable results of latency from other studies.
* Values visually obtained from graph.

	Mean Latency (msec) ± SD		Significance
	Athletes	**Non Athletes**	
Lenoir M(2000)	202.40 ± 35.00	226.80 ± 26.60	Not significant
Di Russo(2003)	240.00 ± 40.00 *	290.00 ± 40.00 *	P < 0.005
Current study	193.33 ± 34.90	191.46 ± 25.49	Not significant

Their study also showed that athletes are able to generate saccades faster than controls. This might be the result of an environmental impact, in this case participation in clay target shooting. Clay target shooting requires shooting at moving targets which necessitates the execution of very short latency responses. The results point to the influences of the environment in generating a physiological response (saccade execution). Another possibility is that, athletes might be quicker than controls in generating saccades in the overlap paradigm which might relate to the ability of clay target shooters to disengage attention faster than controls.

5.2 Accuracy of saccades

This is the first study to report on the accuracy of saccades as a comparative measure between athletes and non athletes. Based on our results, it is evident that the baseline gain (obtained from baseline saccade trials) is similar in athletes and non athletes. Both groups have a mean accuracy greater than 90% (i.e. gains close to 1). This finding is similar to the results of Kowler and Blaser[107] who found that saccades appear to be very accurate, even when tested and compared between an experienced and novice observer. They further showed that the high accuracy and precision was also maintained for large targets. Thus using baseline accuracy as a comparative measure to delineate differences between the two groups appears to be inadequate. Further, the environmental influences of sport to improve saccadic accuracy have not been found, as the accuracy of the saccades for all the subjects tested in this study were equally good. The subjects in our study were adults and hence their ocular motor system is deemed to be fully developed. The nature of the fully developed system is clearly shown by both groups exhibiting high saccadic accuracies. Whether subjects with poor saccadic accuracy, will improve or not due to participation in sports, is yet to be investigated. However, measuring the accuracy of eye movements, in addition to latency, might be valuable in sports vision practice, as it may serve as a useful tool to identify subjects with poor ocular motor control and hence potentially affecting the performance in sports.

5.3 Main sequence - Assessment of peak velocity of saccades

The assessment of the main sequence is used as an effective clinical tool to study the neurological integrity of the ocular motor system. In normal human subjects with neurological integrity, the peak velocities elicited are correlated to the amplitude of the saccades. In case of disorders of the ocular motor system as seen in ocular muscle paresis, Graves disease, Alzheimer's disease, Acquired immuno deficiency syndrome (AIDS), Niemman Pick type C disease and also due to the effect of certain drugs, the peak velocity is reduced for corresponding amplitudes.[50,108-110]

This study compared the main sequence of athletes and non athletes and no difference between the groups was seen. Peak velocities have been found to vary with age.[111-113] However, in this study we looked at athletes and non athletes within the same age group.

Even though athletes have been shown in certain cases to have above normal skills in certain aspects of their visual system (see introduction), they are very similar to non athletes in their saccadic peak velocities. This result is in agreement with the literature.[43]

In the population sample we studied (age: 18 to 30 years) ocular motor development is considered complete. The parameters of the system appear to show a "ceiling effect" in baseline characteristics. The ceiling effect refers to the phenomenon where the response reaches a maximum value such that any further change in the factors affecting the response does not increase the response magnitude. It is quite possible that in a younger age group, where the baseline gain and peak velocity may not be as high as observed in this study, environmental influences on saccades may show greater impact.

5.4 Dynamics of saccadic adaptation

5.4.1 Magnitude of adaptation

This study is the first report on the dynamics of saccadic adaptation and to investigate whether athletes perform better with respect to saccadic adaptation in both positive and negative directions. The results clearly show that there is no change in the magnitude of saccadic adaptation between athletes and non athletes in both gain increasing and decreasing saccadic adaptation. However, the magnitude of gain decrease (15%) obtained in both groups was much higher than the magnitude of gain increase (7% in non athletes and 8% in athletes). This asymmetry in the nature of adaptation with regards to the amount of increase and decrease is consistent with earlier findings in literature.[52,56,114] This supports the idea that the ocular motor system does not tolerate overshooting of the target and also that undershooting is common during saccade execution.[71] Hence the time constant for gain reduction is much shorter in comparison to a gain increase.

Since the results suggest that magnitude differences in saccadic adaptation between the groups is not significant, it provides evidence that the recalibration of the ocular motor system in response to visual error operates at a low level (retinal error), as suggested by Seeberger, Noto and Robinson[66], and Wallman and Fuchs[75]. Thus, the environmental experience does not markedly affect the output of the system in terms of the magnitude of recalibration.

5.4.2 Rate of change of adaptation

The rate of change of adaptation in athletes was higher in the gain increasing paradigm in comparison to non athletes. In the gain increasing paradigm, the athletes appear to be faster in reaching the higher adaptation state.

Undershooting of target position is common during saccade execution. The amount of undershoot is usually a small percentage of the amplitude of saccade.[71] In the gain increasing paradigm, the intrasaccadic jump causes saccades to undershoot the final target position by a higher amount and the system corrects this error by increasing the gain. This degree of undershoot even though a small amount seems to trigger a faster gain change in athletes as shown by the faster rate of adaptation. We hypothesize that in athletes (racquet sports players in this case), even small errors which occur during visual tasks might pose a problem during game situations and the ocular motor system corrects such errors rapidly. This behavior of athletes might lead to the faster adaptation obtained from our results. This again points to the environmental impact on the physiological responses.

In the gain decreasing paradigm, no differences were found in the rate of adaptation from baseline to adaptation. The reason for this presumably is that, even non athletes cannot tolerate the overshooting of target and therefore the system corrects the error much faster for all subjects. Overshooting of saccades demands a corrective saccade in the direction opposite to the progressed saccade and for this to occur, commands has to cross over to the contralateral side.[69,70] Thus to maximize efficiency by eliminating this more complicated processing, the system reduces the gain as fast as possible and accurate saccades are established.

Another possible reason is the interaction of anticipation and prediction on the 'rate of change of gain'. It has been shown by Howarth et al.[86] and Abernethy [115] that athletes have higher advantage in game situations due to anticipatory responses. Accordingly, it would appear that anticipatory responses could trigger faster recalibration even though the magnitude of recalibration is same in both the groups. Since this study did not consider anticipatory responses as part of the analysis protocol, it would be difficult to comment about its effect on the differences found between the two groups.

5.4.3 Recovery from adapted state

The athletes seemed to be faster to recover from the adapted state particularly in the gain decreasing paradigm. The recovery from a decreased gain is similar to the adaptation phases of the gain increasing adaptation paradigm and, hence the athletes are seen to be faster as was observed in the results of rate of adaptation. This study is limited to provide a strong evidence regarding the recovery from gain increasing adaptation as a comparison strictly restricted to this part of trial was not possible as the rate of adaptation was different between athletes and non athletes even before the recovery trial was included in the analysis.

These results are also suggestive of athletes having a higher flexibility in gain changes. Flexibility in gain states were shown by Watanabe et al.[59] wherein differential gain states of saccades in the same direction were shown in monkeys. As shown in one of their experimental conditions, monkeys were able to increase the gain for a 7 deg saccade and also decrease the gain for a 20 degree saccade in the same trial. Time constants of these flexible gain states are not yet investigated and this also could possibly attribute to the differences in the rate of change of gain adaptation from both baseline and towards recovery.

6 Conclusion

The study showed that the athletes did not respond better in terms of reaction time, accuracy and the peak velocity of saccades. The study also shows that recalibration of the ocular motor system is similar in athletes and non athletes. The significant difference in the rate of change of adaptation for the gain increasing paradigm between the groups shows that online modification of saccades (positive direction), although not greater in magnitude, occurs faster in athletes than non athletes. The results point to the impact of environmental influences (participation in racquet sports) on saccade execution in their adaptation to error signals.

Future directions on the study will be to study the environmental influences in a population wherein the ocular motor development is not complete such as in children. The response to online visual error may show greater impact with advantage from environmental influences such as from sports.

Secondly, the flexibility in adaptation could be investigated by employing gain increasing and decreasing paradigms in the same trial and study the time constants of the same. Using this as a comparative measure between athletes and controls will be valuable.

The third direction is to find the role of anticipatory saccades in governing recalibration, since it is already known that anticipation in game situations plays a major role in sports.

7 Appendix 1

7.1 Gain decrease in short term saccadic adaptation: Effects of size of intrasaccadic step

7.1.1 Aim

To study the variation of saccadic adaptation with respect to two different amounts of intrasaccadic step (1 degree and 3 degrees).

7.1.2 Hypothesis

A difference in adaptation would be seen with respect to the amount of intrasaccadic step.

7.1.3 Methods

Eye movements were recorded using the ELMAR eye tracker (see methods section of the chapter 2). Saccadic stimuli were white square targets on a black background and were presented on a black monitor at a distance of 85 cms. All rightward saccades were of the amplitude of 12 degrees originating from random horizontal positions.

Procedure: Four subjects, between the ages of 20 to 30 years participated in the experiment. Two sessions were employed in the study which was separated by a week. The first session included calibration of eye movement followed by the baseline trial, adaptive phase trial and recovery adaptation trial. The adaptive phase was a gain decreasing paradigm with an intrasaccadic jump of 1 degree applied to the saccade once the eye movement reached a velocity of 40 deg/sec. These jumps were in the direction opposite to the direction of the saccade. In the second session a higher intrasaccadic jump of 3 degrees was applied to the saccade in the adaptation phase and all the other trials were similar and in the same order.

Data analysis: Saccades were marked based on velocity detection criteria and the amplitude of the primary rightward saccade was used for further analysis. Data from both eyes were analysed separately and collapsed together. The gains were calculated and normalized with respect to baseline.

7.1.4 Results

The results show that the amount of gain change obtained was higher for the 3 degree intrasaccadic jump in comparison to the 1 degree jump. A repeated measure ANOVA showed significant differences [$F_{[2,6]} = 12.007$; $p = 0.002$] in the means across trials and paired t tests for both 1 and 3 degree sizes showed a significant difference between baseline and recovery trial ($p < 0.05$) (Figure 20 and 21).

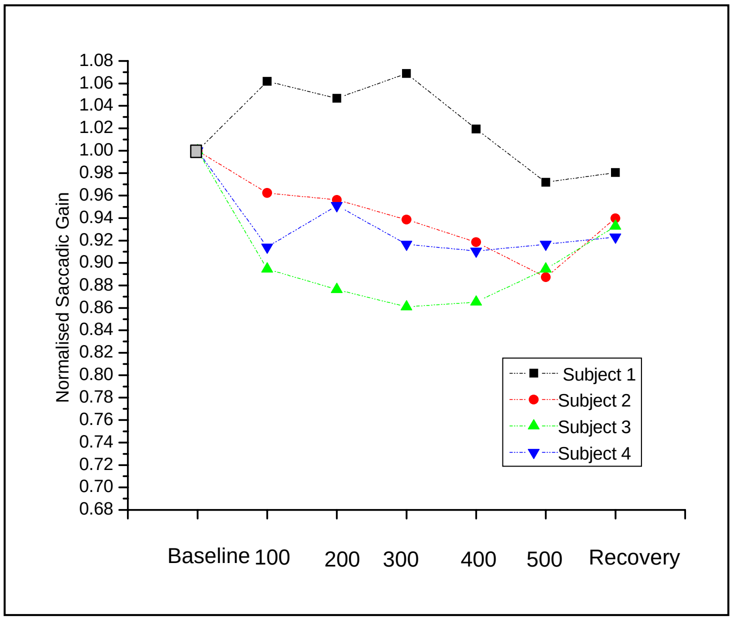

Figure 20. The figure shows the gain change from baseline to recovery for four subjects when an intrasaccadic jump of 1 degree was applied once the eye movement reached a velocity of 40 deg/sec. The saccadic gains are averaged for each trial and normalized with respect to baseline. A decrease in the gain from baseline is seen for 3 of the 4 subjects.

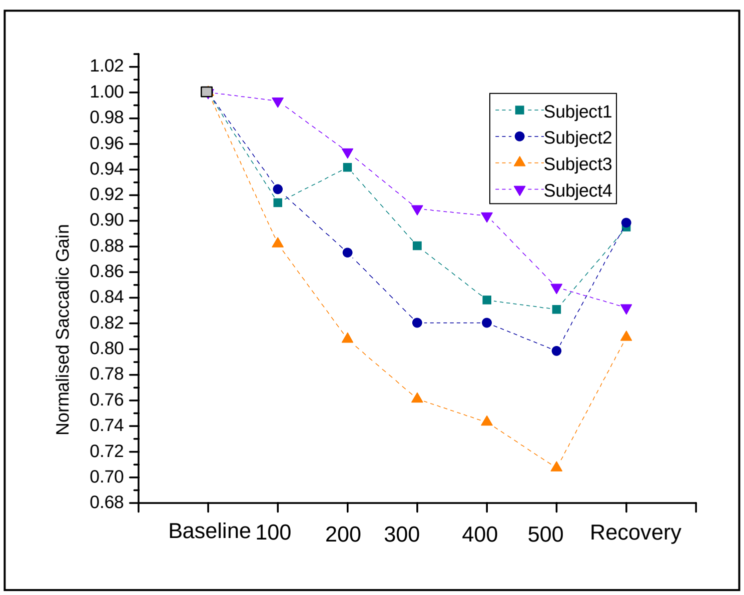

Figure 21. The figure shows the gain change from baseline to recovery for four subjects when an intrasaccadic jump of 3 degree was applied once the eye movement reached a velocity of 40 deg/sec. The saccadic gains are averaged for each trial and normalized with respect to baseline. A decrease in the gain from baseline is seen for all subjects.

7.1.5 Conclusion

The results show a clear decrease in saccadic amplitude following gain decreasing adaptation. It further elucidates the fact that greater intrasaccadic jump following eye movement, elicits greater gain changes of the ocular motor system. The conclusion obtained from this pilot study validated the use of a 3 degree intrasaccadic jump in our adaptation trials for the final experiment.

8 Appendix 2

8.1 Comparison of gain changes without normalization procedure: Method of testing using coefficients of polynomials.

Aim: To investigate the effect of the normalization procedure on the results.

The methodology employed in the study required a normalization procedure in order to ideally compare the two groups without baseline differences in the gain affecting the results.

The magnitude differences in saccadic adaptation were compared using gains which were not normalized. The data from each of the subject were fitted with a third order polynomial of the equation $Y = A + B1*X + B2*X^2 + B3*X^3$ and the coefficients were compared between the athlete and the non athlete group using independent t tests.

Gain decreasing paradigm: In the gain decreasing paradigm, the normalization procedure did not show any effects (See Table 10 and 11 for data of non athletes and athletes). The magnitude of saccadic adaptation was not significantly different between athletes and non athletes. See Table 12 for the statistical results of independent tests on the coefficients.

Table 10. Saccadic adaptation data for non athletes - gain decreasing paradigm.

Non Athletes	A	B1	B2	B3
NA 1	1.035	-0.085	0.008	0.000
NA 2	0.907	0.012	-0.010	0.001
NA 3	1.095	-0.160	0.030	-0.002
NA 4	1.286	-0.094	0.007	0.000
NA 5	1.135	-0.244	0.049	-0.003
NA 6	0.890	-0.090	0.012	-0.001
NA 7	1.612	-0.411	0.090	-0.006
NA 8	0.876	-0.026	-0.005	0.001
NA 9	0.973	-0.103	0.014	0.000
NA 10	0.984	-0.063	0.006	0.000
NA 11	1.189	-0.107	0.001	0.001
NA 12	0.975	-0.093	0.019	-0.001
NA 13	0.823	0.052	-0.023	0.002
NA 14	0.890	0.006	-0.009	0.001

Table 11. Saccadic adaptation data for athletes - gain decreasing paradigm.

Athletes	A	B1	B2	B3
A1	1.033	-0.045	0.002	0.000
A2	1.083	-0.092	0.014	-0.001
A3	1.145	-0.170	0.028	-0.001
A4	1.006	-0.009	-0.005	0.000
A5	1.066	-0.084	0.015	-0.001
A6	1.015	-0.006	-0.018	0.002
A7	1.083	-0.084	0.003	0.001
A8	1.092	-0.112	0.008	0.001
A9	1.094	-0.118	0.018	-0.001
A10	1.099	-0.123	0.016	0.000
A11	1.099	-0.112	0.012	0.000
A12	1.328	-0.435	0.088	-0.006
A13	1.009	0.002	-0.014	0.002
A14	1.072	-0.087	0.000	0.001
A15	1.090	-0.120	0.012	0.000
A16	1.063	-0.066	0.004	0.000
A17	0.931	0.105	-0.047	0.005
A18	1.055	-0.053	0.000	0.001
A19	1.112	-0.126	0.014	0.000
A20	1.128	-0.175	0.040	-0.003
A21	1.150	-0.197	0.038	-0.002
A22	1.003	0.001	-0.012	0.002
A23	1.213	-0.262	0.056	-0.004

Table 12. Hypothesis testing of the coefficients of third order polynomial fit for the groups using independent t tests. Statistically insignificant differences are indicated by the p value greater than 0.05.

	t value	df	p value
B^3	-0.406	35	0.681
B^2	0.181	35	0.856
B^1	0.070	35	0.944

Gain increasing paradigm: The magnitude of saccadic adaptation was not significantly different between athletes and non athletes (Table 13 and 14) when the data was not normalized. Using the coefficient testing method, the results showed no significant differences (Table 15).

Table 13. Saccadic adaptation data for non athletes - gain increasing paradigm.

Non Athletes	A	B1	B2	B3
NA 1	0.843	0.105	-0.017	0.001
NA 2	0.839	0.046	-0.006	0.000
NA 3	0.892	0.104	-0.018	0.001
NA 4	1.001	-0.048	0.017	-0.002
NA 5	0.832	-0.003	0.004	0.000
NA 6	0.910	0.064	0.002	-0.001
NA 7	0.914	0.001	0.008	-0.001
NA 8	0.723	0.079	-0.016	0.001
NA 9	0.791	0.127	-0.029	0.002

Table 14. Saccadic adaptation data for athletes - gain increasing paradigm.

Athletes	A	B1	B2	B3
A1	0.830	0.197	-0.041	0.003
A2	0.507	0.266	-0.067	0.005
A3	0.835	0.086	-0.018	0.001
A4	0.604	0.095	-0.022	0.001
A5	0.813	0.122	-0.028	0.002
A6	0.659	0.279	-0.034	0.001
A7	0.739	0.123	-0.024	0.002
A8	0.923	-0.118	0.040	-0.003
A9	0.869	0.099	-0.018	0.001
A10	0.912	0.040	-0.005	0.000
A11	0.806	0.059	-0.002	-0.001
A12	0.795	0.096	-0.017	0.001
A13	0.724	0.192	-0.049	0.004
A14	0.818	0.061	-0.011	0.001
A15	0.788	0.196	-0.044	0.003
A16	0.863	0.026	0.000	0.000
A17	1.063	0.064	-0.008	0.000
A18	0.768	0.145	-0.027	0.002

Table 15. Hypothesis testing of the coefficients of third order polynomial fit for the groups using independent t tests. Statistically insignificant differences are indicated by the p value greater than 0.05.

	t value	df	p value
B^3	1.540	25	0.135
B^2	1.710	25	0.099
B^1	-1.747	25	0.092

The results of the coefficient testing applied when the gains are not normalized, also appear to show no statistically significant differences. The normalization procedure eliminates the variability at the baseline and hence comparing the coefficients to study the effect of adaptation between two groups appear more logical as we are dealing with similar Y axis values.

9 Appendix 3

9.1 Fatigue effects

9.1.1 Aim

To investigate whether fatigue was induced as a result of the adaptation paradigms in the experiment.

9.1.2 Methods

To study whether fatigue was induced on account of the experiment, the latency of saccades before adaptation (i.e. saccades of the baseline trial) and following adaptation (saccades of the recovery trial) were compared using a paired t test for all subjects. Data from session one and session two were compared separately.

9.1.3 Results

The results show that there is no significant difference in the latency before and after adaptation (Figure 22). For the first session the mean difference in latency before and after adaptation was - 3.59 msec. This was statistically insignificant ($t = -0.932$; $df = 37$; $p = 0.357$). For the second session the mean difference in latency was - 1.802 msec. This was also statistically insignificant ($t = -0.89$; $df = 38$; $p = 0.378$).

9.1.4 Discussion

Latency is the measure of visuo-motor reaction time. It has been considered a reasonable predictor of fatigue effects, as fatigue tends to reduce the initiation of the response.[116] The insignificant difference in latency shows that fatigue effects were not observed in this experiment.

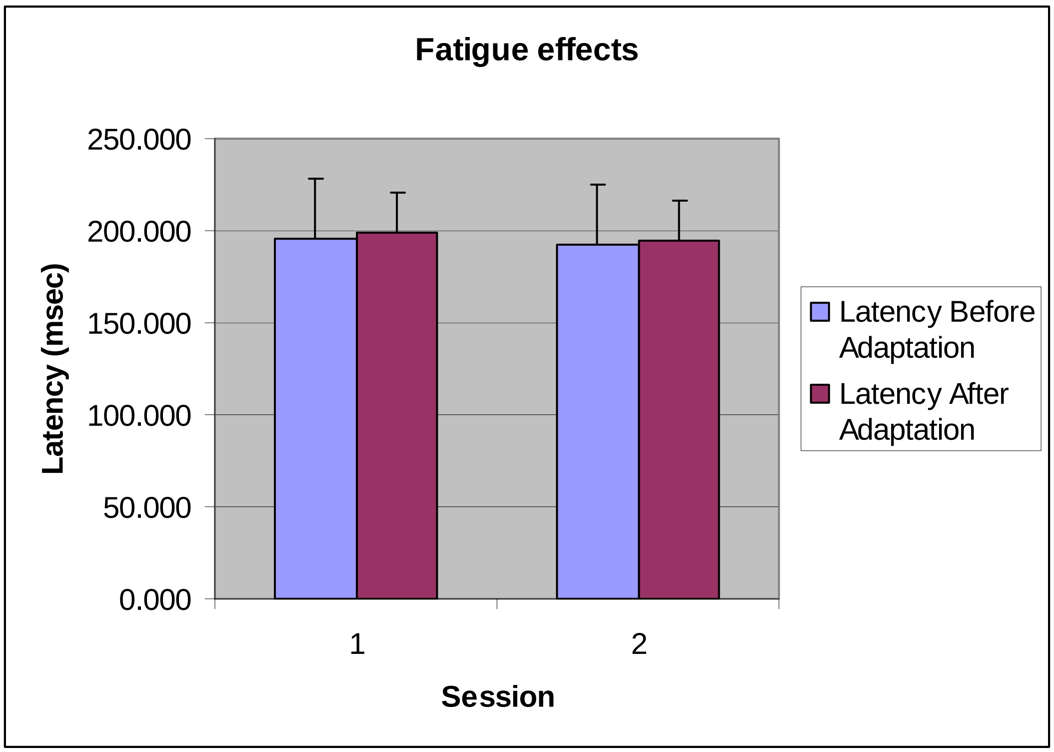

Figure 22. Graph showing the mean saccadic latency before and after adaptation in session one and two.

9.1.5 Conclusion

Fatigue effects were not seen following adaptation in our experiment.

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