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Golfers, coaches and researchers alike, have all keyed in on golf putting as an important aspect of overall golf performance. Of the three principle putting tasks (green reading, alignment and the putting action phase), the putting action phase has attracted the most attention from coaches, players and researchers alike. This phase includes the alignment of the club with the ball, the swing, and ball contact. A significant amount of research in this area has focused on measuring golfer's vision strategies with eye tracking equipment. Unfortunately this research suffers from a number of shortcomings, which limit its usefulness. The purpose of this thesis was to address some of these shortcomings.

The primary objective of this thesis was to re-evaluate golfer's putting vision strategies using binocular eye tracking equipment and to define a new, optimal putting vision strategy which was associated with both higher skill and success. In order to facilitate this research, bespoke computer software was developed and validated, and new gaze behaviour criteria were defined.

Additionally, the effects of training (habitual) and competition conditions on the putting vision strategy were examined, as was the effect of ocular dominance.

Finally, methods for improving golfer's binocular vision strategies are discussed, and a clinical plan for the optometric management of the golfer's vision is presented. The clinical management plan includes the correction of fundamental aspects of golfers' vision, including monocular refractive errors and binocular vision defects, as well as enhancement of their putting vision strategy, with the overall aim of improving performance on the golf course.

This research has been undertaken in order to gain a better understanding of the human visual system and how it relates to the sport performance of golfers specifically. Ultimately, the analysis techniques and methods developed are applicable to the assessment of visual performance in all sports.

Key words: Eye Tracking, Sports Performance, Sports Vision, Vision Strategy

Dedication

"Life isn't about finding yourself. Life is about creating yourself" – Author Unknown

As a way of saying thank you, this thesis is dedicated to all of those who have helped me create – Mark, Doug, Sandie, Johanna, Bryan, Rock & Ida, Harold & Olga, Barrie & Flo, Tracey & Richard, Edwina, Jane, Stephanie, Kathryn, Katherine, Nikki, Viena and Erin.

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Chapter 1

INTRODUCTION

Golf is a popular sport worldwide, and appeals to individuals of all ages. It is one of the few ball games that does not have a standardised playing area; hence every golf course in the world has a unique design which adds to the game at each venue. A “round” of golf typically consists of 9 or 18 holes played in order as determined by the course layout, and the aim is to sink the ball on each of the holes played with as few strokes as possible.

Golf holes are made up of three main components: a tee box, a fairway and a putting green which surrounds the target, more commonly referred to as the cup or hole. In addition to these components, golf holes may also have various obstacles on them including water hazards, sand bunkers and rough. Golfers must hit the ball from the tee box towards the target (the hole) using a combination of shots or strokes, including drives, approaches, chips, pitches and putts. The shot required is determined by where the ball lies in the field of play, the location of the target, and various other factors including the weather conditions and the golfer’s skill.

Each hole, and ultimately each course, designates the ideal number of strokes golfers should use to sink the ball. This is commonly known as “par”. The score on a hole is determined by the number of strokes taken relative to par. A hole completed with the exact number of recommended strokes (par) is given a score of zero, whereas every extra stroke used counts as +1 and every stroke less counts for -1. Scores from each hole are summed over the 18 holes of the round to determine the golfer’s final score. In tournament play the scores from each round are then summed over the number of rounds played. The world’s top professional golfers routinely complete rounds with fewer strokes than recommended and have negative scores which are below par. More commonly, amateur golfers require more than the recommended number of strokes and have positive scores which are above par. A handicap is an average score, calculated on golfers’ performance on individual holes and approximates how many strokes above or below par they should be able to play. It is often used as an indication of a golfer’s skill; a higher handicap is an indication of lower skill and vice versa.

Strokes used in golf include drives off the tee box, iron shots on fairways, chips and wedge shots out of bunkers and sand traps, and putts, used on the putting green. Putts account for approximately 43% of the shots taken in golf game,[1] despite putting greens comprising only a small proportion (approximately 2%) of the total course area.[2] For these reasons, putting is often considered to be one of the most important aspects of a golf game. It is often considered to be one of the most difficult as well.[1]

Visually, putting is a very complex task due to its unpredictable nature and the accuracy and precision required for success. The visual requirements of putting can be broken down into three principle elements, each distinguished by the demands placed on the visual system. These three elements are green reading, alignment, and the putting action phase.

1.1 Reading the Green

Green reading is the most visually complicated of the putting elements, although arguably it is also the skill that requires as much natural talent as technical expertise. Green reading requires accurate judgment of the distance of the ball from the hole, judging the amount of friction the grass will exert on the ball, reading the contours of the green to determine how the ball will break, and understanding how the type and cut of the grass, the time of day, the lighting and the weather will affect the path and speed of the ball once it is hit, not to mention the unpredictable effect of footprints left by other players earlier on the green.

The purpose of green reading is to perceive how the conditions listed above will affect the path of the ball, and to choose a line or a direction to hit the ball, which compensates for the conditions at hand. In choosing a line, golfers must decide on a target to aim towards, which is, more often than not, a blade of grass or a unique feature of the green rather than the actual hole. The hole is rarely chosen as the target of the aim line, because most putting greens are not flat and golfers must aim towards a point which compensates for the slope and speed conditions of the green instead.

In terms of vision, green reading demands the use of stereopsis and colour contrast sensitivity, both of which are affected by a player's visual acuity and colour vision. Stereopsis is important for judging the distance between the ball and the hole, and colour perception and contrast sensitivity are important for perceiving the contours of the green.

Using the club as a plumb-bob has been recommended as a method for reading the slope of greens in some literature[3, 4] and rejected in others.[1, 5, 6] The plumb-bob method requires that the golfer stand behind the ball, perpendicular to the slope of the green beneath their feet, straddling an imaginary line that bisects the hole, golf ball and stance of the golfer. The golfer then suspends the putter at arm's length in front of their face, such that both the ball and the hole can be sighted within the length of the shaft; gravity is then allowed to pull the shaft into a true vertical alignment. Using the dominant eye the golfer aligns the bottom of the shaft with the centre of the ball and in theory, if there is a slope in the green, the top end of the shaft will be on the high side of the hole.

Mackenzie and Sprigings evaluated the plumb-bob method for reading greens, and found that it was an invalid system, particularly because the plumb-bob method was entirely dependent on the slope beneath a golfer's feet, which may or may have had any association with the slope of the green between the ball and the hole. The plumb-bob method was also deemed to be highly inconsistent, as participants' body positions deviated in an unsystematic manner from the normal to the slope by 1.5° on average. This error translated into reading an extra 0.08m of break on a 1.4m (4.5ft) putt, which would result in a missed putt.[7]

Aside from the Mackenzie and Sprigings study, there has been no other peer-reviewed research published on green reading in general, and no peer-reviewed research has been published about the visual strategies golfers use to read greens. This may be a due to the many factors listed above which affect the path of the ball on the green; objectively studying a complex system such as green reading would be very difficult as each factor would need to be studied independently as well as in conjunction with the other factors in order to understand how they impact performance.

Moreover, research has demonstrated that greens themselves are inconsistent. Pelz measured the inconsistency of greens and found that only 84% of putts from 12 feet (3.7m) went in the hole on a green that was considered to be in excellent condition when all other swing characteristics were identical. On a different green, Pelz found that 73% of putts from 12 feet rolled into the hole in the morning and only 30% of putts were holed on the same green after a day of play.[8] Studying vision strategy in green reading is further complicated by the difficulty of extracting internal factors such as attention and experience from the analysis of performance.

1.2 Alignment

Putting consists of two discrete visual alignment tasks that are dependent upon each other. The first of these tasks is aligning the ball with the aim line of the putt; the second is aligning the club with the ball prior to the start of the swing. Aligning the club with the ball actually takes place in the putting-action phase (defined below), but it is discussed in conjunction with ball alignment because they are similar vision tasks. An alignment error in either or both of these tasks usually results in a missed putt. From a vision perspective, both of these tasks are highly dependent on making accurate Vernier acuity judgments.

The majority of alignment research in golf has concentrated on the alignment of the club with the ball, and particular emphasis has been placed on swing mechanics. Pioneering work in this area by Pelz found that angular alignment (face angle) determined 83% of the initial direction of the putt, whereas horizontal alignment (putter path) accounted for a mere 17% of the putt direction.[1] In 2002, Karlsen and Nilsson studied the variability (standard deviation) in face angle, putter path and impact point of eight elite players, and determined them to be 0.5°, 0.8° and 2.9mm respectively.[9] In an additional study, Karlsen and Nilsson found that horizontal miss-hits (toe-heel direction) caused of deviation of 0.034° per millimetre miss-hit from the sweet spot, or centre of the club.[10] However, in both of these studies misses were measured relative to the target direction, making it impossible to differentiate between aiming errors and errors in the stroke.[10]

In 2008 Karlsen, Smith and Nilsson measured alignment errors between the aim line (judged by the face angle of the putter at address prior to the start of the backswing) and the actual stroke direction. Mean variability was expressed as the standard deviation in degrees for face angle and putter path, and in millimetres for the horizontal impact point. An effective variability was calculated for each factor by multiplying each factor's mean variability by its coefficient of effect[**] on initial putt direction as described by Pelz.[1] A stroke direction variability factor was calculated based on the variances and covariances in the face angle, putter path and horizontal impact point.[10]

[**] The coefficient of effect is a numerical value describing the amount of influence each aspect of the putting stroke has on the starting direction of the putt and is based upon calculations by Pelz.[1]

Karlsen, Smith and Nilsson's population of 71 "elite" golfers (handicap 1.8±4.2) included 10 golfers playing in the highest professional level tournaments in the USA and Europe (Top Professionals), 16 other professional golfers (Club Professionals), and 45 golfers who were likely highly skilled amateurs as their handicap <10. The term "elite" used to describe this population of golfers is misleading, as the population consisted not only of elite Top Professional golfers on the American and European professional tours, but also highly skilled amateur golfers with low handicaps. That being said, Karlsen, Smith and Nilsson found that, on average, stroke direction variability was low (European Tour: 0.39°, Overall Population: 0.59°, range 0.28° to 1.2°), as was mean horizontal impact point variability. Overall, the golfers were found to be more consistent in face angle (Mean variability: 0.60±0.22°) than in putting path (Mean variability: 1.04±0.39°). The effective variability, which accounted for the coefficient of effect on initial putt direction, was lower still (0.50±0.18°, 0.18±0.06° and 0.09±0.03mm respectively). Based on these results, Karlsen, Smith and Nilsson concluded that stroke consistency was related to playing handicap ($p<0.001$) but stroke variability was not a significant determinant of putting success. Therefore, it was suggested that coaches and golfers would benefit more from focusing on green reading and aiming in training rather than on stroke technique.[10]

In addition to these studies, alignment has been also been studied under circumstances whereby putter alignment was independent of stroke mechanics. Johnston, Benton and Nishida examined whether the perception of the aim line in address was affected by persistent visual illusions. 15 experienced golfers with handicaps of 0 to 30 (very good club players to average amateurs) were asked to complete an exocentric pointing task by aligning a white pointer on a black background with a target that was 2m distant. Golfers completed the task while standing in a putting stance on the right and left sides of the pointer and standing behind the pointer. The position of the pointer was computer controlled and participants used a mouse to adjust its position. All of the golfers were found to make systematic errors in the pointer alignment, and the errors were dependent upon the golfers' stance. When standing on the left, golfers made significant errors in a clockwise direction (1.25°, $p<0.01$); from the right, golfers made significant errors in the anticlockwise direction (-1.56°, $p<0.01$). Alignment errors made from behind the pointer were not significantly different from zero ($p=0.58$) and were found to be independent of both skill (Handicap, $p=0.67$) and putting accuracy ($p=0.47$). Based on these results, Johnston, Benton and Nishida concluded that golfers demonstrated a systematic perceptual error in reading the aim line from an address position that was unaffected by expertise and did not transfer to errors or bias in the motor task of putting.[11]

Van Lier and colleagues conducted two interesting studies in 2011, which were designed to expand upon the work of Johnston, Benton and Nishida. The initial study investigated novice golfers perceptual error in perceiving the direction of the aim line relative to their head position as well as differences in perceived direction and putting accuracy between novice and skilled golfers.[12] Perceived direction was measured using a computer-controlled pointer (3mm thick needle protruding from the front and back of a perforated golf ball), and the angle (in visual space) between the pointer and the aim line of the putt was measured. Putting accuracy was assessed with a putting task, and the angle between the aim line and the actual path of the ball was measured. Golfers wore liquid crystal shutter glasses to prevent observational feedback on the putting accuracy task. Additionally, no verbal feedback was given to the golfers during either test session.

In the first part of the study, novice golfers took a putting stance on the right and left sides of the pointer and aligned the pointer with the hole on the green. Initially golfers able to position their head either next to the ball or above the ball in free space (n=12), and then the study was repeated with golfers head's fixed (n=15) above the ball so that their line of sight was directly perpendicular to the aim line on the green. Golfers were found to make significant errors in judging the perceived distance when their head positions were either next to or above the ball in free space, but not when their head was fixed above the ball. Additionally, the direction of the perceptual errors depended upon which side of the ball the golfer stood on ($p<0.01$). Golfers who stood on the left tended to make clockwise errors, while golfers who stood on the right tended to make anticlockwise errors. Based on these results, Van Lier, Van der Kamp and Savelsbergh concluded that, a golfer should stand such that their head is positioned directly over the ball allowing the eyes to travel in a plane perpendicular to the green in order to obtain the most accurate information.[12]

In the second part of the study, perceived direction and putting accuracy were compared between novice (n=11) and skilled (n=11, handicap range, 0 to 5) golfers. Based on their handicap, the skilled golfers would be comparable to very good club level players. Both perceived direction and putting accuracy were measured with golfers' heads free and fixed above the aim line while the golfers stood on the left hand side of the ball (they were putt right handed). Novice golfers tended to make clockwise errors in perception, whereas skilled golfers were found to make anticlockwise errors in perception. Novice golfers were also found to make a significant clockwise (rightward) error in putting accuracy ($p<0.05$), but the skilled golfers did not demonstrate any significant errors in putting accuracy. As a result, Van Lier, Van der Kamp and Savelsbergh suggested that highly skilled golfers might have had initial rightward (clockwise) errors in perceived direction and putting accuracy (similar to the novices) which was corrected through the use of visual feedback and calibration of the entire system.[12]

Van Lier, *et al* conducted a second study to determine whether the skill related perceptual differences in perceived direction (i.e. novices making rightward errors versus skilled golfers making leftward errors) were due to a transfer of calibration between putting action and perception in the skilled golfers. This study was again designed in two parts, the first of which involved the determination of the head position associated with the greatest perceived depth error. Right-handed novice golfers (n=10) were asked to complete the same perceptual task described above from four different head positions that varied in height (75cm and 150cm) and lateral distance (75cm and 150cm) from the ball. The results demonstrated that the head position furthest from the ball (150cm high, 150cm wide) was associated with the most consistent and reliable perceived distance error. This head position was then used in the second part of the study, which was designed to examine the effects of calibration.[13]

In the second part of the study, right-handed novice golfers (n=39) were assigned either a perception training (n=9), an action training (n=8) or a control (n=8) group. The two training groups participated in a pretest-practice-posttest-retention type study design, while the control group only completed the pre-test, post-test and retention assessments. At each of the pre-test, post-test and retention visits, both perceived direction error and putting performance accuracy were measured. In the practice session, specific verbal feedback was given to each of the training groups regarding their individual task. Interestingly, both perceived direction and putting accuracy were found to be amenable to training, however improvement only occurred in the group that received the task-specific training. Perceived direction errors were found to significantly smaller in the perception trained group but not in the action trained or the control groups. Putting accuracy was found to significantly improve in the action trained group but not in the perception trained or control groups.[13]

Based on these above results, Van Lier *et al*. concluded that both perceptual and action tasks associated with putting could be trained but that training of one task did not transfer to improvement of the other task in this particular group of novice golfers. As the novice golfers had relatively little experience with golf putting (144 putts over 3 days), the authors suggested that transfer between perception and action training may still occur with longer training periods of months or years.[13] To date, no further investigation of the transfer of skills between perception and action in golf putting have been conducted to investigate the long-term effects of training, nor have any studies been conducted which investigate the effects of training in skilled golfers.

The studies conducted by Johnson, Benton and Nishida,[11] Van Lier, Van der Kamp and Savelsbergh[12] and Van Lier *et al*.[13] provide interesting information regarding the perception of a straight line from a putting stance. Unfortunately, these studies were mostly conducted on novice golfers with no golfing experience and are limited in that they do not represent the behaviour of experienced golfers. Additionally the perceived distance task was not truly representative of golf putting alignment tasks. Typically, golfers walk around the putting green when reading it and then position themselves behind the ball when aligning it. Therefore, when addressing the ball, golfers need only align their club with the ball and hit a straight putt. In aligning the club and the ball, many golfers (professionals included) use the logo on the ball or a straight line as a guideline that can be aligned with both the aim line and the markings on the club. In fact, Van Lier, Van der Kamp and Savelsbergh advocate for the importance of reading the green and using the ball logo as an alignment aid to help overcome the distortions in perceived direction.[12]

When using a guideline on the ball, alignment of the club and the ball essentially becomes a Vernier acuity task. Recent research by Guillon *et al*. supports the use of an alignment guideline, and has found that in terms of horizontal alignment, individuals are actually capable of making finer judgments of alignment than is needed for accurate horizontal club alignment.[14] With respect to angular alignment judgments though, individuals were not as successful. In a study of 25 individuals, who were not golfers, the average angular alignment that could be detected was 0.6°, which on a 12 foot (3.66m) putt was equal to a 31.8mm error.[14] Considering a golf ball must not be less than 42.67mm in diameter[15] this is a significant alignment error which would result in a missed putt.[14]

Alignment judgments have been shown to be more accurate when made monocularly, as monocular judgments do not suffer from the same parallax errors that affect binocular judgments. Unlike traditional Vernier acuity studies where alignment judgments are made under monocular conditions, judgments of alignment in golf are made under binocular conditions. Ocular dominance provides a unique avenue for the creation of monocular-type conditions in a binocular environment. Studying vision strategy in putting alignment requires the study of visual aids and techniques that can assist in these essential alignment judgments, including optimising ball markings and understanding ocular dominance and how it can be manipulated to create ideal conditions for the judgment of alignment in a natural golf environment.

1.3 Putting Action Phase

The putting action phase is the portion of the putt that starts when a golfer addresses the ball with the putter, and ends when the ball has left the putter after contact. This phase is the biomechanical-action phase of the putt, and has attracted the attention of players, coaches and researches alike, as it is believed to significantly influence performance. During this phase that the club is lined up with the ball, the backswing is taken and the ball is struck with a predetermined amount of force to start the ball moving in the direction of the hole. With the highest motor demand of the three putt phases, the putting action phase is highly susceptible to external and internal distracters, including stress.

An early study by Gott and McGown looked at the effect of putting stance and points of aim on the putting accuracy of 16 novice golfers. The conventional and the side-saddle stances were compared as were the eyes on the ball and eyes on the hole points of aim. Subjects were taught each of the four stance/point of aim combinations (one at a time) and were given 2 week training period per combination to learn the method prior to testing. Accuracy testing involved assessment of putting success at both 5 and 15 feet. The analysis revealed that there was no single combination of stance and point of aim which performed significantly better at either distance, and the authors concluded that other putting methods were equally as good as the conventional, eyes on ball stance.[16] However, this conclusion is only applicable to the study population, namely novice golfers who did not have any prior golf experience, and should not be construed to apply to established amateur or professional golfers.

Alpenfels and Christina investigated the strategy of looking at the hole or breakpoint of the putt, rather than looking at the ball immediately before starting the backswing. 40 golfers ranging in handicap from 8 to 36 were split into two groups (n=20 per group) that were balanced in terms of skill, age and gender; one group used the conventional method of looking at the ball during the putt, while the other group looked at the hole. Each golfer completed nine putts from distances of 3 to 43 feet in a random order. On putts between 28 and 43 feet in length, the group who looked at the hole during the stroke putted to within 28 inches of the hole, while the group who looked at the ball during the stroke had 37 inches remaining between the ball and the hole. This difference was stated as being statistically significant, although no p-values were provided. Golfers looking towards the hole during the stroke were found to do better on short putts (3 to 8 feet) as well, although this difference (9 inches to the hole versus 12.5 inches to the hole in the group looking at the ball), was not statistically significantly.[17] Alpenfels and Christina concluded that golfers who looked towards the hole or breakpoint were more successful in getting the ball closer to the hole, than those who looked at the ball. Unfortunately Alpenfels and Christina did not report any information regarding the accuracy of the putts made, and it was not possible to determine if golfers looking at the hole were more accurate overall.[17]

More recently, Mackenzie, Foley and Adamczyk evaluated the impact on the putting stroke of focusing on the ball in the traditional method compared with focusing on the hole during the backswing. 31 participants (handicap 18.7±10.4) participated in this study, which consisted of pre-test and post-test sessions where both focusing techniques were tested at 1.22m and 4m distances. Based on their handicap, the golfers would have been primarily amateurs of average skill level. Between the test sessions, golfers were given a 4 week practice period and were instructed to practice with only one of the focusing techniques (ball or hole). The kinematics, of every putting stroke made during the test sessions were recorded with a TOMI® system. The TOMI® system (www.tomi.com) is an electronic instrument which measures the motion of the putter in three-dimensional space throughout the putting stroke. In this particular study, the TOMI® system was used to assess the variability in putter speed, face angle, stroke path, and impact spot on the putter face at contact. Both practice groups demonstrated improvement at the post-test session and the group that practiced focusing on the hole demonstrated reduced variability in putter speed when compared with the group who practiced focusing on the ball. No other differences were found between the two groups.[18]

A series of similar studies have investigated the effect of ocular dominance on putting stance and visibility of the hole and produced mixed results. This research will be discussed in more detail in Chapter 4, Ocular Dominance and Golf. This chapter focuses specifically on ocular dominance in golf.

All of the studies reviewed above are to some degree based upon the assumption that the golfer makes critical judgments during the putting action phase about the direction and speed of their putt, manipulating their swing if need be to compensate for contours of the green. However, most professional golf coaches are not advocates of golfers manipulating their swing to compensate for the green. Instead coaches recommend that the ball should be aligned in the direction of the putt, and that decisions regarding distance and speed be made before the player addresses the ball. Rather than using the hole as a target, golfers are encouraged to pick an aim line, targeting a break point that will cause a straight putt to bend towards the hole after it is hit. Once a target is selected, golfers need only to align the club with the ball as if they were making a straight, flat putt and swing. The golfer's responsibility during the swing is simply to start the ball rolling along the previously chosen aim line with the correct speed; the contours of the green are meant to do the rest of the work.[1]

From a biomechanical perspective, the approach advocated by coaches is the simpler of the two. Using this approach, golfers' only need to learn one swing, rather than a multitude of swings to compensate for left- and right-breaking, up- and downhill greens, and it is for this reason, that coaches and golfers alike, spend a great deal of time, studying and practicing the swing. Arguably, a perfect swing will be of little help if the ball is not aligned properly, but a highly consistent and repeatable swing, performed with little or no thought, allows golfers to concentrate on other tasks such as reading the green and alignment of the ball with the hole and the putter with the ball.

Automation of the swing helps to reduce the impact of stress on performance as well; once decisions have been made, all that remains is for the golfer to perform an action they have practiced extensively. When the swing is more instinct than conscious action, golfers rely almost entirely on kinesthetic motor memory and do not need to think consciously about their mechanical actions. Neurological magnetic resonance imaging (MRI) studies of golfers' brain activity during video simulations support the coach endorsed, automated swing approach to putting, as they have demonstrated that elite golfers demonstrate less overall brain activity and activation of fewer areas of the brain, compared with novice golfers. This is a important for performance because activation of fewer areas of the brain means that the potential for distracting thoughts and stress to impact performance is smaller.[19, 20] Studies of other sports, such as archery and shooting,[21] have also found differences in neural activity between expert and novices, whereby experts seem to demonstrate more efficient neural processing.[22-26]

From a vision perspective, the putting action phase relies on Vernier acuity, ocular dominance and gaze behaviour control aspects of the visual system. Of these three components, manipulating gaze behaviours to enhance performance has been studied the most extensively. To date, research has focused on understanding the pattern of gaze behaviours used by elite, amateur and novice golfers when putting, how these gaze patterns influence performance in stressful situations, and what happens to performance when the gaze behaviours are specifically trained. Eye tracking equipment is particularly useful for studying the vision strategies of golfers, and it has been commonly used for this research.

1.4 Eye Tracking in Golf

Historically, eye tracking research in sport has focused on understanding both the general pattern of eye movements (fixations, pursuits and saccades) used to collect information from the environment, and the location and duration of gazes during critical moments in the performance of a skill. For example, in basketball researchers studied the pattern of gazes used by athletes throughout a free throw shot, as well as the parameters of the final fixation that was made before the ball was released.[27] The aim of this research has been to improve on-field performance through understanding how gaze behaviours are associated with both higher skill and success. In golf, eye tracking research has focused principally on the fixations and other gaze behaviours used during the putting action phase, including the address, backswing, ball contact and follow through.

The earliest published work investigating the vision strategy of golfers with eye tracking equipment was conducted in the early nineties at the University of Calgary by Dr. Joan Vickers. Vickers recorded the eye movements of both low skill (n=5, handicap 14.1; range 10-16) and higher skill (n=7, handicap 6.2; range 0-8) golfers while they performed consecutive flat 3m putts until 10 hits (successful putts) and 10 misses were obtained. The low skilled golfers would have been considered very good amateurs, or average club level golfers, whereas the higher skilled golfers would have all been very good club level players. Golfers wore a mobile ASL 3001H Eye view monitor (Applied Science Laboratories, Bedford, USA), which was a monocular bright pupil, corneal reflection system that measured gaze direction relative to a helmet. Various gaze behaviours were examined throughout the duration of the putt, including the length and location of specific fixations, and the pattern of fixations and saccades used.[28]

Higher skilled golfers (lower handicap) were found to use a vision strategy that included longer fixations on the ball and the target and fewer fixations on the club compared with the lower skilled golfers (higher handicap). Higher skilled golfers also shifted their gaze between targets faster (used more express saccades), and maintained their gaze on the putting surface longer after ball contact. Finally, the last fixation prior to the initiation of the backswing was found to be longer (1788ms versus 911ms) in golfers with higher skill levels, and on successful putts, regardless of the golfer's skill level. Based upon these results, Vickers proposed that an ideal vision strategy in putting would be one in which express saccades to the putter were used in the preparation phase, along with a single fixation of greater than 1700ms directed to the ball during the back/forward swing phase and a stable fixation on the green for over 200ms after ball contact. This strategy was hypothesised to improve golfer's performance by reducing the amount of distracting information collected throughout the movement (i.e. thoughts about swing mechanics) and by increasing the precision of the visual-motor co-ordination of the hands when the putter contacted the ball.[28]

The last fixation prior to the backswing has since been termed the "quiet eye",[29] and has been examined in many sports, including golf, basketball, ice hockey and volleyball. It has been defined as "the final fixation or tracking gaze prior to the onset of the critical action, that is located on a specific location or object in the visuomotor workspace within 3° of visual angle (or less) for a minimum of 100ms".[29-31] The quiet eye has been proposed as the period of time when task-relevant environmental cues are processed and motor plans are coordinated for successful completion of the upcoming task. Longer quiet eye periods are thought to give performers more time to program their movements, and minimise distractions from other environmental cues.[29-31]

A 2001 report by Fairchild *et al*. looked at the visual strategies of four golfers (one novice, one beginner, one intermediate and one advanced) both qualitatively and quantitatively using an Applied Science Laboratories E5000 eye tracker (Bedford, USA). Each golfer took 20 putts on two different artificial green setups for a total of 40 putts. All 40 putts were assessed qualitatively by authors who viewed the videos recorded by the eye-tracker and noted their impressions of the golfers' performances. Additionally 12 putts (6 from each artificial green condition) were assessed quantitatively on a frame-by-frame basis. The first artificial green setup was an 8 foot, relatively straight uphill putt which broke 1inch to the left, and the second artificial green setup was an 8 foot right-to-left rollover, whereby the green was uphill for the first 4 feet and downhill for the last 4 feet and broke 6 inches to the left.[32]

In the qualitative analysis, the advanced golfer was found to have the most consistent routine which included using the markings on the ball to align it with the target, a practice swing, visualisation of the ball path and a defined set routine. As the skill level of the golfers decreased, so too did the consistency of their routines. This was mirrored by the success rates of the golfers, the highest success rate was found for the advanced golfer (100%), followed by the intermediate (75%), beginner (53%) and novice (3%) golfers. The authors suggested the qualitative analysis was consistent with traditional instruction golfers might receive regarding their stroke from a putting coach.[32]

In the quantitative analysis, the minimum fixation duration that could be measured was 33ms due to the limits of the video frame resolution; the maximum angular subtended by a fixation was not specified.[33] The investigators assessed the average duration of the total number of fixations made between addressing the ball and making the stroke (regardless of location) as well as the duration and location of the final four and final six fixations made prior to striking the ball. No other statistical analyses were conducted. The intermediate and advanced golfers were found to have slightly simpler, more consistent putting routines which averaged 1 or 2 fewer fixations per putt than the beginner and novice golfers (6-7 versus 8-9). The advanced and intermediate golfers' final four (Advanced: 0.88s; Intermediate: 1.19s) and final six (Advanced: 1.08s; Intermediate: 1.23s) fixations were longer than those of the novice (Final four: 0.51s; Final six: 0.57s) and beginner (Final four: 0.57s; Final six: 0.56s) golfers.

With respect to location, the advanced golfer spent relatively more time looking towards both the hole and the club during the final stages of each putt and this lead the authors to suggest perhaps the concept of looking at the ball might impair improvement in some golfers.[32] This study was severely limited in that only one player was included in each skill group and that the specific fixation criteria were poorly defined. Apart from the calculation of means and standard deviations, no other comparative statistical analyses were conducted which makes it impossible to draw any sort of conclusions from the results, particularly as the standard deviations were very large in comparison with individuals' mean values. The lack of statistical analysis was further confounded by the small sample size and the lack of a precise fixation definition, making it impossible to compare these results with other published literature. For these reasons, the study's conclusions are only the authors' opinions, suggestive of trends that require further investigation and validation in an appropriate powered study.

In 2002, Vickers and Crews measured electroencephalographic (EEG) recordings during the quiet eye in novices and members of the Ladies Professional Golf Association (LPGA) while they performed 3m putts on a sloped green. The number of golfers who participated in this study was not specified. Using the previously defined criteria,[28, 29] the LPGA golfers had a quiet eye which was approximately 2s in length, and demonstrated harmonised activity throughout the brain, while novices had shorter quiet eye durations of approximately 1.5s, and demonstrated brain activation which was variable across the brain and greater in some areas than others. Statistical analysis of these results was not presented. The harmonised activity in the brain of the professional golfers was thought to resemble an optimal state of arousal, where all areas of the brain fire synchronously and create an overall coherent and relaxed state. Of particular note in this study, was the fact that brain activation in the occipital region was higher in the novice golfers than in the professionals. The occipital region of the brain is highly involved in vision, and Vickers and Crews suggested this was due to the professionals having a more stable gaze (longer quiet eye) in which the same information was continuously processed, compared with the novice golfers who did not display the same precision and control of their gaze.[30, 34] Due to the lack of statistical testing and information about the study population, these results cannot be generalised to the population. As none of the conclusions drawn can be accepted at this time, these findings, much like those presented in the last study, can only be used to direct future research.

Based on the results of the quiet eye research,[28, 30, 34] Vickers later reported that good putters used rapid shifts of gaze between the ball and the target, alternating between fixations on the hole lasting one to two seconds and fixations on the back of the ball lasting 300 – 500ms. Good putters fixated the back of the ball through the back and forward swings, and maintained this fixation for almost a half second after contact. Finally, good golfers tended to take about eight seconds to putt when they are successful, and use an average of ten gazes (fixations and saccades) per putt. Taking longer and using more gazes reduced performance in good putters. Poor putters were found to have an entirely different gaze-control strategy, which included shorter fixations on the hole and the ball, an erratic scan path with gaze shifts which were either to fast or two slow, and an unstable fixation through the swing and at ball contact. Unlike good putters, poor putters' performance improved when they took more time and used more gazes per putt.[35]

Naito, Kato and Fukuda published a study investigating golfer's scanning patterns while putting. 17 golfers (three experts, three intermediates, eleven beginners) took part in this study which required golfers to complete ten 2m putts on a practice green while wearing an eye tracker (EMR-8, NAC Image Technology Inc., Tokyo, Japan) which recorded their gaze behaviours at 30Hz.[36] Each putt was analysed on a frame by frame basis, and the location of golfer's line of sight was recorded. Rather than measuring the duration of gaze behaviours (fixations, saccades, etc.), various locations were defined within the golfers' field of view, and the mean percentage of time the line of sight was in each of the location was quantified. The locations investigated included the side of the ball closest to the target, the centre of the ball, the hitting side of the ball, the club face and the direction of the target on the putting line. To facilitate analysis, putts were divided into five distinct phases. Phase 1 started 150ms before the club head moved in the backswing, phase 2 included all frames where the club head moved in the backswing, phase 3 included all frames where the club head moved towards the ball in the downswing, phase 4 was the frame in which the club made contact with the ball and phase 5 started immediately after phase 4 (ball contact) and lasted for 300ms. Line of sight locations were analysed in each phase independently.[36]

Overall, in each of the five putt phases, experts', intermediates' and beginners' gaze locations were significantly different (Beginner versus Intermediate, all phases: $p \leq 0.01$, Beginner versus Expert, all phases: $p < 0.001$, Intermediate versus Expert, all phases: $p \leq 0.001$). A secondary analysis of the percentage duration of gazes to the ball only (targeted side of the ball, centre of the ball, hitting-point side of the ball) found that beginners (Phase 1: 73.6%, Phase 2: 78.9%) and intermediates (Phase 1: 89.7%, Phase 2: 85.6%)

spent more time looking at the ball during Phases 1 and 2 compared with experts (Phase 1: 18.4%, Phase 2: 24.6%). Rather than looking at the ball, experts directed their line of sight opposite of the targeted direction along the putting line (along the putting line, on the side of the ball opposite the target). In Phase 3, experts and intermediates total gazes to the ball were similar (Experts: 33.4%, Intermediates: 66.3%,), and shorter than beginners (92.5%). At ball contact (Phase 4), experts and intermediates spent more time looking at the targeted direction on the putting line and less time looking at the ball (Experts: 10.0%, Intermediates: 21.9%) than beginners (84.1%). In the final phase of the putt, beginners spent most of their time looking at the rolling ball, whereas experts spent most of their time looking at either the rolling ball or at the club head. Intermediates spent most of their time in Phase 5 with their gaze in the same location it was in Phase 4, (primarily the targeted direction on the putting line). [36]

Based on their results, Naito, Kato and Fukuda concluded that beginners relied heavily on their central vision for information, and looked at the ball more as a result. Expert golfers on the other hand, were thought to be capable of using their peripheral vision to collect information more efficiently, as demonstrated by their use of a "visual pivot" which was not positioned on the ball.[**] Naito, Kato and Fukuda felt that the use of a visual pivot allowed experts to collect sufficient information about the putt with their peripheral vision while maintaining a stable head and gaze position. Although not specified, the information collected with the peripheral vision may have included spatial information about the green and information about the movement of the club relative to the ball. Intermediate golfers were found to behave like beginners in the early stages of the putt, and like experts in the later stages; this was thought to be an indication having higher skill than the beginner golfers that was not yet at an expert level. At this time the concept of a visual pivot, while an intriguing concept, is only a theoretical model put forward by the authors, which is not currently supported by research on peripheral visual attention and its relationship to the line of sight. Additionally, there were many more beginners enrolled in this study than either experts or intermediates, and this sample size bias could significantly affect the statistical analysis. Therefore, this study can only be considered as an indication of an aspect of golfers' visual strategy that merits further investigation, rather than a conclusive finding regarding golfers' visual strategies.

[**] A visual pivot is a virtual fixation point, which is not of significant value itself, but is an important locus for collection of peripheral vision information.

Van Leir, Van der Kamp and Savelsbergh conducted a study to examine the effects of slope on gaze in putting which was primarily focused on examining visual search behaviours at the hole, but also measured the final fixation prior to action (equivalent to the quiet eye). Gaze data from twelve high-skilled golfers (teaching golf professionals) was analysed in the study and the golfers were divided into two groups based on their skill level (High skill = >62% success on a putting task; Low skill = <40% success on a putting task). During the study golfers were asked to complete forty-five 1.8m putts on a green with a variable slope (0% or flat, 1% slope with a right to left break, 2% slope with a right to left break) while wearing an Applied Science Laboratories (Bedford, USA) monocular eye tracking system (25Hz) and using standardised equipment (putter and golf balls). Participants were asked to try hole the ball or at least get the ball as close to the hole as possible without overshooting.[37]

Fixations were defined as points of gaze that were directed at the same location within 1.5° visual angle for a minimum of 120ms. Four gaze locations were identified as being of particular interest: the hole and surrounding area, the area between the hole and the ball, the ball and putter head and a rest category which included fixations that were deemed to be unrelated to the execution of the task and excluded from further analysis. The number of gaze fixations, the mean fixation duration and the percentage viewing time (time spent viewing a single area divided by total fixation time) were measured for the hole, the area between the ball and the hole, and the ball and putter. The final fixation on the ball before the onset of the back swing was measured and the location of the hole fixations were established through the use of a linear scale to determine the location of the final hole fixation on every trial, the location of the highest hole fixation and the average hole fixation location. Additionally the outcome of the putt (success, miss to the left, miss to the right) was recorded and the proportion of successful, missed left and missed right putts was calculated for each slope condition independently.[37]

Putting performance (success, miss left, miss right) was not significantly affected by slope, although the successful group did hole significantly more putts than the less successful group ($p<0.001$). The visual search behaviours (number of fixations, mean fixation duration, percentage viewing time to the hole and the area between the ball and the hole), the final ball fixation duration, and the final hole fixation duration were similar between groups, on successful and missed putts and in all three of the slope conditions. Interestingly, the time between the final hole fixation and the initiation of the backswing was longer on successful putts (1.74s) than missed putts (1.58s, $p<0.05$), and the percentage of time spent viewing the ball was significantly shorter ($p<0.01$) in the 2% slope condition compared with the 0% and 1% conditions.[37]

With respect to hole fixations, they were located significantly further to the right on steeper slopes ($p<0.05$ to $p<0.01$), and this effect was more pronounced on successful putts. Van Lier, Van der Kamp and Savelsbergh concluded that golfers' successful adaptation to more complex environments, as demonstrated by the equal putting success rates on all slope conditions, was a result of changes in their visual search behaviour, particularly the visual search behaviour at the hole.[37]

In 2009, Wilson and Pearcy also investigated of golfers' gaze behaviours in both the preparation (line reading) and execution (ball striking) phases of putts with different break[**] characteristics. Six right-handed, university team golfers with reported normal vision were asked to take a series of twenty-five 3m putts on a green with a variable slope (0.9° left-to-right and right-to-left producing a 13cm break, 1.8° left-to-right and right-to-left producing a 25cm break, and flat with no break). Gaze behaviours were recorded at 25Hz with an Applied Science Laboratories Mobil Eye gaze-registration system (Bedford, USA), which is a monocular corneal reflection, dark-pupil eye tracker.[38]

The number of aiming fixations (three or more gaze points to the same location within 1° of visual angle, for 120ms or more), the duration of the final aiming fixation (the last fixation to the target location), the quiet eye duration and putt performance were assessed for each of the slope conditions. Although performance was worse on the severely sloped putts than in the moderate sloped ($p<0.001$) and flat conditions ($p<0.001$), and quiet eye duration was shown to be shorter on missed putts ($p<0.05$), no difference was found in quiet eye duration between the sloped and flat conditions (Hit: Sloped 1620ms, Flat 1816ms; Miss: Sloped 1176ms, Flat 1514ms). Participants were found to use more aiming fixations on sloped putts (Hit 6.75, Miss 8.11) compared with flat putts (Hit 5.53, Miss 6.36;, $p<0.05$) but there was no difference in the duration of the final aiming fixation (Hit: Sloped 536ms, Flat 653ms; Miss: Sloped 697ms, Flat 640ms).[38] Comparisons were not made between the different severities

[**] The break of a putting green refers to how much the path of a ball curves due to the contours of the green. A straight putt hit on a flat green ends in the hole and has no break. A straight putt hit on a contoured green with a break of 14cm would end up 14cm away from the hole.

of slope conditions (0.9° and 1.8°) due to a lack of putts holed under the most severe conditions.[38]

Individual differences in gaze strategies with respect to the specific locations fixated and the scan paths adopted were noted, but the longer duration of the quiet eye stood out as the distinguishing factor between successful and unsuccessful putts, as it did in Vickers earlier work.[28, 34] Although the quiet eye period was hypothesised to be longer for more difficult shots as had been previously demonstrated in billiards,[39] this was not found. The larger number of aiming fixations found was suggested to be a result of golfers' search for the abstract target towards which they would aim.[38]

1.4.1 Theoretical Background for Golf Vision Strategy Research

Gaze behaviour research in golf and other sports has typically been undertaken from a cognitive perspective whereby eye movements are believed to represent conscious attention. Subjects are thought to gather information using shifts in their gaze, which are initiated by eye movements. Occasionally, researchers have studied gaze behaviours from an ecological perspective, where researchers believe that valid information can be obtained unconsciously through the ambient system and optical flow of information through the environment.[31] The ecological perspective has been used in some sports vision strategy research,[40-42] but it has not been used for golf specific research and will not be discussed further.

1.4.2 The Cognitive Perspective on Eye Movements

Cognitive researchers believed that subjects gain information by using shifts in gaze, which are initiated by eye movements.[43-45] In order to facilitate vision strategy studies, cognitive researchers needed to define the criteria used to classify each of the eye movements (fixations, pursuits, saccades and express saccades) studied. The following definitions are based upon cognitive researchers' interpretations of how ocular gaze behaviours are related to neural processing of information, rather than upon the mechanics of eye movements.

In the field of cognitive research, a fixation is believed to be a conscious ocular movement associated with a conscious vision strategy for information gathering. Based on research published in the mid-1980s, which showed that the minimum duration of a fixation varied between 80ms (for highly practiced tasks) to 150ms,[46, 47] cognitive gaze behaviour researchers chose 100ms as the minimum duration of a fixation. They believed their participants were highly skilled in the tasks being studied, and the 100ms minimum fixation duration has been used ever since.[28]

Pursuits, were defined as gaze behaviours where subjects' gaze was stable on a moving object (within 3° visual angle) and tracked that object for a minimum duration of 100ms (or 99.99ms for videos recorded at 30Hz),[28] and were thought to represent conscious processing of a moving target.

Cognitive researchers defined saccades as gaze shifts between one location to another which lasted for a minimum of 133.2ms (4 movie frames at 30Hz), and express saccades as gaze shifts between two locations that lasted for a duration of 66.6 to 99.9ms (2 to 3 movie frames at 30Hz).[28] Both movements were thought to demonstrate voluntary changes in attention, [45, 46, 48] but unlike saccades, express saccades were thought to be anticipatory in nature, programmed while a participant is still fixating the previous location, and a result of practice an familiarity with a task,[49] hence their shorter duration.[48, 50]

There are major differences between cognitive and vision science research definitions of eye movements, which are a result of the cognitive assumption that a relationship exists between gaze behaviours (mechanical eye movements) and attention (conscious processing). These differences will be discussed in more detail shortly [1.4.5 Limitations of Cognitive Research].

1.4.3 Cognitive Research and the Quiet Eye

The quiet eye discussed previously, is a unique fixation which is thought to represent a period of cognitive pre-programming of movement parameters while minimising distraction from other environmental or internal cues.[29, 31] Since its original definition, it has become accepted within the literature as a measure of optimal visual attentional control,[51, 52] and has been studied in numerous sports, including basketball, volleyball, billiards, biathlon, archery, shooting, ice hockey and football (soccer).[39, 53-58]

Posner and Raichle conducted an extensive number of functional imaging studies of the brain[59] and conceptualised a system based on three neural networks (posterior orienting, anterior executive and vigilance networks) which Vickers has used as a foundation in understanding how the quiet eye works.[31] In Posner and Raichle's system, the posterior orienting network was responsible for directing the location of the gaze in space, while the anterior executive network processed what was being seen and made necessary adjustments and the vigilance system acted as a coordinator. During the quiet eye fixation then, performers would use the posterior orienting network to maintain their stable and steady gaze on the target. They would then use their anterior executive network to understand what is being seen and make adjustments in the timing of the critical action to improve accuracy. Their vigilance network worked to coordinate both networks and also helped to minimise interference and distractions during the sustained focus, particularly during periods of high pressure and anxiety.[59] Thus, longer quiet eye periods were thought to provide performers with an extended duration of cognitive programming while minimising distractions from other internal or environmental cues.[31] From a performers' perspective, the quiet eye fixation should help minimise distractions, streamline the thought process and improve performance and consistency. Research in the areas of anxiety control and performance which suggest that an external attentional focus can be of great importance in controlling stress and anxiety, [31, 53, 55, 60-62] appears to support this hypothesis.

1.4.4 Quiet Eye Training for Golf

Training the quiet eye has been shown to improve motor performance in various tasks, including golf putting.[42, 51-54, 56, 63, 64] Vickers reported unpublished data from a study of 14 golfers who were split into two skill matched groups, one of which received specific quiet eye training and the other received basic gaze training. Golfers participated in a pre-test and a post-test visit which were separated by 6 months, and consisted of putts taken on a sloped surface from randomised distances of 4 and 6ft (122 and 183cm). An additional transfer test from a novel 6ft putt location was also conducted during the post-test visit. Training was conducted immediately after the pre-test visit, and took approximately 30 minutes. The gaze trained group was only shown the videos of their own gaze data, whereas the quiet eye trained group viewed an elite prototype golfer who exhibited quiet eye behaviours, were given specific instructions regarding the quiet eye. They were also shown their own gaze data and asked to identify how it differed from that of the elite prototype. After 6 months, the quiet eye duration in the quiet eye trained group increased significantly from 3s to 4s; the exact statistical significance was not reported. In the gaze trained group, the pre-training quiet eye duration was not stated, but after 6 months, the quiet eye duration was less than 2s. The quiet eye dwell time was also found to have increased from <100ms to >700ms in the quiet eye trained group; the gaze trained group maintained a quiet eye dwell time of 100ms on the post-test, which was similar to their performance on the pre-test, although again the exact statistical significance of these differences was not stated.

A significant improvement in accuracy was found in both groups from pre-test to post-test to transfer, but surprisingly the improvement was similar in both the quiet eye and gaze trained groups, regardless of skill level.[30] The high-skilled (HS) quiet eye trained group made 50% of their putts prior to training; the HS gaze trained group made 42%. In the low-skilled group (LS) pre-training performance was similar in the quiet eye and gaze trained groups (32%). During the post-test, the HS group improved its accuracy to 51% in the quite-eye group and 46% in the gaze trained group and the LS group improved its accuracy to 47% in the quiet eye trained group and 44% in the gaze trained group. In the transfer test, the HS quiet eye trained group made 77% of their putts, where as the gaze trained group made 70%. The LS quiet eye and gaze trained groups made 59% and 60% of their putts, respectively.[30] The exact statistical significance of the improvements in accuracy was not stated.

Clearly, this study demonstrates that those golfers who received quiet eye training improved their quiet eye duration more than the golfers who were trained in different visual skills. However, both methods of training had similar effects on performance which lead Vickers to suggest that in golfers with an awareness of the quiet eye concept, simply viewing their gaze behaviours was as effective as specific quiet eye training, at least with respect to performance.[30] Arguably, the vision performance of both groups of golfers improved (as demonstrated by the improvement in putting performance), but only the quiet eye was used as an indication of visual performance. Had the vision performance of both groups also been measured on the metrics used in training the gaze trained group, it is likely the gaze trained group would have demonstrated greater improvement in these areas than the quiet eye group.

Without more information about the quiet eye duration of the gaze trained group, the statistical significance of all of the changes measured and a comparison of both groups performances on both training metrics it is impossible to draw any firm conclusions about the effectiveness of either training method. Additionally, the tests of visual performance needed to take into account more than simply quiet eye performance in order to understand how training affected each group. Again, these results can only be interpreted as having demonstrated a trend in the population that could be used to guide future research projects.

Vine and Wilson published the first study designed to examine the efficacy of a quiet eye training program in golf putting on novice performers. This was the first peer-reviewed publication of its kind, both with respect to golf and novice performers.

14 novice golfers participated in this study, and were randomly assigned to either a quiet eye training group or a control group. The control group received coaching guidance related to the mechanics of their putting action and stroke; the quiet eye trained group received a specific quiet eye training element which was derived from the earlier work of Vickers[30] in addition to the same basic coaching instructions as the control group. For purposes of this study, performance was assessed with a performance score (0 (low) to 400 (high)) derived from the distance between the final ball position and the target,[52] and the quiet eye was defined as the final fixation towards the ball, prior to the initiation of the backswing,[28, 30, 38] within 1° of visual angle or less for a minimum of 120ms (3 frames at 25Hz). [52]

A retention-transfer (pressure)-retention test design was used to assess the effects of the training. A retention-transfer (pressure)-retention design involves a simple retention test (A), followed first by a transfer (pressure) test (B) which is identical to the retention test except it is administered competitively to manipulate levels of cognitive anxiety, and then by another basic retention test (A) which is identical to the first test creating an A-B-A design.[65] During the study, 13 blocks of 40 putts were completed by each participant. The blocks consisted of 1 pre-test (baseline) block, 9 acquisition phase (training) blocks and 3 post-test (Retention test 1, Pressure test and Retention test 2) blocks.[52] Mean values reported below are reported to the nearest whole number, as they were only presented graphically in the manuscript text.

Performance improved significantly throughout the acquisition phase (training blocks) for all golfers (Baseline, Quiet eye: 257, Control: 254; Final training block, Quiet eye: 316, Control: 306; $p<0.001$) and significant improvements from baseline were found from training block 4 ($p<0.05$) onwards. The rate of acquisition was similar for both groups..[52]

Performance also improved significantly from pre-test to post-test ($p < 0.001$) in both groups. The quiet eye trained group (303) was found to perform significantly better than the control group (258) in the pressure test ($p < 0.005$), although the performance of the two groups on the other tests was similar. Within the groups, the quiet-eye trained group improved significantly between the pre-test and retention test 1 (Pre-test: 257, Retention test 1: 313, $p < 0.001$), but there were no significant differences between performance between retention test 1 or retention test 2 (307) and the pressure test (303). The control group's performance improved significantly between the pre-test and retention test 1 (Pre-test: 254, Retention test 1: 297, $p < 0.05$), but decreased significantly between both retention test1 and retention test 2 (293) and the pressure test (258, $p < 0.001$).[52]

Initially, the quiet eye duration was similar in both groups (Quiet eye: 1025ms, Control: 900ms, $p = 0.38$), but after training, the quiet eye trained group (Retention test 1: 3250ms, Pressure test: 2800ms, Retention test 2: 3200ms) had a significantly longer quiet eye than the control group (Retention test 1: 1400ms, Pressure test: 850ms, Retention test 2: 1350ms) on all three post-tests ($p < 0.001$). In the quiet eye trained group, quiet eye duration increased significantly between pre-test to retention test 1 ($p < 0.05$), decreased significantly between retention test 1 and the pressure test ($p < 0.05$), and was not different between the pressure test and retention test 2 ($p = 0.26$) or between retention test 1 and retention test 2 ($p = 0.87$). In the control group, quiet eye duration increased significantly between pre-test and retention test 1 ($p < 0.05$), decreased significantly between both retention test 1 ($p < 0.001$) and retention test 2 ($p < 0.05$) and the pressure test, although there was no significant difference in quiet eye duration between retention test 1 and retention test 2 ($p = 0.76$).[52] The quiet eye was found to predict 36% of the variance in putting performance ($R^2 = 0.358$, $\beta = 0.60$, $p < 0.001$) during the test phase.

Based on their results, the authors concluded that longer duration of the quiet eye was associated with increased putting success irrespective of training group or test type, but the quiet eye trained group was found to have a longer quiet eye duration compared with the control group after training. The quiet eye trained group performed significantly better than the control group on the pressure test and they maintained the duration of their quiet eye under pressure. Authors suggested this was an indication of a more effective attentional control strategy in the quiet-eye trained group compared with the control group, which was a result of the specific quiet eye training.[52] Although these results are interesting, it is important to recognise that the quiet eye trained group received more training that the control group, which included specific quiet eye training. The control group did not receive any type of visual training at all, making the two training paradigms markedly different. Despite these differences, the performance of both groups was similar after training, on all tests except for the pressure test. An unbiased metric was not used to assess performance of both groups; the quiet eye duration would be expected to improve if training was conducted specifically for this parameter. Some sort of vision training should have been included in the control groups training and an additional vision parameter should have been included in the post-test evaluation.

Vine, Moore and Wilson, conducted a second study which evaluated the impact of quiet eye training in elite golfers (mean handicap 2.78±2.24) using the same quiet eye definition that was used in their 2010 study.[52] Golfers who participated in this study (n=22) were asked to record their putting stats for 10 consecutive rounds of golf and were then randomly assigned to either a quiet eye or a control group. Both groups undertook 20 putts wearing eye tracking equipment, after which they were given video feedback on their performance. The quiet eye group received additional training with respect to the quiet eye specifically, but the control group did not receive any further training. All of the golfers were then asked to record their putting statistics for their next 10 rounds of golf, and return for post-training retention (20 putts) and pressure (15 putts) tests.[51] As in the previous study by Vine and Wilson,[52] the pressure tests were designed to create cognitive anxiety through competition. A cash prize for the best performance was offered and golfers were told their scores would be compared with others taking part and may be sent to their respective golf courses. Additionally, a non-contingent feedback[**] method was employed, whereby golfers were told their retention test performance would put them in the bottom 30% of those who had already completed the testing.[51, 52]

Unlike their previous study,[52] the percentage of the putts holed (Performance outcome) and the distance that the ball finished from the hole (Performance error) were used as performance measures on the pre-, retention and pressure tests. Competitive performance on the 10 rounds of golf prior to and after training was assessed by asking golfers to record the number of putts taken per hole, whether they had a putt of 6-10 feet in length on each hole, and if they were successful with that putt.[51] Pre-test and retention test quiet eye duration and performance holed results, and the pre-test performance error results presented in the following text were read from a graph and as such are only presented as values rounded to the nearest whole number.

The quiet eye trained group was found to maintain their quiet eye under pressure (2794.31ms), unlike the control group, whose quiet eye duration decreased with anxiety (1404.74ms) and was significantly shorter than the quiet eye duration of the quiet eye trained group ($p<0.05$). On the pre-test and the retention tests, the quiet eye duration of both groups was statistically similar. The quiet eye trained group also performed better on the pressure test, holing more putts (60%, $p<0.005$), and leaving putts closer to the hole (4.45cm, $p<0.005$) when not successful than the control group (36%; 10.28cm), despite the two groups similar performance on the pre-test. These performance differences were found to transfer to putting performance outside of the laboratory, as the quiet eye group found they were using 1.9 fewer putts per round compared to their original statistics after training ($p=0.001$). There was no change in the control group's statistics pre- and post-training ($p=0.86$). The quiet eye trained group (27.61putts) also used significantly fewer putts per round than the control group (29.89putt) at post-training ($p<0.05$), despite their similar performance pre-training. Finally the quiet eye was found to predict 43% of the variance in putting performance ($R^2=0.43$, $\beta=13.93$, $p<0.005$).[51]

All of these studies, particularly the latter two, would suggest that training the quiet eye is an effective way to improve performance in novice and elite golfers alike, although other factors, such as additional training and practice associated with improving the quiet eye may have affected performance as well.

1.4.5 Limitations of Cognitive Research

Current cognitive gaze behaviour research, while revolutionary in many ways, has also been limited by two major factors. The first being technology (including recording and analysis technology) and the second being the assumptions made by cognitive psychologists regarding the relationships between gaze behaviour and attention.

** Non-contingent feedback refers to feedback that is based on false or misleading information.

1.4.5.1 Technological Limitations

Most of the commercially available eye trackers are only monocular, due to the difficulty of recording and processing three video channels in real time, and all of the research that has been undertaken on golf vision strategy has used monocular eye tracking equipment. This is a significant limitation, because the human visual system has been designed to work binocularly. It responds to information gathered from both eyes, which is combined in the visual cortex to create our three-dimensional perception of our environment. As monocular units, neither eye is as effective as the binocular vision system, nor is either eye representative of the entire system. Monocular gaze behaviour research is incapable of providing any information about the effects of binocularity on gaze behaviours.

The introduction of binocular eye tracking equipment alone has not solved this problem, because the current analysis techniques are incapable of dealing with the extra information obtained from the second eye. Gaze behaviour analysis is traditionally done with manual video analysis programs, whereby the gaze videos are synchronised with an external video feed that records the golfer's actions. Both videos are then analysed frame by frame, with gaze behaviours and putt phases being coded by a manual observer. This method is very time consuming, and would be made more so by the addition of a second eye. There has also been difficulty in synchronising data from both eyes with backswing and other performance aspects of the putt. Researchers have been able to synch gaze videos from one eye with external videos recording golfers' actions, but they have not yet found a method for synchronizing the gaze videos from both eyes. Therefore the lack of useable binocular gaze data remains as a significant problem in studying the vision strategy of golfers.

1.4.5.2 Methodological Limitations

All cognitive gaze behaviour research is based on the assumption that gaze behaviours are indicative of conscious attention. Individuals have been shown to consciously attend to visual targets within 80-150ms of a fixation, and the time needed to attend to a target decreases with increased task familiarity. [46, 66] All of the golf research to date has been based on fixations with a minimum duration of 100-120ms, but this is only an average assumed fixation time and does not account for skill or experience.[28] Eye tracking instruments measure mechanical gaze behaviours, not conscious attention, therefore a 100ms fixation cannot be assumed to be indicative of conscious attention. Until the relationship between conscious attention and gaze behaviours is objectively studied, minimum fixation duration times specified in the current literature will remain as arbitrary conditions that have not been validated. The 100-120ms fixation may actually be either an over estimation or an under estimation of the length of an attentional fixation in any given individual.

While the minimum fixation duration used by cognitive researchers is similar to that used by vision scientists,[67, 68] the angular subtense of a fixation in cognitive research is significantly larger than in vision science research. Cognitive researchers typically define fixations as stable gazes within 1° to 3° visual angle,[27, 28, 30, 31, 38] while vision researchers in reading studies for example, measure fixations that subtend an angle of 0.29° visual angle at a distance of 85cms.[67] Golfers stand approximately 1.5m above the ball during golf, and a fixation at this distance would subtend an angle of only 0.51° visual angle. The marked exaggeration of the fixation criteria used by cognitive researchers is further demonstrated by the fact that a golf ball subtends a visual angle of 1.6° at 1.5m; 3° visual angle is nearly twice this size.

Vision scientists also define pursuits and saccades differently than cognitive researchers. In vision science research, pursuits are tracking gazes with velocities of 5° to <50° visual angle per second without a minimum duration.[47, 69] While vision scientists recognise that pursuits have, on average a latency of 100ms,[47] they do not specify a minimum duration of the pure eye movement as this depends on the duration of the target movement. The minimum duration of pursuits is a major limiting factor of cognitive vision research, but this research is more significantly limited by their definition of a fixation. The 3° fixation criteria permits eye movements with velocities up to 90° per second, meaning that pursuit eye movements could easily be misclassified as fixations.

Saccades are defined by vision scientists as short duration eye movements with velocities of 50° to 700° per second which range from 20 to 300ms in duration depending upon their amplitude.[70, 71] The minimum duration of 4 movie frames (133.2ms) specified by cognitive researchers does not agree with vision scientists and results in small duration saccades never being detected. Additionally, the fixation criteria used by cognitive researchers permits small saccades (up to velocities of 90° per second) to be classified as fixations. Furthermore, vision scientists differentiate saccades and express saccades based on their latencies (150ms and 100ms respectively),[72] rather than the duration of the saccadic movement as in cognitive research.

Cognitive researchers assume that gaze behaviours represent cognitive processing, yet defining them in such a way limits their usefulness in understanding the basic mechanics of a vision strategy. A study of physical gaze behaviours, independent of cognitive psychological assumptions is needed to determine what gaze behaviours are truly important in the visual strategy of golfers.

1.5 Thesis Proposal

The purpose of this thesis is threefold:

1. To develop an analysis method for the accurate assessment of binocular eye tracking data to investigate the vision strategies of golfers recorded with a novel, binocular eye tracker. The development of the analysis method requires a re-assessment of the current gaze behaviour definitions in an objective manner based on the basic physiological functions of the visual system rather than on any prior assumptions associated with cognitive attention.

2. To assess the visual strategies of golfers of various skill levels. An objective assessment of gaze behaviours recorded throughout the entire putt would facilitate the determination of what aspects of the vision strategy are associated with the highest levels of performance and success.

3. To develop and evaluate methods for training the binocular vision strategies of golfers, and to assess the impact of visual training methods on both gaze behaviours and putting performance.

All of this research will be undertaken in order to gain a better understanding of the human visual system and how it relates to sport performance of golfers specifically. Ultimately, the analysis techniques and methods developed should be appropriate for the assessment of individuals' vision strategies in all sports.

Chapter 2

GazeDetection SOFTWARE DEVELOPMENT

2.1 Overview

The purpose of this chapter is to discuss the theory behind the golf putting data analysis; issues that have arisen during the analysis of golf putting eye tracking data; and the resolution of these issues through the development of custom software designed specifically for analysing eye tracking data in golf.

2.2 Eye Tracking

2.2.1 Current Instrumentation

The ViewPoint binocular eye tracker (Arrington Research Inc., Scottsdale, AZ, USA) was used in these studies, in conjunction with the ViewPoint PC60 software (Arrington Research Inc., Scottsdale, AZ, USA).

The ViewPoint binocular eye tracker is a wired system, whereby video information is transported along a 10m cable directly to a computer via BNC connectors that attach to a PCI video card. Using the ViewPoint Software, both eye and scene camera videos were observed in real time. The eye and scene cameras were mounted on simple plastic frame, without lenses, held in place by a draw string strap (Figure 2-1).

Figure 2-1: ViewPoint binocular eye tracker

2.2.1.1 Scene Camera

The scene camera was mounted on the bridge of the eye tracker frames (Figure 2-2 A). It recorded NTSC video at 60Hz, which was then modified by the ViewPoint PC60 software and output as an uncompressed .avi file at 30Hz, with a resolution 320 x 240 and a 1.0 pixel aspect ratio. The .avi video files could have been stored in either a Raw or Painted format; in the Painted format coloured dots corresponding to each eye's position were marked in the video. Although it was possible to store the .avi files in a compressed format, the uncompressed format was preferred for data analysis purposes as the uncompressed .avi files contained the same gaze co-ordinate information and time stamps as the data files. The 'Painted' setting was used to record most of the video files so golfers could be given immediate feedback on the day of their eye tracking assessments.

The image recorded by the scene camera, was in theory equal to what was seen by the athlete. It was possible to vary the field of view (and consequently the magnification) of the scene camera image simply by changing the lens that was attached to the camera. The two different scene camera lenses which were used were labelled as having 23° and 44° fields of view along the diagonal. The fields of view of these lenses were provided by the manufacturer, but they were not exact measurements of the lenses' true fields of view. The fields of view (in degrees of visual angle) have been measured and are listed in Table 2-1. For golf, both the 23° and 44° lenses were used successfully, although the 44° lens was preferred, because the field of view of the 23° lens was found to be too restrictive. Therefore, the 44° lens was used for all of the studies presented in this thesis. .

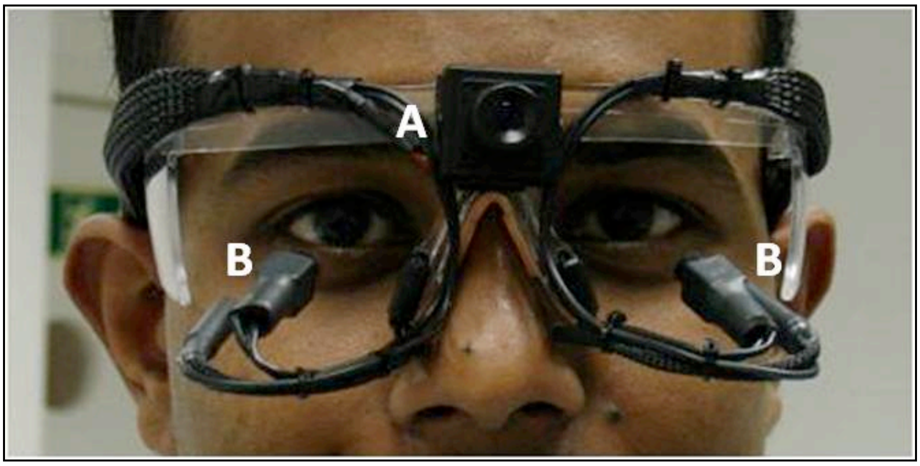
Lens	Horizontal Length	Vertical Length	Diagonal Length	Functional Field of View at 1.5m
23° field of view	19.93° (1450mm)	15.41° (1082mm)	24.33° (1809mm)	0.5m x 0.4m
44° field of view	28.72° (2192mm)	22.10° (1624mm)	34.29° (2728mm)	0.8m x 0.6m

Table 2-1: Measured field of view of both the 23° and 44° lenses. Horizontal and vertical measurements were taken in mm at a distance of 4 meters; angular dimensions and diagonal length were then calculated. Functional field of view at 1.5m was calculated based upon the angular dimensions of each lens

2.2.1.2 Eye Cameras

Two eye cameras were mounted on the eye tracker frames, one in front of each eye (Figure 2-2 B). These cameras were infrared cameras, and were each mounted on a flexible bracket in conjunction with an LED light that illuminated the eye and enhanced pupil contrast. Each eye camera recorded NTSC video at 60Hz; the eye camera recordings could be combined and output as an uncompressed .avi file at 30Hz, 640 x 240 (two 320 x 240 images side by side) with a 1.0 pixel aspect ratio if desired. No eye camera videos were recorded during this research, as it was impossible for this particular system to record scene and eye camera videos simultaneously, although it is possible to view both the scene and eye camera live feeds simultaneously while recording.

Figure 2-2: ViewPoint binocular eye tracker. The scene camera (A) is mounted in the middle of the bridge, while the eye cameras (B) are mounted in front of the right and left eyes.



2.2.1.3 ViewPoint PC60 Software

The ViewPoint PC60 Software was designed to act as an interface that allowed researchers to have complete, real time control over all aspects of the eye tracking measurements. The software was capable of tracking gaze position monocularly or binocularly; gaze position measurements could be collected at either 30Hz or 60Hz and gaze position was reported as (x, y) co-ordinates for each eye. The video drivers for the PCI card were included with the ViewPoint software.

2.2.1.4 Data Output

The eye position data was saved as a tab-delimited text document (.txt) which could easily be imported into various other programs, including Microsoft Office Excel. Information about the data file, including the date and time the video was recorded, was included in a header at the top of the data file. Each line of data was unique and was labelled with a "*Tag*" value in the first column. Some commonly used data tags included:

- **Tag #10:** EyeData containing a variable number of columns depending on the options selected for data collection.
- **Tag # 3:** An ASCII character string generated by ViewPoint to provide general information, such as when the data file was created.
- **Tag # 5:** An ASCII character string generated by ViewPoint to provide column heading information.
- **Tag # 6:** A three character data column identifier generated by ViewPoint.
- **Tag # 777:** Movie Frame Number.

The data was sorted into a number of different columns such as those listed below (Table 2-2). There was a separate set of columns for each eye recorded in the binocular mode; right eye data was denoted as Eye A and left eye data as Eye B. A small sample of the data output file format can be found in Table 2-3; the data contained in Table 2-3 was from Eye A only, all of these columns were repeated for Eye B; additional data columns labelled "Count" and "Mark" were also included at the end of the data files.[73]

Column Heading	Type	Description
Tag	integer	The value 10 in the first column indicates an eye data record.
TotalTime	float	TotalTime = time elapsed in seconds
DeltaTime	float	dt = delta time in milliseconds since the previous data entry
X_Gaze	float	X = direction of gaze normalized with respect to the x-axis
Y_Gaze	float	Y = direction of gaze normalized with respect to the y-axis
Region	list	Which ROI or ROIs the gaze point is in
PupilWidth	float	Pupil width normalized with respect to the EyeCamera window width
PupilAspect	float	Dimensionless aspect ratio of the pupil, i.e. 1.0 is a perfect circle
Quality	integer	Code describing quality of eye movement data.
Fixation	float	Fixation duration in seconds. A zero value indicates a saccade.
Torsion	float	Torsion in degrees. -998 indicates Torsion not being calculated. -999 indicates "*Range Error*". Only displayed if torsion is being measured.
Count	integer	Eye movement data record count, useful for sorting.
Mark	char	Any printable ASCII character, e.g., {a-z, A-Z,0-9,=,#,+,%, etc.}.

Table 2-2: Common data column labels found in Arrington Research Data files[73]

6	ATT	ADT	ALX	ALY	ARI	APW	APH	AQU	AFX
5	TotalTime (s)	DeltaTime (ms)	X_Gaze	Y_Gaze	Region	PupilWidth	PupilHeight	Quality	Fixation (s)
777	2.4569	MovieFrame	1	73					
10	2.4657	16.6376	0.5359	0.7293	-1	0.0977	0.0945	1	0.1166
10	2.4824	16.6829	0.5451	0.7561	-1	0.0976	0.0904	1	0.1333

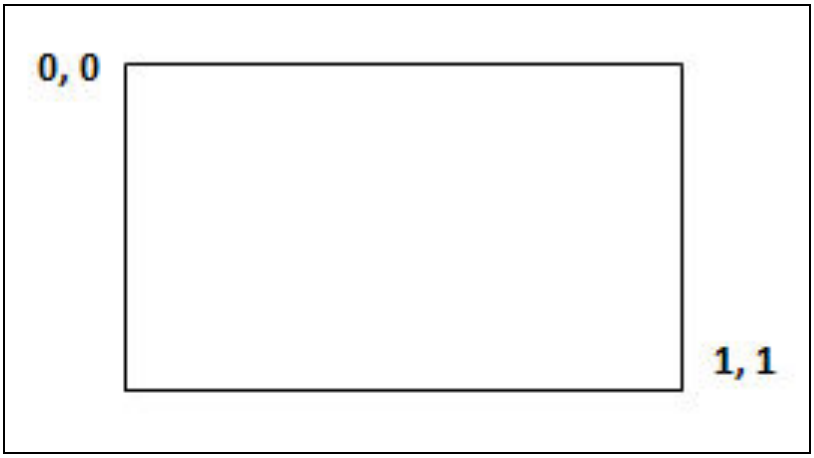
Table 2-3: Sample data output from Arrington Research ViewPoint software program. Data presented for Eye A only; a second complete set of columns was present in the data files for Eye B, as well as the additional data columns 'Count' and 'Mark'.

2.2.2 Data Collection

2.2.2.1 Gaze Tracking

Gaze position was measured relative to the scene camera display, and reported on an (x,y) co-ordinate plane that was referenced to the field of view of the scene camera. The coordinate plane was rectangular (320 x 240 pixels) with the origin in the top left hand corner (Figure 2-3) and varied in size depending upon the field of view on the camera at the time of recording (i.e. 23°, 44°, etc.). (0,0) was the top left hand corner of the scene camera field of view, (0.5,0.5) the centre of the field, and (1,1) the lower right hand corner.[73] The coordinate plane was continuous and the eye tracker was capable of tracking eye position outside of the field of view of the scene camera (x, y <0 or x, y >1); the coordinates of these gaze positions were extrapolated by the software relative to the calibrated field of view of the scene camera.

Figure 2-3: Co-ordinate plane referenced to the field of view of the scene camera



ViewPoint PC60 software provided three options for pupil tracking. They were Pupil-Glint, Pupil Only and Glint Only. Glint Only was not a recommended method because Glint Only is more susceptible to noise and is difficult to track precisely without knowing the location of the pupil, and it is not discussed further here. Both the Pupil-Glint and Pupil Only methods are discussed in more detail below.

2.2.2.1.1 Pupil-Glint Method

This method of line of sight tracking was based on the detection of the centre of a dark pupil and the detection of the first Purkinje image, known as the corneal reflex or glint. The corneal reflex appears as a bright, round reflection on the corneal surface. ViewPoint PC60 detected both the corneal reflex and the pupil by measuring the contrast changes between the targets and their respective backgrounds; for the pupil, an ovoid fit was used. The software then calculated the vector length between the centres of the pupil and the corneal reflection, which it monitored and used as an indicator of eye position. This method has been shown to be relatively robust with respect to horizontal and vertical movements of the eyes relative to the scene camera, although it can be affected by extreme gaze positions because reflections off the sclera can mimic the corneal glint inducing errors in the positional calculations.[73]

2.2.2.1.2 Pupil Only Method

This method again detected the centre of a dark pupil by measuring the contrast differences between the iris and the pupil using an ovoid pupil fit. Unlike the pupil-glint method, only the centre of the pupil was used as an indicator of eye position in this method. This method has been shown to be more sensitive to noise induced by horizontal and vertical movements of the eyes relative to the scene camera, but it has also been shown to be less sensitive to translational (z-axis) movements relative to the scene camera and to errors caused by extreme gaze positions. This method was chosen because it was less sensitive to translational movements along the z-axis and extreme gaze positions; when putting golfers use extreme gazes regularly when looking at the hole and the angle of their head also changes. The increased sensitivity to horizontal and vertical movements relative to the scene camera was a small drawback with this method, but when fixating the ball in putting, eye movements are relatively small compared with the field of view of the scene camera (the ball is 1.6° in size); fixations at the hole, associated with large changes of gaze, although measured they were not of primary interest, making this drawback of minor concern. Finally, this method was much faster to set up because there was only one feature to track instead of two, and this made it much easier to use in natural sporting environments.[73]

2.2.2.2 Calibration

Calibrating eye trackers for use in golf scenarios should be done at the testing distance of interest to minimise errors due to parallax. Calibration was needed to synchronise the gaze position information recorded by the eye cameras with the information recorded by the scene camera mounted on the top of the eye frame. Because golfers' heads are not fixed in one position while putting, the eye cameras had to be calibrated relative to the scene camera position, rather than relative to a fixed positional reference. One of the drawbacks of working with higher magnification lenses was that they have smaller fields of view than lower magnification lenses. For this reason, the alignment of the scene camera with golfers' gaze position could be dramatically affected by their body position. Errors due to body position were minimised by completing the calibration with golfers in the same stance as that used when addressing a putt.

Golfers were asked to remain as still as possible in their natural stance during the calibration process. A numerical grid was laid on the ground in front of them such that it was visible in the scene camera display observed on the computer. They were then asked to direct their gaze to numbers corresponding to the system calibration points, which were visible in the scene camera video feed in the ViewPoint PC60 software. The x- and y-positions of each eye were calibrated relative to the scene camera field of view using a 16-point grid calibration that spanned the entire field of view.

In golf, as in other sports, head and body positions varied constantly. Unfortunately, this meant that unless a head tracker was used in conjunction with the eye tracking system, it was impossible to determine the exact position of gaze in space because the calibrated plane (scene camera field of view) did not remain in a fixed position. Fortunately the relative position of the gaze and the stability of the gaze could still be determined with accuracy. A head tracking device was not used during these studies as we did not have one available to us.

2.2.2.3 Measurements

Eye tracking data in this study was collected primarily under two conditions – on artificial greens and on real practice greens. On artificial greens, data was collected for 20 putts in total, alternating between putts of 6 and 10 feet in length. On real greens, data was collected for 12 putts in total, which were taken from 4 different locations (3 putts at each location). A small amount of data (16 putts, 2 golfers) was collected from golfers who putt on a felt matt. The felt matt was used as a putting surface in the office prior to obtaining an artificial green. For the purpose of analysis, each distance on the artificial green (6 feet and 10 feet) were considered as individual conditions, meaning there were a total of four types of putting data collected during this study: artificial green 6 foot, artificial green 10 foot, real green and felt matt.

2.2.3 Data Analysis

Traditionally golf eye tracking research has focused on the number of, duration of, and pattern of fixations and saccades that were used during putts. Previously, fixations have been defined as a gaze position that is stationary within 1° to 3° of visual angle for 80-150ms, while saccades were defined as a change in gaze position for a minimum of 60-100ms.[27-29, 57, 74, 75] These criteria were felt to be unacceptable for reasons described previously, including the fact that these gaze behaviours have been judged subjectively using manual video analysis techniques [Chapter 1, Introduction]. In order to permit the objective assessment of gaze behaviours, a bespoke computer program was designed and written at Aston University in conjunction with OTG Research and Consultancy for use in this thesis.

GazeDetection, as this software was called, was designed specifically for the analysis of golf eye tracking data recorded with the Arrington Research ViewPoint eye tracker, and is described in detail below. Microsoft Office Excel (2003 and 2007 versions) and SPSS 18.0 for Windows (Release 18.0.0, 30 July 2009, http://www.spss.com) were also used to analyse the data.

2.3 GazeDetection Software

2.3.1 Analysis Outcomes

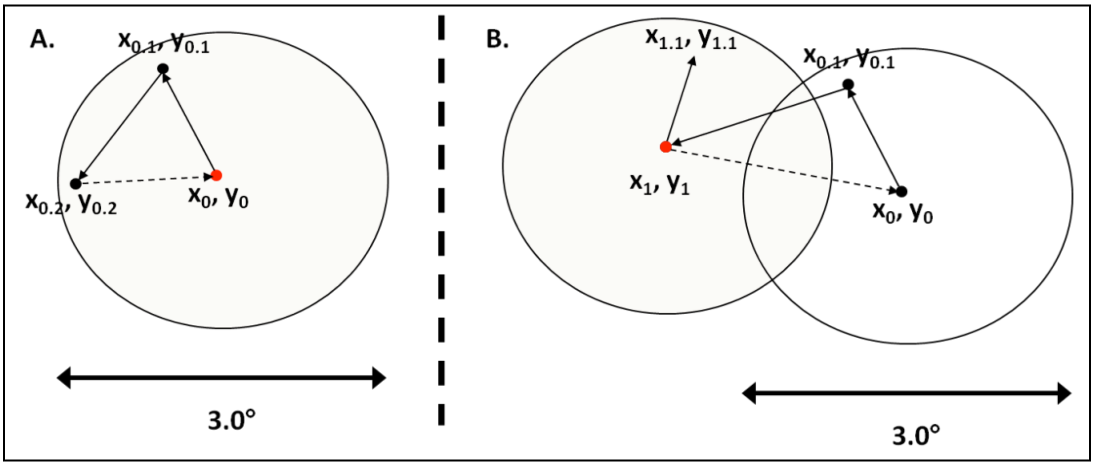
The total time data and the (x, y) coordinate data for each eye were of particular interest for these analyses. For the purpose of this analysis a fixation was classified as a stable eye position; to be considered stable, the eye position had to remain within a circular fixation zone of a specified diameter. The fixation parameters of interest in this analysis are: fixation duration and fixation location.

2.3.1.1 Fixation Zone

The fixation zone was defined as a circle of a fixed diameter; gazes were considered to be "fixations" as long as the x, y-coordinate position of the eye remained within the diameter of the fixation zone. The fixation zone was centred on a single x,y – coordinate (x_0, y_0) which was the x, y-coordinate corresponding to the eye's position at time zero (T_0). T_0 was initially taken to be the first (x, y) co-ordinate of the data file. For each subsequent data point in the file, GazeDetection would calculate the length of the vector formed between (x_0, y_0) and ($x_{0.n}$, $y_{0.n}$). As long as the length of the vector was shorter than the radius of the fixation zone, ($x_{0.n}$, $y_{0.n}$) had to be inside the fixation zone, and the gaze was considered to be a fixation (Figure 2-4 A).

When the eye position changed such that the length of the vector between (x_0, y_0) and the current position of the eyes ($x_{0.n+1}$, $y_{0.n+1}$) was greater than the radius of the fixation zone, the fixation criteria were violated and the fixation ended. A new fixation zone would then be defined at (x_1, y_1). As long as the length of the vectors between (x_1, y_1) and subsequent points ($x_{1.n}$, $y_{1.n}$) were not longer than the radius of the fixation zone, the gaze behaviour was defined as a fixation (Figure 2-4 B).

Figure 2-4: (A) Fixation zone centred on x_0, y_0; as long as the length of vectors calculated between subsequent points ($x_{0.n}$, $y_{0.n}$) and (x_0, y_0) were not larger than the radius of the circle, the gaze behaviour is defined as a fixation. (B) If the fixation criteria for the fixation zone centred on x_0, y_0 were exceeded, a new fixation zone defined at (x_1, y_1). As long as the length of the vectors between (x_1, y_1) and subsequent points ($x_{1.n}$, $y_{1.n}$) and were not longer than the radius of the circle, the gaze behaviour was defined as a fixation.

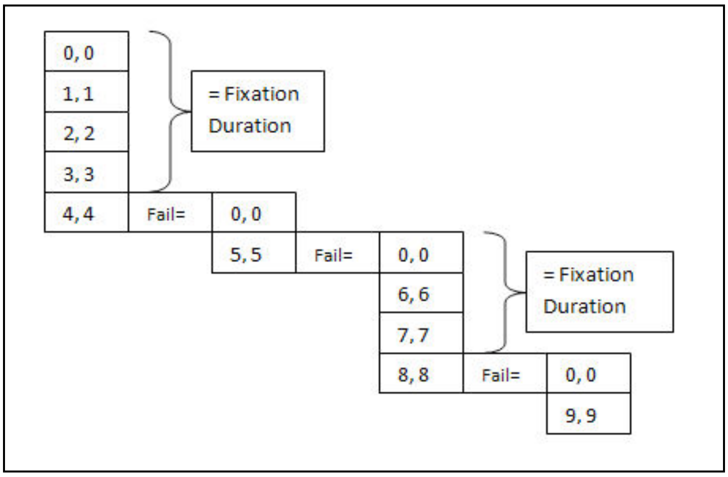


2.3.1.2 Fixation Duration

Fixation duration was calculated as the length of time the gaze remained within the fixation zone. Each x, y-coordinate recorded by the ViewPoint software had a corresponding data time value. Data time started from 0.00s at the beginning of each file and ran for the entire duration of the file. The ViewPoint software recorded the data time with millisecond precision and fixation durations were calculated based on this information.

Just as the first fixation zone was centred on (x_0, y_0), the first (x, y) co-ordinate of the data file, the first fixation duration was determined from T_0, which was the data time that corresponded to (x_0, y_0). Fixation duration was calculated as the total time that elapsed between the first and last gazes that met the fixation zone criteria, and an example of this is given in Figure 2-5. If the gaze coordinates broke the fixation zone criteria (i.e. (x_1, y_1) in Figure 2-4 B above), a new fixation duration was calculated from the data time ($T_{0.1}$) of the new reference point of the next fixation zone (x_1, y_1).

Figure 2-5: Calculation model for determining fixation duration; Fail=fixation zone criteria exceeded.



Fixations had minimum duration of 16.67ms, which was equal to the length time between subsequent data points. Fixations shorter than this were recorded if data points were collected closer together. Unlike previous studies, where fixations had to have a minimum duration of 100ms, no minimum fixation duration criterion was set in this study. This ensured that all fixations and stable gaze positions were recorded, as well as all pursuits and saccades. Maximum fixation duration was not set either.

2.3.1.3 Fixation Location

Previous studies have defined fixation location through subjective observation of the gaze position markers within the field of view of the scene camera during video analysis. The manual approach was considered and found to be unsuitable due to the associated lack of objectivity and precision. This study involved a very large body of data and required a much higher resolution level than previously applied therefore the system had to automatically and objectively classify all important gaze parameters used during golf putting.

Unfortunately, fixation location could not be defined as precisely as in previous research because of the mobile nature of the reference frame (scene camera field of view, described above). Golfers stood up and often moved their feet between each putt therefore it was impossible to guarantee that the ball, for example, would be in an identical position on each putt.

Fortunately, in golf there are two primary gaze positions, the ball and the hole, which both lie along a relatively horizontal plane. In a right-handed golfer the hole lies to the left of the ball and in a left-handed golfer the hole lies to the right of the ball. Knowing this, it was possible to define two fixation locations within the putting data. Ball fixations were defined as gazes whose average x, y-coordinate positions fell within the field of view of the scene camera ($0 < x, y < 1$). Hole fixations for right-handed golfers were defined as fixations whose average x, y-coordinate positions were to the left of the field of view of the scene camera ($x, y < 0$). Hole fixations for left-handed golfers were defined as fixations whose average x, y-coordinate positions were to the right of the field of view of the scene camera ($x, y > 1$). Despite the lack of a more detailed classification system, these two locations defined the golfer's fixations with reasonable accuracy, as the vast majority of gaze behaviours recorded between fixations on these two targets were saccades. Without a fixed reference mark or a head tracker it was impossible to define gaze position objectively with any greater accuracy.

2.3.2 Basic Principles of GazeDetection Software

2.3.2.1 Mathematics

All fixation zone criteria and results are reported in units of degrees (°) visual angle, but all vector calculations were completed in a Cartesian plane. The exact size of the co-ordinate plane in degrees visual angle had to be known; hence the horizontal and vertical widths of the field of view of each scene camera lens were measured in metric units at a distance of 4m (Table 2-1). The visual angle of each field was then calculated using simple triangulation.

The challenge with this analysis was that resolution of the scene camera was different in the horizontal and vertical meridians. In order to make accurate calculations in visual space, this difference needed to be accounted for. This was done by normalising the vertical meridian of each field to create a square reference plane. Vertical values were adjusted based on the horizontal values of each field of view. For the 44° lens, vertical values were adjusted by 0.7409, for the 23° lens they were adjusted by 0.7462.

Fixation zone criteria were converted from angular distances to coordinate distances on the normalised plane. The Pythagorean theorem was used to calculate the length of the vector between normalised gaze coordinates (vector length = $\sqrt{((X_{n+1} - X_n)^2 + (Y_{n+1} - Y_n)^2)}$, which was compared to the normalised radius of a fixation zone.

All of the calculations were completed by the GazeDetection software, and the final output contained the start and end times (in seconds), the duration (in milliseconds), the start (x, y) and end (x, y) positions of and the average (x, y) position of each fixation in the file (Table 2-4). Pursuit and saccade data were not included in the output files.

StartTime (s)	EndTime (s)	Duration (ms)	StartXPos	StartYPos	EndXPos	EndYPos	AverageXPos	AverageYPos
5.1309	5.4646	0.3337	0.7062	-0.2912	0.6644	-0.3151	0.6743	-0.2897
5.4807	5.7473	0.2666	0.6556	-0.3457	0.6617	-0.3801	0.6643	-0.3589
5.8472	5.9306	0.0834	-0.1982	-0.0372	-0.1539	-0.0639	-0.1693	-0.0556
5.9472	5.9972	0.05	-0.1463	-0.0679	-0.156	-0.0665	-0.1492	-0.0696
6.0138	6.597	0.5832	-0.2278	0.0252	-0.2636	0.0351	-0.2507	0.036
6.6136	7.0968	0.4832	-0.2804	0.0382	-0.2649	-0.002	-0.3028	0.0125
7.1634	7.18	0.0166	-0.4161	0.7326	-0.4161	0.7326	-0.4161	0.7326

Table 2-4: Sample data output from GazeDetection software program.

2.3.2.2 Data Errors

Occasionally errors were found in the raw data files, where a zero was recorded instead of a data point; this zero could appear in any of the 4 raw data columns (TotalTime, DeltaTime, X_Gaze, Y_Gaze) as shown below in Tables 2-5 to 2-9. All erroneous lines of data were removed prior to any calculations taking place.

6	ATT	ADT	ALX	ALY	ARI	APW	APH	AQU	AFX
5	TotalTime (s)	DeltaTime (ms)	X_Gaze	Y_Gaze	Region	PupilWidth	PupilHeight	Quality	Fixation (s)
777	56.0078	MovieFrame	1	1678					
10	**0**	16.6409	0.7328	0.8886	-1	0.0978	0.0919	1	0.5664
10	56.0278	16.6806	0.7334	0.8899	-1	0.0983	0.0919	1	0.5831

Table 2-5: Data recording error in TotalTime (ATT) column (error is highlighted and shown in bold type text).

6	ATT	ADT	ALX	ALY	ARI	APW	APH	AQU	AFX
5	TotalTime (s)	DeltaTime (ms)	X_Gaze	Y_Gaze	Region	PupilWidth	PupilHeight	Quality	Fixation (s)
777	48.334	MovieFrame	1	1448					
10	48.3308	**0**	0.4611	1.3005	-1	0.9355	0.6359	3	0.1333
10	48.3642	33.3251	0.4611	1.3005	-1	0.9445	0.6259	3	0.1333

Table 2-6: Data recording error in DeltaTime (ADT) column (error is highlighted and shown in bold type text).

6	ATT	ADT	ALX	ALY	ARI	APW	APH	AQU	AFX
5	TotalTime (s)	DeltaTime (ms)	X_Gaze	Y_Gaze	Region	PupilWidth	PupilHeight	Quality	Fixation (s)
777	284.5583	MovieFrame	1	8528					
10	284.6039	16.7139	**0**	0.6064	-1	0.0971	0.0937	1	1.4495
10	284.6205	16.6012	0.7289	0.6117	-1	0.0981	0.0912	1	1.4661

Table 2-7: Data recording error in X-Gaze (ALX) column (error is highlighted and shown in bold type text).

6	ATT	ADT	ALX	ALY	ARI	APW	APH	AQU	AFX
5	TotalTime (s)	DeltaTime (ms)	X_Gaze	Y_Gaze	Region	PupilWidth	PupilHeight	Quality	Fixation (s)
777	323.7956	MovieFrame	1	9704					
10	323.8383	16.6356	0.6896	**0**	4	0.0995	0.0911	1	0.5164
10	323.855	16.6855	0.6897	0.7579	4	0.0991	0.09	1	0.5331

Table 2-8: Data recording error in Y_Gaze (ALY) column (error is highlighted and shown in bold type text).

6	ATT	ADT	ALX	ALY	ARI	APW	APH	AQU	AFX
5	TotalTime (s)	DeltaTime (ms)	X_Gaze	Y_Gaze	Region	PupilWidth	PupilHeight	Quality	Fixation (s)
777	53.8391	MovieFrame	1	1613					
10	53.8453	16.6347	0.2316	-0.5784	-1	0.1014	0.0784	1	0.0166
10	53.862	16.6888	**0**	**0**	-1	0.0998	0.0786	1	0.0333

Table 2-9: Data recording error in X_Gaze (ALX) and Y_Gaze (ALY) columns (error is highlighted and shown in bold type text).

One additional error was found in the data files in the TotalTime column, whereby the TotalTime did not change between two data point recordings (Table 2-10). This caused an error in the calculation of the DeltaTime between these two data points, as DeltaTime was determined to be equal to 0. These erroneous lines of data were also removed from the data files prior to calculation.

6	ATT	ADT	ALX	ALY	ARI	APW	APH	AQU	AFX
5	TotalTime (s)	DeltaTime (ms)	X_Gaze	Y_Gaze	Region	PupilWidth	PupilHeight	Quality	Fixation (s)
777	21.7419	MovieFrame	1	651					
10	**21.7414**	**16.6822**	0.4611	1.3005	-1	0.9353	0.6381	3	0.1333
10	**21.7414**	**0**	0.4611	1.3005	-1	0.9253	0.6358	3	0.1333
777	21.7753	MovieFrame	1	652					
10	21.7747	33.3199	0.4611	1.3005	-1	0.9215	0.605	3	0.1333
10	21.7913	16.6382	0.4611	1.3005	-1	0.9143	0.6038	3	0.1333

Table 2-10: Data recording error in TotalTime (ATT) column, where TotalTime value did not change (error is highlighted and shown in bold type text).

2.4 Validation of GazeDetection Software (1)

2.4.1 Manual Analysis

In order to validate GazeDetection, the automatic outputs were compared with raw data that had been analysed manually for the same files. Three putts were randomly selected from three different golfers for this purpose. The right and left eye data from each putt were analysed at three different fixation zone diameters (0.5° (0.0087 Cartesian coordinates), 1.5° (0.0261), and 3.0° (0.0522)). The manual fixation analysis followed the same principles as the computer-generated fixation analysis outlined in sections 2.3.1.1 (Fixation Zone) and 2.3.1.2 (Fixation Duration) above. All manual calculations were carried out with Microsoft Office Excel 2003. Any erroneous data points (as described in section 2.3.2.1 Mathematics) were removed from the files prior to the manual calculations being completed.

Differences between the manual analysis and GazeDetection were calculated for the following parameters: Start Time, End Time, Start X Position, Start Y Position, End X Position, End Y Position, and Fixation Duration. If a difference was found between the two files, the manual file was checked to confirm that the difference was not due to a calculation error. Calculation errors in the manual data file were corrected, but no other changes were made to either of the files.

2.4.2 Results

A total of 2068 fixations were compared in the validation analysis. Distribution statistics were calculated for the differences between the manual and GazeDetection values for each parameter and are presented in Table 2-11.

Statistic	Start Time (s)	End Time (s)	Start X Position	Start Y Position	End X Position	End Y Position	Fixation Duration (ms)
Mean	0.000000	0.000000	0.000000	-0.000009	0.000000	-0.000009	0.000067
Standard Deviation	0.0000000	0.0000000	0.0000000	0.0000361	0.0000000	0.0000361	0.0002104
Minimum	0.0000	0.0000	0.0000	-0.0002	0.0000	-0.0002	-0.0006
Maximum	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0042

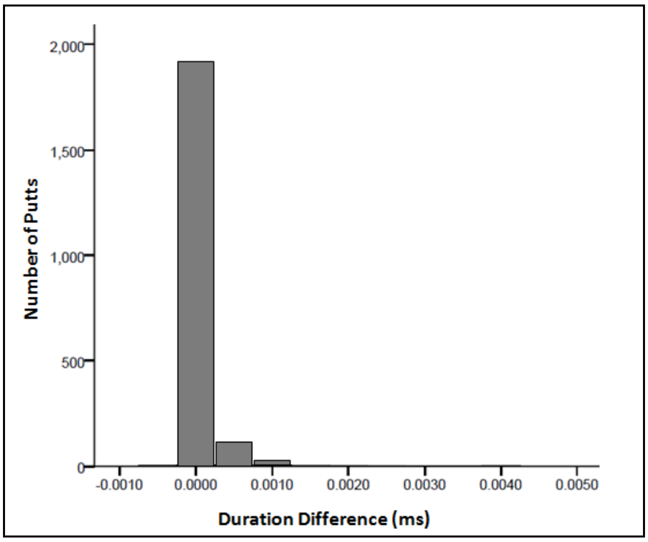
Table 2-11: Distribution analysis of the difference between the manual and GazeDetection parameters (Start Time, End Time, Start X Position, Start Y Position, End X Position, End Y Position and Fixation Duration) included in the validation analysis.

Start Time, End Time, Start X Position and End X Position differences between the manual and automated measurements all had mean, standard deviation, minimum and maximum values of zero indicating that there was no difference between the any of the fixation characteristics between the software and manual calculations.

Small differences in Start Y Position and End Y Position were observed, but these were well below the level of precision of the instrument (coordinates were measured to 4 decimal places), therefore these parameters were also considered to be equal for the two analytic methods. The small difference was attributed to the normalisation of the y-coordinate; manually this normalisation was carried out at a significance level of four decimal places, while in the GazeDetection program calculated the normalised values using “double precision” which is accurate to 15 or 16 decimal places.

Small differences were found in the Fixation Duration values calculated by GazeDetection when compared with the manual calculations. Examination of the distribution graph (Figure 2-6) revealed that the vast majority of durations measured had a difference of zero, therefore the program as it was written was considered to be acceptable for use in a preliminary analysis. The small differences found between the manual and GazeDetection results were again attributed to the extra precision of the maths in the GazeDetection program.

Figure 2-6: Distribution graph for the difference in Fixation Durations found between the manual analysis and GazeDetection.



2.5 Additional GazeDetection Software Development

2.5.1 Time Calculations

Preliminary analysis of putting data highlighted another problem with the original data files. When the ViewPoint software recorded the uncompressed .avi files, they were not recorded at exactly the same time as the raw data files. When the files were matched on elapsed time (calculated for the .avi files as Time(s) = frame number * frame rate (fps); TotalTime column in the raw data files) there was a difference in the total length of the two files ranging from 0.5s to more than 50s. The delay was non-linear and could become progressively longer throughout a file in a random, unpredictable fashion. For this reason the files could not be synchronised with a simple calculation as was initially thought.

Fortunately, the raw data files contained frame number references that could be matched with the frames of the .avi video file. As long as there was ±1 frame difference between the raw data and video files, they were matched on frame number. If the difference was greater than one frame between the two files, the default option was to match the files on elapsed time, although this could be overwritten by the investigator. Due to the unpredictable nature of the recording delay, data and video files with more than one frame difference between them, were deemed to be unacceptable for analysis and excluded from the data set.

An additional feature was added to the program whereby the data file (x, y) coordinates were tracked using small boxes containing "A" (Eye A, right eye) and "B" (Eye B, left eye). Visually these overlay the respective gaze points when the two files were synchronised based on frame number; when the frames were synchronised based on elapsed time, the degree of overlap decreased as the time difference between the two files increased.

2.5.2 Additional Raw Data Errors

In the process of identifying the time coding errors described above, two other errors within the raw data files were noted.

2.5.2.1 Quality codes

Quality codes were not data errors *per se*; rather they were indicators of the reliability of the collected data. They are an inherent part of the ViewPoint data file and were unfortunately over-looked in preparing the first version of GazeDetection. Quality codes are an integer ranging from 0 to 5; 0 is the best possible case, while 5 is the worst possible scenario (Table 2-12). As a Pupil Only method of gaze tracking was used, quality codes 0 and 2 were not relevant. All data with a quality code 1 was considered as acceptable, but quality codes 3, 4 and 5 were considered to be unacceptable. Quality codes 3, 4 and 5 are all indicators of poor pupil tracking. In the Pupil Only method there are no other indices of gaze position therefore unreliable pupil data was considered unfit for analysis. All data points with quality codes 3, 4 or 5 were excluded from the analysis prior to the calculation of fixations in the final version of GazeDetection.

Code	Description
0	The user has selected to use the *glint-pupil vector* method and both features are successfully located.
1	The user has selected to use the *pupil only* method and the pupil was successfully located.
2	The user has selected to use the *glint-pupil vector* method, but the glint was not successfully located. Defaults to *pupil only* method for data recorded.
3	In either the *pupil only* or *glint-pupil vector* method, the pupil exceeded criteria limits set.
4	In either the *pupil only* or *glint-pupil vector* method, the pupil could not be fit with an ellipse.
5	In either the *pupil only* or *glint-pupil vector* method, the pupil scan threshold failed.

Table 2-12: Quality codes and their descriptions.[73]

2.5.2.2 X, Y stationary positional error

These errors occurred when either the X_Gaze position or the Y_Gaze position (or both) did not change between subsequent data points (Table 2-13), leading to a calculation error whereby the change in gaze position between these two subsequent data points was 0. Originally (validation 1), these data points were left in the data files, but were subsequently removed in the final version of the program as they were determined to be errors in raw data file rather than a stable gaze position.

6	ATT	ADT	ALX	ALY	ARI	APW	APH	AQU	AFX
5	TotalTime (s)	DeltaTime (ms)	X_Gaze	Y_Gaze	Region	PupilWidth	PupilHeight	Quality	Fixation (s)
777	94.9782	MovieFrame	1	2846					
10	94.979	16.6943	**0.2697**	**0.6386**	-1	0.857	0.239	3	0
10	94.9956	16.6247	**0.2697**	**0.6386**	-1	0.8271	0.2469	3	0

Table 2-13: Data recording error in X_Gaze (ALX) and Y_Gaze (ALY) columns, whereby X_Gaze and Y_Gaze values did not change (error is highlighted and shown in bold type text).

2.6 Validation of GazeDetection Software (2)

2.6.1 Manual Analysis

The same three putts used in the first validation [2.4] were re-analysed in the second software validation. Fixation and fixation duration were calculated in exactly the same way as described previously after all of the erroneous data points previously mentioned [2.3.2.2, 2.5.2.1 and 2.5.2.2] were removed from the file. The second validation was done to ensure that the elimination of the extra data errors did not interfere with the fixation analysis. The second validation was only done on the 3.0° fixation zone diameter because the fixation zone diameter criteria had been validated in the original comparison.

2.6.2 Results

A total of 552 fixations were compared in the validation analysis. Distribution statistics were calculated for the differences between the manual and GazeDetection values for each parameter and are presented in Table 2-14.

Start Time, End Time, Start X Position, End X Positions and Fixation Duration all had mean, standard deviation, minimum and maximum values of zero indicating that there was absolutely no difference between the software and the manual calculations for these parameters.

Small differences in Start Y Position and End Y Position were noticed and once again attributed to the difference in the normalisation methods used in the manual and GazeDetection analysis. As these differences were still well below the level of precision of the instrument, the manual and automated GazeDetection results were considered to be essentially equal, and the newest version of the GazeDetection software was used for all subsequent analyses.

Statistic	Start Time (s)	End Time (s)	Start X Position	Start Y Position	End X Position	End Y Position	Fixation Duration (ms)
Mean	0.000000	0.000000	0.000000	-0.000033	0.000000	-0.000033	0.000000
Standard Deviation	0.0000000	0.0000000	0.0000000	0.0000431	0.0000000	0.0000427	0.0000000
Minimum	0.0000	0.0000	0.0000	-0.0002	0.0000	-0.0002	0.0000
Maximum	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 2-14: Distribution analysis of the difference between the manual and GazeDetection parameters (Start Time, End Time, Start X Position, Start Y Position, End X Position, End Y Position and Fixation Duration) included in the second validation analysis.

2.7 General Use

When using GazeDetection the data file and the .avi file must be in the same location. Upon loading the data file, the program automatically loads the movie file as well. Normalisation values have to be entered before a file is loaded, or they are not recognised. If more than one fixation zone is to be analysed, these values can be entered into the Auto Analysis option and the program runs them sequentially. When the Auto Analysis option is used, data for each fixation zone analysed is included in the same output file.

Using the Video tab, investigators can move through the scene camera videos on a frame by frame basis (or faster) and can mark the various time points of interest in the video file. A detailed explanation of the time points of interest in the analysis of golf putting is given in Chapter 3, Analytic Strategy Development. Using the time points marked in the scene camera video file, GazeDetection is able to give each individual fixation a 2 digit, “phase, fixation ID" code (phase, fixation ID) which is used to identify all of the fixations made during a putt.

Golfer-specific parameters (i.e. dominant eye, ID number) and putt-specific parameters (i.e. putt ID, putt type, success/failure) can be entered on the Video tab and are included in the final output file. A sample of the final data output produced by GazeDetection is shown in Figure 2-7.

Figure 2-7: Sample data output from the final version of the GazeDetection software program.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	PlayerID	PuttID	A/B	DomEye	PuttDiam	PuttType	PuttResult	AddrsStar	BkSwgSta	Contact	PuttPhase	FixationID	StartTime	EndTime	Duration	StartXPos	StartYPos	EndXPos	EndYPos	AverageXI	AverageYPos
2	20	1	1	2	0.0087	1	1	103.7843	113.8606	114.8282	0	0	94.5627	94.6127	0.05	0.623	0.3406	0.6159	0.3359	0.6185	0.3413
3	20	1	1	2	0.0087	1	1	103.7843	113.8606	114.8282	0	0	94.6293	94.6627	0.0334	0.6122	0.3333	0.6079	0.3274	0.6081	0.3284
4	20	1	1	2	0.0087	1	1	103.7843	113.8606	114.8282	0	0	94.6793	94.696	0.0167	0.601	0.3184	0.5997	0.3132	0.5997	0.3132
5	20	1	1	2	0.0087	1	1	103.7843	113.8606	114.8282	0	0	94.7128	94.7293	0.0165	0.5991	0.3093	0.5916	0.3074	0.5916	0.3074
6	20	1	1	2	0.0087	1	1	103.7843	113.8606	114.8282	0	0	94.746	94.7626	0.0166	0.5883	0.3004	0.5847	0.2941	0.5847	0.2941
7	20	1	1	2	0.0087	1	1	103.7843	113.8606	114.8282	0	0	94.7793	94.7959	0.0166	0.582	0.2858	0.5837	0.2857	0.5837	0.2857

2.8 Discussion

GazeDetection is a software program, written and developed via collaboration between OTG Research & Consultancy and Aston University, for the analysis of golf putting eye tracking data recorded with the binocular ViewPoint eye tracker from Arrington Research, Ltd.

Although the program was designed specifically for golf, the base code has been written in a general format so that it would require limited additional work to be used for data collection in other sports. Eye tracking data collected from other sports is not included in this thesis, as it is limited to golf.

GazeDetection has been shown to be capable of objectively quantifying fixations using binocular x, y gaze co-ordinates without the use of extensive manual video analysis; it was also relatively easy to use. Therefore, GazeDetection is an ideal program for studying putting vision strategy in golf. At the moment, GazeDetection is not commercially available, although the intention is to make it so.

GazeDetection, in combination with Microsoft Office Excel 2003 and SPSS version 18 were used to complete all of the golf putting data analyses hereafter.

2.9 Summary

Chapter 2, GazeDetection Software Development discussed the development and validation of novel software for the analysis of golf putting binocular eye tracking data. The next chapter (Chapter 3, Analytic Strategy Development) will examine the practical feasibility of using GazeDetection, including an analysis of the repeatability of the video coding techniques and the selection of objective criteria for the definition of gaze behaviours.

Chapter 3

ANALYTIC STRATEGY DEVELOPMENT

3.1 Introduction

Previous eye tracking research in golf has focused primarily on the concept of 'quiet eye' which was defined as the final fixation or tracking gaze that was located on a specific location or object in the visuo-motor workspace within 3° of visual angle or less for a minimum of 100ms.[30] Unfortunately, as discussed earlier, there were significant problems with this early research [Chapter 1, Introduction]. The most significant of these problems was that a golf ball subtends a visual angle of 1.6° at a distance of 1.5m, the average distance between the eyes and the golf ball when putting. Therefore, a 3° fixation was not representative of the precise fixation demands of putting as it was almost twice the size of the ball. The other significant problem with this analysis was that it was carried out via manual, subjective video analysis that lacked precision, particularly for fixations measured with the 0.5° visual angle criterion.

Advent of new eye tracking technology (Arrington Research, Inc., Scottsdale, Arizona, USA) and development of GazeDetection software (Aston University and OTG Research & Consultancy) has made it possible to measure fixations both objectively and with a high degree of precision. In light of these new technologies, the criterion for defining a fixation needed to be reviewed and possibly updated. If the fixation criteria were to change significantly, gaze behaviours other than the quiet eye may be found to be important in the vision strategy of golfers when putting. The purpose of this work was two-fold: (i) to measure the repeatability and precision of the time stamps used in defining the action phases of each putt to ensure that the methods for video coding and data analysis were consistent between putts, and (ii) to determine objectively what the optimal fixation criteria for the analysis of vision strategy in golf putting would be so that the gaze behaviours definitions were accurate and consistent with current vision science knowledge. The outcome variables considered to be of interest were the repeatability and the precision of the video coding techniques, as well as the identification of optimal criteria for measuring a fixation. These parameters are of interest because, once defined they can be used to direct future analyses with greater purpose and efficiency.

3.2 Methods

3.2.1 Study Design

This study was designed as a retrospective analysis of eye tracking data collected during optometric examinations and optometric screenings on golfers of various levels. The golf-specific optometric examinations and screenings were completed by practitioners at the Michel Guillon Sports Vision Clinic, London, UK, either on the premises or in a mobile clinic set up in various locations around the United Kingdom (UK). This study received ethics approval from Aston University Audiology/Optometry Research Ethics Committee (AO2010.20).

3.2.2 Study Population

Files from all golfers who had been examined at the clinic were eligible for inclusion in the study and were included as long as no critical information was missing from the file. A total of 482 putts from 27 golfers of various skill levels were included in this analysis. Putts were taken on an artificial putting green from 6 or 10 feet, on real grass from variable distances or on a felt matt from a distance of approximately 10 feet. On average, each golfer took 18 putts. All golfers gave informed consent prior to commencement of the optometric examination or screening.

3.2.3 Study Procedures

To assess the repeatability of the video coding methods, 10 putts were randomly selected and coded with GazeDetection by one observer on three different occasions. Each video coding session was conducted independently without knowledge of the previous video coding results. At least 24 hours separated each video coding session. Six time points including Stationary Ball, Address, Backswing, Pre-Contact, Post-Contact and Gaze Break were coded based on scene camera video footage. The definition of these time points is discussed in more detail below. Two different video coding definitions ("Resting Address" and "Tangent Address") were compared for Address.

To determine the optimal fixation criteria, each of the 482 putts were analysed with six different fixation zone criteria of 0.5°, 1.0°, 1.5°, 2.0°, 2.5° and 3.0° visual angle. All visual angles were calculated for a distance of 1.5m. The total number of fixations on the ball, the mean duration of fixations on the ball and the total duration of fixations on the ball during both the Address and Swing phases of the putt were included in this analysis.

3.2.4 Statistical Analysis

Statistical analysis was completed using SPSS 18.0 for Windows (Release 18.0.0, 30 July 2009, http://www.spss.com).

3.2.4.1 Video Coding Repeatability and Precision

The time differences in milliseconds were calculated for each of the six coded time points (Stationary Ball, Address, Swing, Pre-Contact, Post-Contact, Gaze Break) in the following manner: Trial 2 – Trial 1, Trial 3 – Trial 1, Trial 3 – Trial 2. The mean of the time differences for all three trials was calculated for each coding parameter in each video analysed; this was defined as the coding error. The coding error was then compared with the duration of the putt phase associated with the time point (Stationary Ball, Address, Backswing and Gaze Break time points were compared with the Preparation, Address, Swing and Post-Contact phase durations respectively), and a percentage error was calculated for each time point in each of the ten videos assessed. Finally, the mean, standard deviation and 95% confidence intervals were calculated for the percentage error for every video coding parameter based on the results of the 10 videos examined. The percentage error of each video coding parameter was used as the index of repeatability.

3.2.4.2 Fixation Criteria Determination

Means and standard deviations were calculated for each of the six fixation zones (0.5°, 1.0°, 1.5°, 2.0°, 2.5°, and 3.0° visual angle) for the following parameters:

1. Total number of fixations on the ball in Address
2. Mean duration of fixations on the ball in Address
3. Total duration of fixations on the ball in Address
4. Total number of fixations on the ball in Swing
5. Mean duration of fixations on the ball in Swing
6. Total duration of fixations on the ball in Swing.

Pearson correlations were calculated between the six fixation zones for the Total Number of Fixations on the ball, the Mean Duration of Fixations on the ball and the Total Duration of Fixations on the ball during both the Address and Swing phases. The results were then compared amongst themselves and with previous eye tracking research to determine which fixation zone criteria gave the best representation of the gaze behaviours being studied. From these, optimised criteria were determined and then used all remaining analyses [Chapter 5, Vision Strategy in Golf Putting: Skill and Success].

3.2.5 Video Coding Parameters

In order to examine golf putting vision strategy, various time points and phases within each putt were defined. Time points were determined subjectively from scene camera video footage examined frame-by-frame with the GazeDetection software. The video frames which corresponded to the Stationary Ball, Address, Backswing, Pre-Contact, Post-Contact and Gaze Break time points were manually marked in each putt by an observer. The criteria used to define each of the six aforementioned time points are outlined below [3.2.2.1]. The Data Start and Data End time points were automatically calculated by GazeDetection.

Four putt phases (Preparation, Address, Swing and Post-Contact) were defined within in each putt by GazeDetection using the individually coded time points. These phases are described in more detail below.

3.2.5.1 Time Points of Interest

All of the time points of interest were defined by their corresponding frame in the scene camera video.

3.2.5.1.1 Data Start

Data Start was defined as the point in a data file when an individual putt began. It was not manually coded, but was automatically calculated by GazeDetection. Data Start was defined as the frame occurring 1.00s before Stationary Ball or -1.00s further from Ball Contact.

3.2.5.1.2 Stationary Ball

Stationary Ball was defined as the time when the ball was perceived to be resting in a stationary position without anything touching it. Golfers used a variety of techniques to position the ball and the definition of this time point has been written to reflect this. It was important to try and capture as much information as possible during the putt; therefore, the definition of Stationary Ball was hierarchical. When coding video files, Stationary Ball was recorded for the different types of ball positioning as follows:

1. If a golfer crouched to position the ball, and the ball was visible in the field of view of the scene camera, then Stationary Ball was coded immediately upon the golfer's release of the ball after placing it. This type of Stationary Ball was recorded as "Stationary Ball".

2. If a golfer crouched to position the ball, but the ball was not visible in the field of view of the scene camera, then Stationary Ball was coded when it was first perceived that the golfer was in the process of standing up. This type of Stationary Ball was recorded as "Stands Up".
3. If the golfer placed the ball, stood up fully and looked at the green, and then crouched to adjust position the ball, Stationary Ball was coded at the initial placement of the ball, rather than at the re-positioning. The re-positioning was considered to be an adjustment to the original ball position and a continuation of the preparation phase of the putt, rather than a new ball placement which would re-start the putt preparation phase unless there was a significant evidence otherwise (i.e. unless the ball was picked up and moved to an entirely new position). If the ball was re-positioned without the golfer standing up in between, the Stationary Ball was coded from the frame where the ball was finally released; this was considered to be part of the same ball placement process.

4. If the golfer did not crouch to position the ball, but rather stood and used the club to position the ball, then Stationary Ball was coded when the club was no longer touching the ball and the ball was resting in a stationary position. If the ball rolled after the club was removed, then Stationary Ball was not coded until the ball had come to rest. This type of Stationary Ball was also recorded as "Stationary Ball".

5. If a golfers' coach placed the ball for them, than Stationary Ball was coded when the coach was no longer touching the ball and it was sitting in a resting position. This type of Stationary Ball was recorded as "Placed by Coach".

6. If the golfer did not position their ball, or the positioning of the ball was not been in the video, then Stationary Ball was coded as the first frame where the ball appeared in a stationary position in the field of view of the scene camera This type of Stationary Ball was recorded as "Ball Appearance".

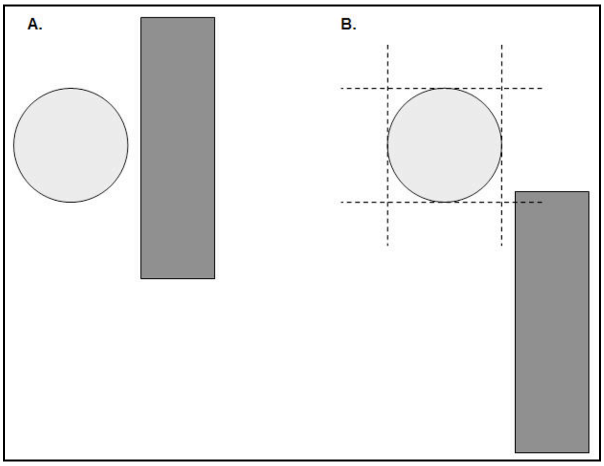
3.2.5.1.3 Address

Originally, an Address was coded as the frame when the club was first perceived to come to rest in a motionless position beside the ball (Figure 3-1 A). The club did not need to be in the same position in the Address as it was at the start of the backswing; the club position could have been adjusted prior to the backswing, as long as part of the club face remained in line with the ball and the player did not break their putting stance. This Address coding was termed "Resting Address".

During the analysis Resting Address was found to be quite time consuming and challenging to code, and a new Address definition was created (Tangent Address). Tangent Address was defined as the frame in which the club was first perceived to break any of the horizontal or vertical tangents to the ball during club placement (Figure 3-1 B). If the frame in which the club broke a tangent of the ball was not recorded, Tangent Address was coded as the first frame in which the club had crossed a tangent of the ball and both the ball and the club were visible.

It was possible for more than one Address to be coded within the same putt. The criterion for additional Addresses within a putt was the same for both the Resting and Tangent Addresses. If, during the Address phase, the golfer moved their club such that no part of the club face remained in line with the ball and then re-positioned it next to the ball, a Secondary Address was coded. The start of the Secondary Address was defined by the Address type being used (i.e. Resting or Tangent).

Figure 3-1: Resting Address (A) and Tangent Address (B). In Resting Address, an Address was coded when the club (dark grey) first came to rest in a stationary position next to the ball (light grey). In Tangent Address, an Address was coded when the club first broke any of the horizontal or vertical tangents of the ball.



The Address that occurred closest to ball contact was considered to be the Primary Address. It was not possible to have a putt without a Primary Address. All other Addresses in the putt were classified as Secondary Addresses. There was no limit to the number of Secondary Addresses that could occur in a single putt, but there was usually fewer than three. Secondary Addresses were labelled in increasing order from Ball Contact. The second last Address before Ball Contact was called Address 2. The third address from Ball Contact (which is chronologically earlier than Address 2, but further from Ball Contact), was labelled as Address 3. This number system continued ad infinitum for however many Secondary Addresses were coded within a putt.

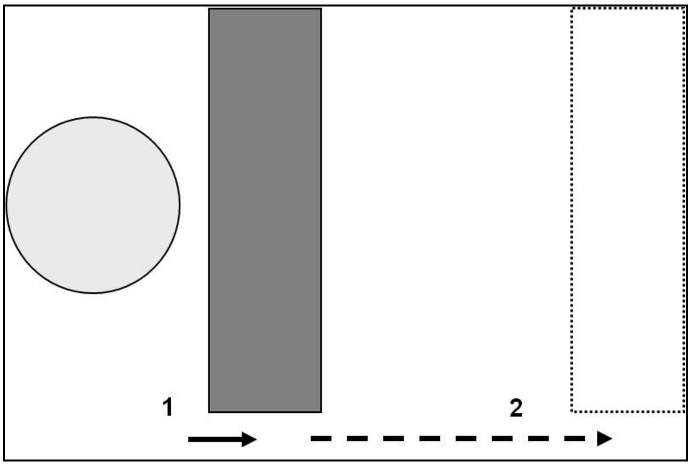
Address Time (T_A) was used as a reference to determine the end of the Preparation phase of the putt and the start of the Address phase. The Primary Address Time was labelled as "T_{A1}", and Secondary Address Times were labelled as "T_{A2}, T_{A3}, …, T_{An}" in reverse chronological order from Ball Contact.

3.2.5.1.4 Swing

Swing was coded as the first frame in which the club face was detected to be moving away from the ball in the backswing. If the club moved away from the ball but did not continue to move in the backswing motion, than the movement of the club away from the ball was considered to be a readjustment of the club position and was ignored (Figure 3-2).

Swing Time (T_s) was used as a reference to determine the end of the Address phase of the putt and the start of the Swing phase of the putt.

Figure 3-2: Backswing was coded when the club was first perceived to move away from the ball (1) and continue into a backswing motion (2).



3.2.5.1.5 Ball Contact

Ball Contact (T_0) was used as the zero time reference for every putt. All of the events that occurred during the putt prior to Ball Contact (i.e. Address and Swing) had a negative time value, and all events that occurred after Ball Contact (i.e. Gaze Break) had a positive time value (Figure 3-3).

It was not possible to code the true contact time of the ball in most videos, as it typically fell between two video frames rather than appearing as its own distinct video frame. For this reason it was decided to define Ball Contact by two references: Pre-Contact and Post-Contact. Pre-Contact was defined as the frame which immediately preceded contact of the ball, where the ball was still resting in the same position it was in the Swing. Post-Contact was defined the frame immediately after ball contact, where the ball had moved away from its Swing position. Pre- and Post-Contact time points were coded based upon ball position not club position. This was important because occasionally, in rare cases the club appeared to be in contact with the ball for both Pre- and Post-Contact time points, the only difference between the two being the position of the ball (Figure 3-4).

Figure 3-3: Primary Address (T_A), Swing (T_S) and Contact (T_0) time points in the golf putt.

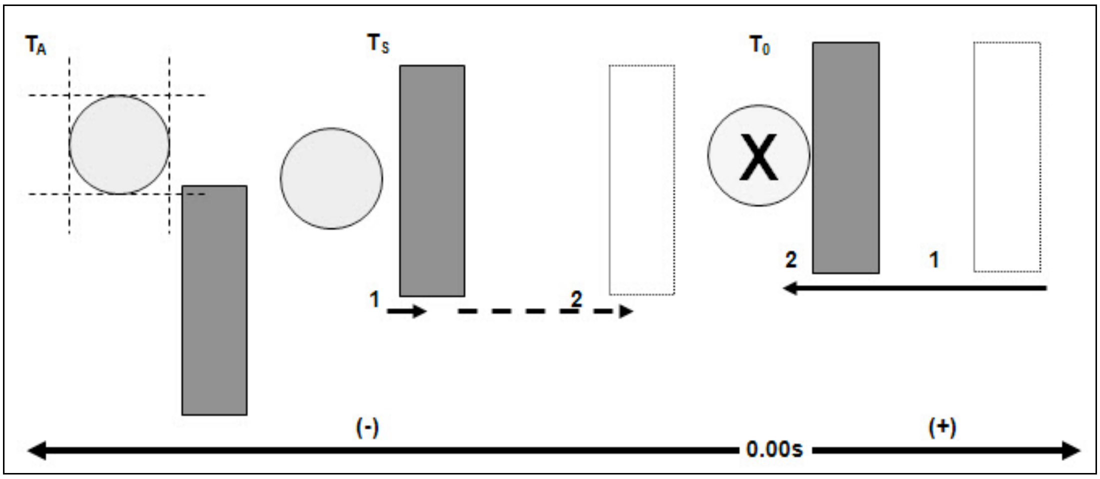
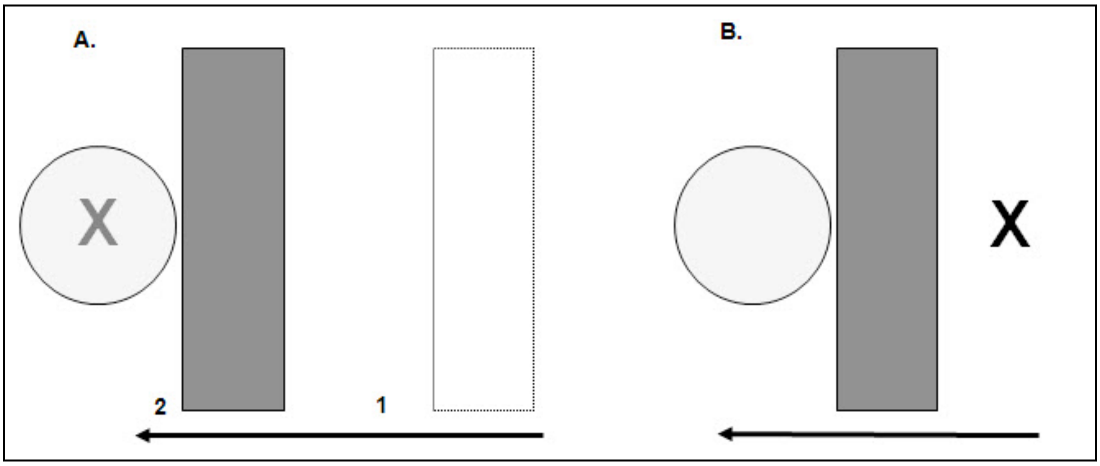


Figure 3-4: Pre-Contact (A) was coded as the frame which immediately preceded ball contact and Post-Contact (B) was coded as the frame immediately after ball contact. "X" represents the stationary position of the ball.



3.2.5.1.6 Gaze Break

Gaze Break was coded when it was perceived that the golfer's gaze had broken away from the line of the putt and/or the hole. Often, golfers would look away from or move away from their putting stance at Gaze Break. On occasion, golfers looked back to their club rather than away. If the golfer looked back to their club while maintaining their putting stance, Gaze

Break was not coded until the club was released from its follow through position and the golfer looked away from the club or broke their putting stance.

3.2.5.1.7 Data End

Data End determined where in a data file, an individual putt ended. It was not visually coded, but was automatically calculated by GazeDetection. Data End was defined as the frame that occurred 1.00s after Gaze Break or +1.00s further from Ball Contact.

3.2.5.2 Phases of Interest

3.2.5.2.1 Preparation Phase

The Preparation phase was defined as the portion of the putt that started at Stationary Ball and ended at Address (T_{An}). If there was only one Address in the putt, the Preparation phase ended at Primary Address (T_{A1}). If there was more than one Address in the putt, the Preparation phase ended at the earliest Address. For example, if a putt had three Addresses, the Preparation phase ended at Address 3, not at Address 2 or Primary Address.

3.2.5.2.2 Primary Address Phase

The Primary Address phase was the portion of the putt that started at the Primary Address (T_{A1}) and ended at Swing (T_S). The Primary Address phase was the Address phase that occurred closest to Ball Contact.

3.2.5.2.3 Secondary Address Phases

Secondary Address phases refer to the portions of the putt that started at Address (n) and ended at Address (n-1). For example, Secondary Address phase 3 started at Address 3 (T_{A3}) and ended at Address 2 (T_{A2}); Secondary Address phase 2 started at Address 2 (T_{A2}) and ended at Address (T_{A1}). There may have been more than one Secondary Address phase per putt, and they were labelled in reverse chronological order from Ball Contact (i.e. Secondary Address phase 3 occurs further from Ball Contact than Secondary Address 2).

For the sake of brevity and consistency, Secondary Address phase 2 will be referred to as Secondary Address 2, Secondary Address phase 3 as Secondary Address 3, et cetera.

3.2.5.2.4 Swing Phase

The Swing phase started at Backswing Time (T_S) and continued until Ball Contact (T_0). There was only one Swing phase per putt.

3.2.5.2.5 Post-Contact Phase

The Post-Contact phase was the remainder of the putt that occurred after Ball Contact (T_0). The Post-Contact phase ended at the Gaze Break.

3.3 Results

3.3.1 Video Coding Repeatability and Precision

Video coding of the Stationary Ball, Resting Address and Gaze Break demonstrated moderate repeatability (mean coding error: 100-500ms), while coding of Tangent Address, Backswing, Pre-Contact and Post Contact times demonstrated high repeatability (mean coding error: <100ms) (Table 3-1).

Tangent Address and Backswing coding errors were, on average, less than one video frame (16.67ms), while Pre-Contact and Post-Contact coding demonstrated errors of zero. As Pre- and Post-Contact define T_0, the time reference for the entire analysis, it was important that these parameters showed little or no error.

The error in the Resting Address coding was approximately eight times greater than the error in the Tangent Address coding. The experience of the observer responsible for coding the data was that Resting Address coding was more difficult to use. This was supported by the significantly higher mean coding error found for this coding parameter. For these reasons, the use of Resting Address coding was discontinued.

Stationary Ball and Gaze Break showed significantly higher coding errors than any of the other coding parameters. This was expected due to the variable nature of these parameters. Stationary Ball was inherently variable due to the various methods used by the golfers to place the ball. The limited field of view of the scene camera was another cause of this inherent variability, because the release of the ball was not visible in all videos.

Gaze Break showed the largest overall coding error. Based on the observer's experience, it was also the most difficult parameter to judge, as it was highly variable between golfers and often between putts from the same individual. The limited field of view of the scene camera made it difficult to judge where the golfer was gazing when the eyes were in extreme gaze positions (i.e. looking at the hole); if the golfer was not standing in a putting stance, (i.e. stood up after follow through) than the scene camera field of view was not aligned with the golfers' line of sight. All of these factors ultimately affected the judgment of Gaze Break. The higher variability in Stationary Ball and Gaze Break was considered to be acceptable, as these two time points were not used to define the Address or Swing phases of the putt which were the principle phases of interest.

Video	Stationary Ball	Resting Address	Tangent Address	Backswing	Pre-Contact	Post-Contact	Gaze Break
1	266.9	88.9	44.5	22.2	0.0	0.0	22.1
2	0.0	200.2	44.5	0.0	0.0	0.0	0.0
3	44.6	22.3	0.0	44.5	0.0	0.0	3603.5
4	0.0	22.3	0.0	0.0	0.0	0.0	0.0
5	1067.7	734.0	0.0	0.0	0.0	0.0	22.3
6	1223.4	66.7	0.0	0.0	0.0	0.0	200.2
7	0.0	0.0	44.5	0.0	0.0	0.0	0.0
8	0.0	66.7	0.0	0.0	0.0	0.0	0.0
9	39.8	0.0	0.0	44.2	0.0	0.0	66.7
10	44.5	0.0	22.2	0.0	0.0	0.0	756.3
Mean	268.7	120.1	15.6	11.1	0.0	0.0	1126.5

Table 3-1: Coding error (ms) for the six coding parameters of interest; overall mean coding error for all 10 videos is displayed in the final row of the table.

Percentage coding error was calculated for the Preparation, Primary Resting Address, Primary Tangent Address, Swing and Post Contact phases using the corresponding time point (Equation 3-1 and Table 3-2). The Pre- and Post-Contact coding parameters did not have an associated phase as Contact was an isolated time point and percentage error was not calculated for these parameters.

Equation 3-1: Percentage Error Calculation

*% Error = (Mean Time Point Coding Error (ms) / Mean Phase Duration (ms)) * 100*

For all of the coding parameters analysed, the percentage error for the phase was 2.5% or less, except for Stationary Ball and Gaze Break which had a percentage errors of 22.4 % and

15.8% in the Preparation and Post-Contact phases respectively. The higher error was expected for both Stationary Ball and Gaze Break, as these were the most difficult parameters to code and they were the parameters with the most inherent variability.

Tangent Address had a significantly lower coding error as well as a significantly lower percentage error when compared with Resting Address. The percentage error of Resting Address was 8 times greater than the percentage error of Tangent Address. These results confirmed that Tangent Address was the more repeatable coding criterion.

The 95% confidence intervals of percentage error were quite narrow for both Tangent Address and Backswing, which further highlights the good repeatability of these coding variables. Stationary Ball, Resting Address and Gaze Break had wider confidence intervals indicative of poorer repeatability, as was expected. The reasons for the greater variability in these values were explained above.

Video	Preparation	Resting Address	Tangent Address	Backswing	Gaze Break
1	0.9	2.3	0.9	2.7	0.6
2	0.0	8.7	1.5	0.0	0.0
3	1.3	0.3	0.0	4.4	124.1
4	0.0	0.4	0.0	0.0	0.0
5	4.8	9.2	0.0	0.0	0.6
6	215.7	2.4	0.0	0.0	10.0
7	0.0	0.0	0.6	0.0	0.0
8	0.0	1.0	0.0	0.0	0.0
9	1.4	0.0	0.0	3.8	2.2
10	0.1	0.0	0.2	0.0	20.4
Mean	22.4	2.4	0.3	1.1	15.8
Std Dev	67.9	3.6	0.5	1.8	38.6
95% C.I.	[9.4, 35.4]	[1.0, 3.8]	[0.1, 0.5]	[0.5, 1.7]	[6.6, 25.0]

Table 3-2: Percentage error (%) for Stationary Ball, Resting Address, Tangent Address, Backswing and Gaze Break; overall mean, standard deviation and 95% confidence intervals for the percentage error are displayed in the final rows of the table. There was no phase duration or percentage error information for the Contact parameters, as Contact was a single time point not a phase.

3.3.2 Fixation Criteria Determination

Two phases of the putt were included in this portion of the study: the Primary Address phase and the Swing phase. In this particular analysis, Resting Address coding was used because this analysis was completed prior to the completion of the video coding repeatability study. Therefore, in this analysis the Primary Address phase started when the putter was deemed to come to rest in a motionless position next to the ball and ended with the first detection of the movement of the club away from the ball in the backswing. The Swing phase started with first movement of the club away from the ball in the backswing and ended with ball contact. These criteria are similar to those used previously by other researchers.[28]

As expected, the Total Number of Fixations in each phase decreased as the fixation zone size increased for both the Primary Address (Table 3-3) and Swing phases (Table 3-4). Fewer total fixations were made during the Swing phase compared with the Primary Address phase at all fixation zone diameters. The Swing phase was also significantly shorter than the Primary Address phase, and this was the principle reason there were fewer total fixations in the Swing phase.

Mean Fixation Duration and Total Fixation Duration both increased as fixation zone size increased in the Primary Address (Table 3-3) and Swing (Table 3-4) phases alike. Interestingly, the Mean Fixation Duration was similar in both phases but the Total Fixation Duration was much longer in the Primary Address phase. Considering there were significantly more fixations in the Primary Address phase, and the Primary Address phase was longer than the Swing phase, the greater Total Duration of Fixations in this phase was not unexpected.

Mean Fixation Durations were significantly longer in the 3.0° fixation zone than in the 0.5° fixation zone: 6.7x for the Primary Address and 5.5x for the Swing, however the Total Duration of Fixations was only 1.9x longer in the Primary Address and 3.0x longer in the Swing. Interestingly, the increase in the Total Duration of Fixations was directly proportional to the decrease in the Total Number of Fixations made in each of the phases (Primary Address, 2x decrease; Swing, 3x decrease). These results suggest that fixation zones of different sizes may be measuring different gaze behaviours.

Fixation Zone	Number of Fixations*	Mean Fixation Duration (ms)*	Total Fixation Duration (s)*
0.5 degree	36.41 ± 19.12	71.0 ± 62.1	2.15 ± 1.18
1.0 degree	30.03 ± 16.54	148.1 ± 180.8	2.94 ± 1.36
1.5 degree	25.23 ± 15.10	230.1 ± 300.3	3.38 ± 1.45
2.0 degree	22.00 ± 13.84	312.4 ± 439.0	3.67 ± 1.49
2.5 degree	19.65 ± 13.00	393.7 ± 578.7	3.90 ± 1.53
3.0 degree	17.88 ± 12.08	473.4 ± 701.8	4.15 ± 1.58

*All values are reported as Mean ± Standard Deviation

Table 3-3: Summary of parameters of all fixations on the ball during the Address phase.

Fixation Zone	Number of Fixations*	Mean Fixation Duration (ms)*	Total Fixation Duration (s)*
0.5 degree	11.86 ± 3.65	57.7 ± 48.3	0.62 ± 0.31
1.0 degree	9.30 ± 3.28	134.7 ± 134.7	0.96 ± 0.45
1.5 degree	7.05 ± 2.82	232.7 ± 225.6	1.20 ± 0.56
2.0 degree	5.61 ± 2.42	357.2 ± 345.6	1.42 ± 0.75
2.5 degree	4.64 ± 2.19	476.3 ± 442.4	1.58 ± 0.86
3.0 degree	4.00 ± 2.02	611.6 ± 559.4	1.83 ± 0.96

*All values are reported as Mean ± Standard Deviation

Table 3-4: Summary of parameters of all fixations on the ball during the Swing phase.

3.3.3 Fixation Detection Thresholds

The maximum gaze velocity permitted at each fixation zone diameter is shown below in Table 3-5. These velocities were calculated to be the maximum speed with which the gaze position could move in one frame (16.67ms) while remaining inside the defined fixation zone. Based on these calculations, it can be seen that the only fixation zone which represented of a true fixation where the gaze was essentially stable, was the 0.5° fixation zone.

Within the fixation zone diameter of 1.5°, which is equivalent to the size of a golf ball, a maximum gaze velocity of 45°/s was tolerated, indicating that both fixation and pursuit movements could be made without exceeding the criteria for fixation. At a fixation zone diameter of 3.0°, which has been previously used in the literature,[28, 30] fixations, pursuits and small saccadic eye movements were permissible within the 'fixation' criteria. A fixation criterion of 3.0° is not representative of pure fixations, and cannot be used to analyse putting vision strategy in golf.

Fixation Zone Diameter (°)	Fixation Zone Radius (°)	Maximum gaze velocity permitted (°/s)	Gaze Behaviours
0.5	0.25	15°/s	Fixation
1.0	0.50	30°/s	Fixation, Slow Pursuit
1.5	0.75	45°/s	Fixation, Pursuits
2.0	1.0	60°/s	Fixation, Pursuits, Small Saccades
2.5	1.25	75°/s	Fixation, Pursuits, Saccades
3.0	1.5	90°/s	Fixation, Pursuits, Saccades

Table 3-5: Maximum gaze velocity tolerated within each fixation zone diameter[47, 69, 70]

3.3.3.1 Phase Specific Gaze Behaviours

The Pearson correlations of the Total Number of Fixations made in each of the different fixation zones for both the Primary Address and Swing phases of the putt are displayed in Table 3-6 and Figure 3-5.

In the Primary Address phase, the correlation between the Total Number of Fixations measured between the 0.5° fixation zone (pure fixation) and the 1.0° fixation zone (fixation plus small pursuits) was strong, but as the fixation zone size increased, the strength of the correlations with the 0.5° fixation zone decreased dramatically.

The correlations between the 1.0° and 1.5° fixation zones and between 1.5°, 2.0°, 2.5° and 3.0° fixation zones are near perfect in the Primary Address phase with r-values greater than 0.900, suggesting that these fixation zones are all measuring similar gaze behaviours. The 1.0° and 1.5° degree fixation zones both measured all fixation and some pursuit eye movements, while the 2.0°, 2.5° and 3.0° zones measured all fixation and pursuit eye movements and some saccadic eye movements.

	0.5 degree	1.0 degree	1.5 degree	2.0 degree	2.5 degree	3.0 degree
0.5 degree						
1.0 degree						
Address	0.798**					
Swing	*0.499***					
1.5 degree						
Address	0.584**	0.924**				
Swing	*0.247***	*0.833***				
2.0 degree						
Address	0.469**	0.858**	0.968**			
Swing	*0.110***	*0.741***	*0.862*			
2.5 degree						
Address	0.395**	0.804**	0.940**	0.978**		
Swing	*0.021*	*0.648***	*0.874***	*0.867***		
3.0 degree						
Address	0.353**	0.768**	0.917**	0.963**	0.984**	
Swing	*-0.037*	*0.582***	*0.840***	*0.908***	*0.899***	

** Correlations are significant at the 0.01 level (2-tailed)

Table 3-6: Pearson correlation (r) values for the Total Number of Fixations between the 0.5°, 1.0°, 1.5°, 2.0°, 2.5° and 3.0° fixation zones during the Address and Swing phases of the putt. All values are reported for an n=964.

The correlation between fixations measured between the 0.5° fixation zone (pure fixation) and the 1.0° fixation zone (fixation and small pursuits) was also high during the Swing phase, but this correlation was not as high as it was Primary Address phase. The correlations between the 0.5° fixation zone and the larger fixation zones decreased significantly from 1.5° onwards as seen in the Primary Address, although the decrease was more marked in the Swing phase as the correlations between 0.5° and 2.5° and 0.5° and 3.0° were not statistically significant. As noted previously, the 1.0° and the 1.5° fixations zones, and the 1.5°, 2.0°, 2.5°, and 3.0° fixation zones are again highly correlated with each other.

Figure 3-5: Correlations between the Total Number of Fixations in both the Address (A,B,C) and Swing (D,E,F) phases of golf putts for 0.5° versus 1.0°, 0.5° versus 1.5° and 0.5° versus 3.0° only.

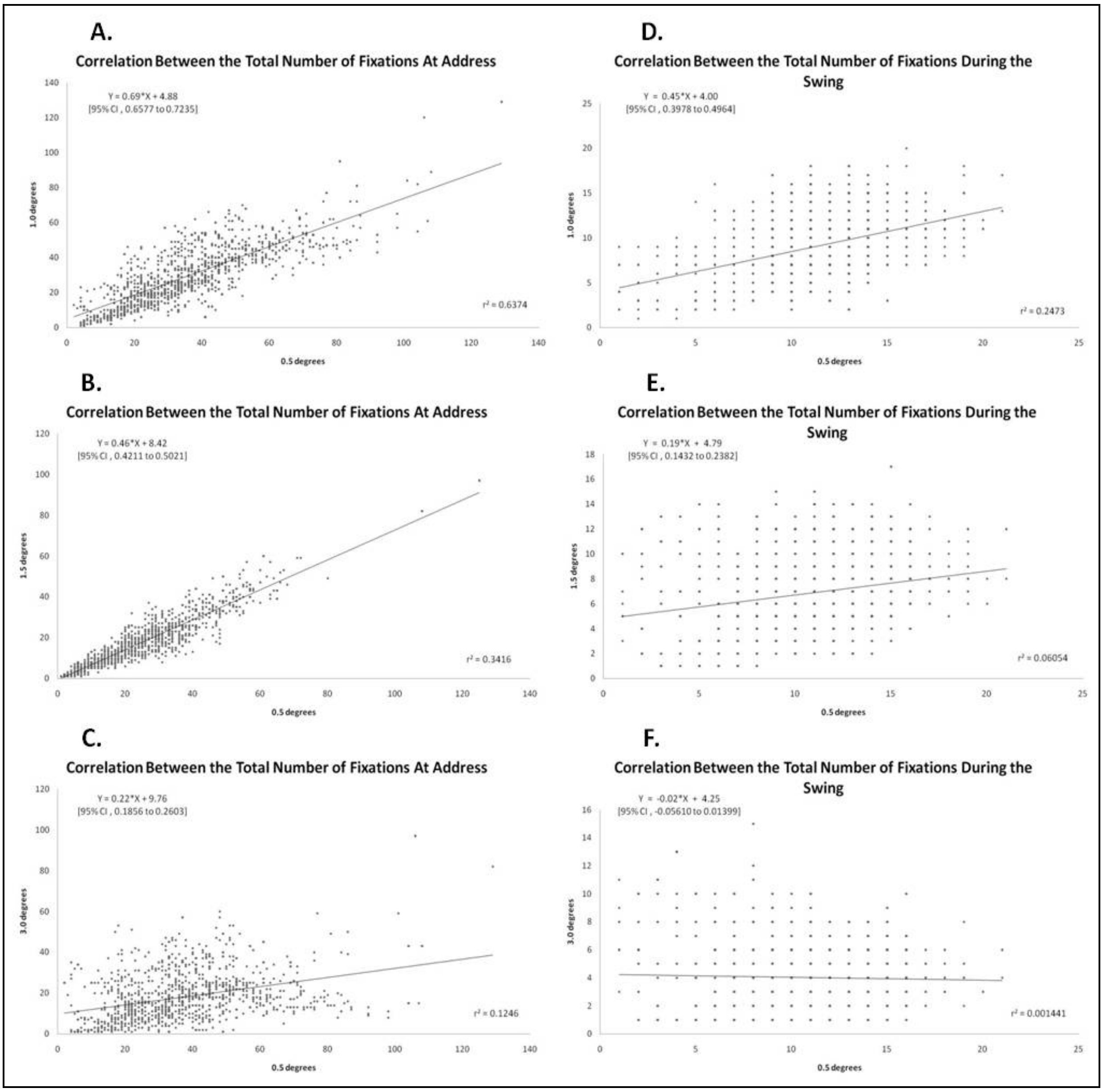


Table 3-7 and Figure 3-6 depict the Pearson correlations between the Mean Fixation Duration in the different fixation zones for both the Primary Address and Swing phases of the putt. Similar to the results for the Total Number of Fixations on the ball at each fixation zone, the correlation between the Mean Fixation Duration in the 0.5° fixation zone (pure fixation) and the 1.0° fixation zone (fixation plus small pursuits) during the Primary Address phase was very high. The strength of the correlations for Mean Fixation Duration (versus 0.5° fixation zone) in the Primary Address phase decreased as the fixation zone size increased, although not as dramatically as they did with the Total Number of Fixations. The correlations between the 1.0° and 1.5° fixation zones and between 1.5°, 2.0°, 2.5° and 3.0° fixation zones were again quite high during Address.

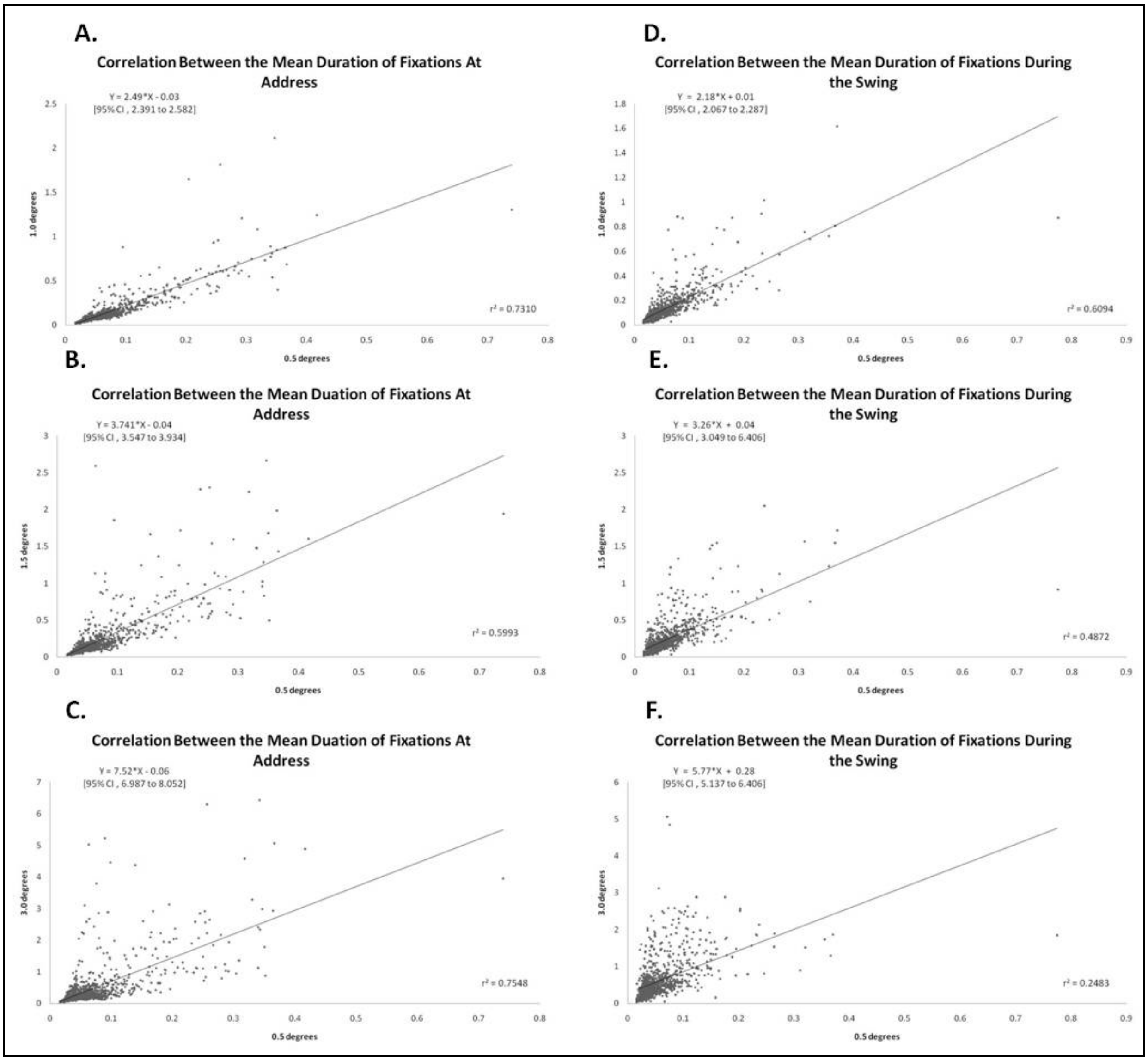
	0.5 degree	1.0 degree	1.5 degree	2.0 degree	2.5 degree	3.0 degree
0.5 degree						
1.0 degree						
Address	0.855**					
Swing	*0.781***					
1.5 degree						
Address	0.774**	0.888**				
Swing	*0.698***	*0.819***				
2.0 degree						
Address	0.720**	0.800**	0.862**			
Swing	*0.649***	*0.743***	*0.776***			
2.5 degree						
Address	0.673**	0.774**	0.874**	0.867**		
Swing	*0.513***	*0.667***	*0.677***	*0.732***		
3.0 degree						
Address	0.666**	0.782**	0.840**	0.908**	0.899**	
Swing	*0.498***	*0.594***	*0.657***	*0.715***	*0.779***	

** Correlations are significant at the 0.01 level (2-tailed)

Table 3-7: Pearson correlation (r) values for the Mean Fixation Duration between the 0.5°, 1.0°, 1.5°, 2.0°, 2.5° and 3.0° fixation zones during the Address and Swing phases of the putt. All values are reported for an n=964.

The Pearson correlations of Mean Fixation Duration and fixation zone size demonstrated an analogous pattern in the Swing phase of the putt. The correlation between the 0.5° and 1.0° fixation zones were high ($r=0.781$, $p(\text{2-tailed})<0.01$); the remaining correlations between the larger fixation zones and the 0.5° fixation zone decreased as the fixation zone diameter increased (1.5°, $r=0.698$, $p(\text{2-tailed})<0.01$; 2.0°, $r=0.649$, $p(\text{2-tailed})<0.01$; 2.5°, $r=0.513$, $p(\text{2-tailed})<0.01$; 3.0°, $r=0.498$, $p(\text{2-tailed})<0.01$). The correlation between the 1.0° and 1.5° fixation zones was quite high ($r =0.819$, p (2-tailed) < 0.01), as were the correlations between the 1.5°, 2.0°, 2.5° and 3.0° fixation zones ($r >0.650$, $p(\text{2-tailed})<0.01$). It is worth noting, that in the Swing phase, the correlations between the 1.0° fixation zone and the 2.0°, 2.5° fixation zones were also relatively strong (r >0.6500, p(2-tailed)<0.01).

Figure 3-6: Correlations between the Mean Fixation Duration in both the Address (A,B,C) and Swing (D,E,F) phases of golf putts for 0.5° versus 1.0°, 0.5° versus 1.5° and 0.5° versus 3.0° only.



The Total Fixation Duration Pearson correlations for the Primary Address and Swing phases can be found Table 3-8 and Figure 3-7. Unlike the Total Number of Fixations and the Mean Fixation Duration results, the Total Fixation Durations measured in each fixation zone during the Primary Address phase were all highly correlated. Despite this, a trend towards a similar pattern in the correlations was still present; the highest correlations were found between the 0.5° and 1.0°, the 1.0° and 1.5°, and the 1.5°, 2.0°, 2.5° and 3.0° fixation zones.

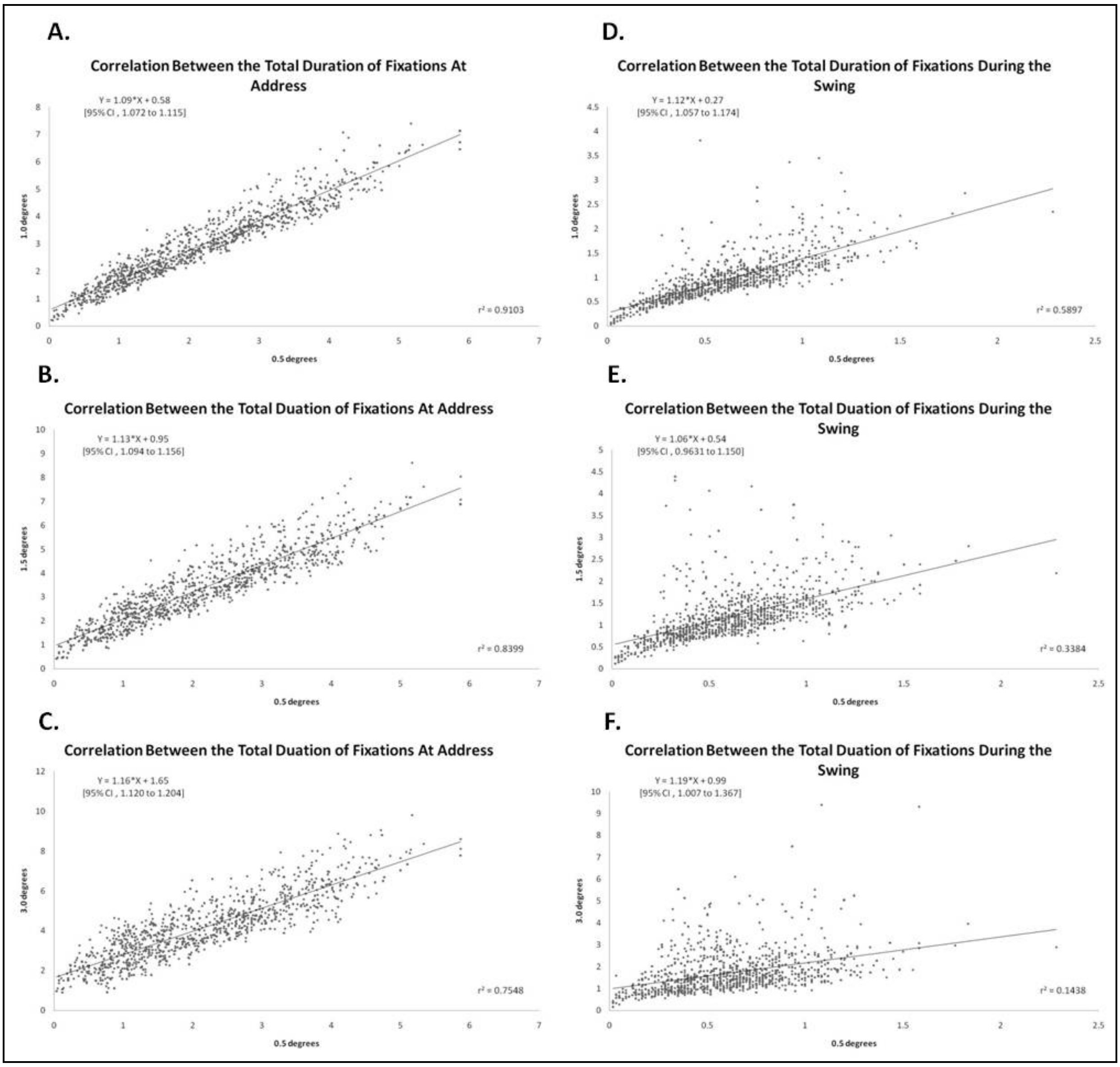
	0.5 degree	1.0 degree	1.5 degree	2.0 degree	2.5 degree	3.0 degree
0.5 degree						
1.0 degree						
Address	0.954**					
Swing	*0.768***					
1.5 degree						
Address	0.916**	0.980**				
Swing	*0.582***	*0.699***				
2.0 degree						
Address	0.888**	0.963**	0.979**			
Swing	*0.514***	*0.649***	*0.691***			
2.5 degree						
Address	0.874**	0.951**	0.967**	0.974**		
Swing	*0.426***	*0.590***	*0.661***	*0.725***		
3.0 degree						
Address	0.869**	0.936**	0.957**	0.960**	0.967**	
Swing	*0.385***	*0.534***	*0.611***	*0.704***	*0.784***	

** Correlations are significant at the 0.01 level (2-tailed)

Table 3-8: Pearson correlation (r) values for the Total Fixation Duration between the 0.5°, 1.0°, 1.5°, 2.0°, 2.5° and 3.0° fixation zones during the Address and Swing phases of the putt. All values are reported for an n=964.

In the Swing phase, the differences in the Total Fixation Duration correlations were much more marked between fixation zones than they were in the Primary Address phase, although none of the correlations were as strong. The correlation between the 0.5° and 1.0° fixation zones was relatively high ($r=0.768$, $p(2\text{-tailed})<0.01$), and the strength of the correlations decreased dramatically as the fixation zone diameter increased (1.5°: $r=0.582$, $p(2\text{-tailed})<0.01$; 2.0°: $r=0.514$, $p(2\text{-tailed})<0.01$; 2.5°: $r=0.426$, $p(2\text{-tailed})<0.01$; 3.0°: $r=0.385$, $p(2\text{-tailed})<0.01$). The correlations between the 1.0° and 1.5° fixation zones ($r=0.699$, $p(2\text{-tailed})<0.01$) and between the 1.5°, 2.0°, 2.5° and 3.0° fixation zones ($r>0.610$, $p(2\text{-tailed})<0.01$) were also relatively high as seen previously.

Figure 3-7: Correlations between the Total Fixation Duration in both the Address (A,B,C) and Swing (D,E,F) phases of golf putts



3.4 Discussion

The purpose of this analysis was to optimise a novel technique for investigating the vision strategy of golf putting. To achieve this, three aspects of gaze behaviour analysis were considered: (i.) examination of the entire putt, including all of its phases, (ii.) video analysis methodology, and (iii.) the definition of a fixation; each of these aspects of gaze behaviour analysis will be discussed in turn below.

3.4.1 Putt Phase Analysis

Apart from Vickers' original paper in 1992,[28] the only parameters considered to be important in the putting vision strategy were the quiet eye, and to some extent the quiet eye dwell time. Although Vickers' statistical analysis in the original paper supported the evidence that these were the only two parameters of importance in the vision strategy of golfers, these conclusions are flawed due to the analysis methods and fixation definitions used, as discussed previously. In light of the new technology developed for analysis (GazeDetection) and the new fixation criterion being used, it will be of utmost importance to examine the entirety of the putt again, as it is highly likely that there are other aspects of the vision strategy which are associated with both higher skill and success. This analysis has been conducted and will be discussed in detail in Chapter 5, Vision Strategy in Golf Putting: Skill and Success.

3.4.2 Video Analysis

Traditional eye tracking research in golf and other sports has all been analysed manually, by individuals watching the videos and classifying the gaze behaviour frame by frame. This method is limited in that it was very subjective and time consuming. Furthermore, the method is also limited by the fact that the results are entirely dependent on the gaze behaviour criteria chosen, and the ability of the individual examiner to consistently follow these criteria when analysing data. Manual analysis of video files depends upon being able to see the "gaze points" painted into the scene camera video files with enough resolution to discern different gazes. Most commercially available eye trackers paint dots into the scene camera videos which usually represent 1° visual angle; equivalent in the particular case of golf to ⅔ the size of the ball. Analyses based on criteria for subjectively tracking the movement of a 1° target are inherently limited in the precision they can obtain, especially when compared with GazeDetection, which is capable of tracking individual coordinate points instead.

GazeDetection provides a unique platform from which to analyse golf eye tracking data. Rather than manually coding gaze behaviour in every single frame of the video files, GazeDetection requires six time points to be coded per putt. These time points are, in chronological order: Stationary Ball, Address, Backswing, Pre-Contact, Post-Contact and

Gaze Break. The remaining analysis is carried out automatically on the gaze coordinates recorded by the eye tracker.

The results of the above repeatability study demonstrates that Address, using the Tangent Address criteria, Backswing, Pre-Contact and Post-Contact points can be coded with exceptional consistency. Each of these time points demonstrated less than a single frame (16.67ms) error over a series of three repeated evaluations. The single frame error in the measurements was equivalent to a 1.1% error or less in the duration of the associated putt phase. Stationary Ball and Gaze Break were found to have significantly higher coding errors (>250ms). The error in Gaze Break coding was equivalent to approximately a 15% error in the duration of the Post-Contact Putt phase, while the Stationary Ball coding error was equivalent to a 22% error in the duration of the Preparation phase. Although these errors were greater, the coding of these parameters was still considered to be acceptable as these parameters did not define any of the critical phases of the putt being considered for analysis (Address and Swing). Had an analysis been done on either the Preparation or Post-Contact putt phases, more repeatable coding criteria should have been implemented if possible.

Two Address coding definitions were compared in this study: the Resting Address and the Tangent Address. Coding of the Resting Address was deemed to be more difficult and had poorer repeatability overall compared with Tangent Address coding. Therefore the Tangent Address coding definition was used in all other analysis, excluding the fixation parameter analysis presented in this chapter. The fixation parameter analysis presented in this chapter had been conducted prior to the video coding repeatability study therefore it was completed using the original Resting Address coding definition.

3.4.3 Fixation Criterion

Conceptually, a fixation occurred when the eyes were not moving and their velocity was nearly equal to zero. The velocity of the eyes cannot be equal to zero exactly, because of the small eye movements, including micro-saccades which occur with stationary gazes.[76] In eye tracking research, where both the individual and the target of interest are in fixed positions, such as in reading, it is relatively simple to determine when the eyes are stationary. In golf and other sport eye tracking research it is much more difficult to measure gaze behaviour because all of the cameras are head mounted and there was no fixed frame of reference to compare too. Using a head tracker could help, although it would increase the amount of equipment an athlete needs to wear.

When conducting eye tracking research in golf and other sports, it was important that the gaze behaviours examined are studied using the same analysis parameters that are used in other eye tracking research. Previous research has demonstrated that smooth pursuit movements occur when the eyes track a target that moves with some velocity. Although it has been demonstrated that individuals can track targets with velocities up to 100°/s,[69] other research has suggested that the maximum target velocity that can be tracked with smooth pursuit movements is somewhere in the area of 40-50°/s.[66] Therefore, saccades are fast eye movements with velocities greater than 50°/s.[70] Previous research on the quiet eye and vision strategy in golf have used fixation zone sizes which are either 1° or 3° visual angle in size. At a distance of 1.5m, 3° fixation zones permit the eyes to move with velocities up to 90°/second, meaning that pursuits and some small saccades could be classified as fixations. The 1° fixation zone was better, as this permitted only small pursuit movements to be classified as fixations, but this criterion has not be used as frequently.

The results presented in this chapter demonstrate that fixations can be quantified using GazeDetection in a 0.5° fixation zone, which was representative of a true fixation. Fixations were measured in both the Primary Address and Swing phases at all six of the tested fixation zones examined, including 0.5°. As expected Mean and the Total Fixation Durations increased in both phases, while the Total Number of Fixations decreased as the fixation zone size increased. Mean Fixation Duration increased in a linear fashion, and was approximately 6x longer at 3° than at 0.5°. The changes in Total Fixation Duration (2.5x increase) and the Total Number of Fixations (2.5x decrease) were not linear. If all six fixation zone criteria were measuring pure fixations, than a linear change, proportional to the fixation zone size change would have been expected in all three parameters. Instead, the 2.5x changes in Total Fixation Duration and the Total Number of Fixations suggest that the fixation zones were measuring different gaze behaviours, and that fixation durations were increasing due to inclusion of pursuit and saccadic eye movements.

These findings were supported by the correlation analysis of the six fixation zones. On all three measures (Total Number of Fixations, Mean Fixation Duration and Total Fixation Duration) the 0.5° and 1.0° fixation zones were highly correlated with each other, as were the

1.0° and 1.5° fixation zones, and the 1.5°, 2.0°, 2.5° and 3.0° fixation zones. The 0.5° fixation zone measured pure fixation, while the 1.0° fixation zone measured fixations and slow pursuits, therefore the correlation between these groups is expected as they were measuring similar gaze behaviours. The 1.5° fixation zone also measured fixations and pursuits, but the speed of the eye movements permitted with this zone was more similar to the saccadic eye movements allowed in the fixation zones larger than 2.0° than to the pure fixations allowed in the 0.5° zone. Understandably then, 1.5° correlated well with 1.0° as they both measured fixation and pursuits, but 1.5° also correlated well with the 2.0°, 2.5° and 3.0° zones, because their permissible eye movement velocity was similar. The 2.0°, 2.5° and 3.0° zones correlated well with each other, but correlated poorly with the 0.5° and 1.0° zones because they were measuring entirely different gaze behaviours. These results, from both the Primary Address and Swing phases suggest that measurements taken at larger fixation zone criteria did not represent true fixations, and that the longer Mean Fixation Durations measured with these criteria are a result of misclassification of the combination of fixation, pursuit and saccade movements as fixations.

3.4.4 Conclusion

These results demonstrate that GazeDetection is an efficient, objective and repeatable method for assessing golfers' putting vision strategy. Golfers are capable of making precise, pure fixational eye movements, which can only be measured if small fixation zone criteria are used. Assessing gaze behaviour over different fixation zone criteria may be able to give some indication of the quality of a golfer's fixations, and the quality of fixation may be an indication of skill. This will be investigated shortly [Chapter 5, Vision Strategy in Golf Putting: Skill and Success]. All vision strategy analyses conducted from this point forward will use a 0.5° fixation criterion. Due to the new analysis methods and fixation criteria, the entire putt needs to be re-examined, not just the quiet eye, and again this will be investigated shortly [Chapter 5, Vision Strategy in Golf Putting: Skill and Success].

The high correlation between data collected in fixation zones of 0.5° and 1.0° was encouraging as it suggests that 1.0° could be used as the fixation criteria in studies where the eye tracking equipment used does not have the ability to measure 0.5° changes in gaze position.

3.5 Summary

Chapter 3, Analytic Strategy Development demonstrated that GazeDetection is an efficient, objective and repeatable method for assessing golfers' putting vision strategy, and that golfers are capable of making precise, pure fixational eye movements, which can only be measured if small fixation zone criteria are used. Chapter 4, Ocular Dominance and Golf will examine the importance of ocular dominance and hand dominance in golf, and will examine the effect of putting stance on ocular dominance strength.

Chapter 4

OCULAR DOMINANCE AND GOLF

4.1 Introduction

The concept of ocular dominance has been studied for many years by researchers across various disciplines, including optometry, ophthalmology and psychology. As a clinical measure, ocular dominance has been used for variety of applications, the most common of these are monovision contact lens wear,[77, 78] cataract surgery,[79] sports performance,[80-82] military marksmanship, [83, 84] education and learning disorders.[85, 86]

Roughly 60% of the population has been shown to be right handed, 30% left handed and 10% ambidextrous;[87-91] similarly approximately 67% of the population has been shown to have right eye dominance.[92] Originally, researchers thought that ocular dominance was related to handedness or foot dominance, especially as in both handedness and ocular dominance, there seems to be a strong predisposition towards favouring the right side of the body. Researchers have now agreed that while handedness and foot dominance have been found to be highly correlated with each other, they are neither indicative nor predictive of ocular dominance.[80, 93-95] Hand and foot dominance are thought to be related to the dominance of one cerebral hemisphere in the brain, but ocular dominance cannot be created in this way. A semi-decussation of optic nerve fibres at the optic chiasm means that visual information from the right and left eyes are represented in both hemispheres.[80, 93, 94]

Despite a vast amount of time and effort that has been invested in understanding the physiological basis of ocular dominance and its functional roles, little agreement between researchers has been reached. Perhaps the only tenuous consensus amongst ocular dominance researchers has been that there are two, relatively distinct types of dominance: motor ocular dominance and sensory ocular dominance. Traditionally, motor ocular dominance is measured through sighting and pointing tasks, and is thought to exist in situations where the individual is forced to choose between the two eyes (for example, sighting a rifle). Sensory ocular dominance is thought to be a more inherent process, associated with binocular rivalry in the processing of visual information.[96]

4.1.1 Motor Ocular Dominance

Motor ocular dominance tests tend to create a forced choice situation, in which the only possible outcomes are right or left dominance. "No dominance" is assessed with these tests based on repetition; the more consistent an individual's responses are, the stronger their dominance. The most commonly used motor ocular dominance tests are the "hole-in-card" test and the "pointing" test. The "hole-in-card" test requires that individuals hold a card with a small hole in it, directly in front of them with both hands and site a distant target through the hole with both eyes open. The individual is then asked to alternatively close their right and left eyes, without moving the card in their hands, to determine which eye sees the distant target. The eye which sees the distant target under monocular conditions is the dominant eye, and the eye which does not see the target is the non-dominant eye.[97]

The pointing test is similar to the hole-in-card test, except individuals are required to point with both index fingers (hands clasped together) at a distant target under binocular conditions. When the right and left eyes are closed alternatively, the eye which lines up with the pointed fingers is considered to be the dominant eye, while the eye that does not line up with the pointed fingers is considered to be the non-dominant eye.[98]

Other motor ocular dominance tests include asking people to look through the view finder of a camera held in both hands (the eye that they use is the dominant eye) and asking people to make a small triangular hole between the index fingers and thumbs of their right and left hands, and look through the hole in their hands a distant target.

4.1.2 Sensory Ocular Dominance

Sensory ocular dominance is usually measured under binocular conditions, where a variety of responses are possible as individuals see either a unique image associated with either the right or left eye, or they see a combined percept of the two.[96] Some tests rely upon counting the number of responses (left, right or no dominance) to quantify the strength of the ocular dominance, while others measure a gradient of responses (strong right or left, weak right or left, no dominance). Gradient tests are usually conducted under stereoscopic conditions where two images are fused and the perception of the fused images determines the type and strength of the dominance.

Common clinical tests for sensory ocular dominance include the Worth 4 Dot and blur sensitivity. The Worth 4 Dot test, a common binocular fusion test, requires individuals look through a red filter with one eye and a green filter with the other, at a target of four dots. Three of the dots are either red or green, while the fourth dot is white; if an individual perceives the fourth dot as being red, the eye with the red filter would be the dominant eye (and vice versa for a green dot) but if the fourth dot was perceived as being a muddled yellow colour, there is no dominance as the red and green percepts contribute equally to perception.

Blur sensitivity tests are often conducted when fitting presbyopic contact lens corrections. Under binocular conditions, plus lenses (+0.25D, +0.50D, +1.00D) are alternately added to the right and left eye distance refractive corrections. The eye in which the blur is less noticeable and binocular visual acuity less affected is considered to be the non-dominant eye.

4.1.3 Motor versus Sensory Ocular Dominance

There is a lack of consensus in ocular dominance research resulting from a lack of consistency in how ocular dominance is measured.[97, 99-101] Measures of sensory and motor dominance do not agree well with each other, although individuals with strong ocular dominance tend to give more consistent results across tests.[94] Studies which have tried to measure the strength of individuals' ocular dominance have found that the vast majority of individuals seem to have a weak ocular dominance (61%). It has been suggested that this is a reason for the decreased reliability of motor ocular dominance (sighting dominance tests), and may be a contributing factor to the disagreement between different dominance measures.[96]

4.2 Ocular Dominance and Golf

Ocular dominance in sports has been primarily studied in conjunction with handedness, and most studies have investigated the effects of uncrossed (right eye, right hand or left eye, left hand) and crossed (right eye, left hand or left eye, right hand) dominance on performance. In golf, ocular dominance and handedness have been studied with mixed results. Coffey *et al*. suggested that crossed dominance (right hand, left eye or left hand, right eye) would be advantageous, but their study of PGA Tour players, young amateurs and senior amateurs did not find a difference in the incidence of crossed dominance between groups (p>0.05; Range: 17% (PGA Tour Players) to 47% (Amateurs with High Handicaps).[102] Coffey *et al*. also noted that 10% of all the golfers did not demonstrate a consistent eye preference.[102] The incidence of crossed dominance in this population of golfers is not different than that of the general population, which demonstrates an incidence of crossed dominance of 26%.[95]

A 1995 study of 48 novice golfers investigated the effect of gaze location on putting performance. An equal number of male and female golfers were included in each of the crossed (n=24) and uncrossed (n=24) dominance groups, although the exact distribution of male and female golfers in each group was not specified. Golfers in each group were asked to putt in two gaze conditions: with their focus directly over the ball and with their eyes positioned midway between their feet and the ball; the order in which golfers putt in each gaze condition was allocated randomly and a 5 minute break was given between conditions. Handedness was determined by putting stance, and all golfers in this study were right handed. Ocular dominance was determined with a peep-hole test, during which golfers were asked to binocularly site a 6m target through a 0.5cm hole in an 8cm paper cone and then to alternatively close the right and left eyes and report which eye was open when the object disappeared. The eye that was open when the object disappeared was classified as the non-dominant eye, while the eye that was open when the object was still observed was classified as the dominant eye. The peep-hole test was repeated a second time to confirm the results.[103]

The hypothesis tested was that crossed dominant golfers would demonstrate greater accuracy when the eyes were positioned directly over the ball, as the line of sight of their dominant eye would not be blocked by the bridge of the nose. Uncrossed dominant golfers were expected to perform better when they focused their eyes between the ball and their feet, as this was the condition where the bridge of their nose did not block their view. Putting performance was measured through the assessment of golfers' absolute error (the average absolute deviation between the hole and the final ball position on each trial) and variable error (the standard deviation of the ball position on each trial about the average score).[103]

Golfers with uncrossed dominance were reported to demonstrate less absolute error and less variable error in their putting performance when they focused their eyes midway between their feet and the ball, whereas no difference in error scores was reported under either condition for golfers with crossed dominance.[103] The authors suggested that eye-hand dominance may have a significant effect on putting performance in golf performance, even though no statistical comparison of putting performance was carried out between the two dominance groups and the response distribution did not suggest a difference in their performance under either gaze condition (Uncrossed Gaze over ball: Absolute 10.65±2.10, Variable 11.76±1.85; Crossed Gaze over ball: Absolute 9.13±2.50, Variable 10.87±2.77; Uncrossed Gaze between ball and feet: Absolute 8.98±2.50, Variable 9.99±2.44; Crossed Gaze between ball and feet: Absolute 9.49±1.78, Variable 10.87±1.88).[103]

Unfortunately this study suffered from two major setbacks. The distribution of crossed and uncrossed dominance in the study population, while equal between groups does not reflect the distribution of crossed and uncrossed dominance in the general population. Additionally, all of the golfers were novices with limited playing experience, which meant that their performance would have depended on a significant number of factors, including the consistency, or lack thereof, in their stroke, their ability to read the putting surface and their ability to align their club with the ball. Hence no reliable conclusions about the effects of hand-eye dominance can be drawn from this study.

Sugiyama *et al*. studied the impact of binocular, right eyed (left eye occluded) and left eyed (right eye occluded) gaze conditions in two groups of right handed novice golfers – one group was right eye dominant (n=24) and the other was left eye dominant (n=23).[104] Dominance was determined by the Point Test,[85] whereby golfers were asked to point a finger, alternately using their right and left hands at an examiner's nose. The examiner observed what eye the finger lined up with, and this eye was defined as the dominant eye. Right eyed participants were found to perform better under all three gaze conditions, even though they were using their non-dominant eye in the left eye gaze condition. Participants rated their subjective visibility of the ball, the cup, both the ball and the cup and the direction of the putt during the study and visibility was found to be better in all cases with the dominant eye. Suigyama *et al* concluded that putting performance may not always be linked directly to visibility in Japanese golfers.[104] Much like the study discussed above, this study is limited by its population in that the distribution of ocular dominance was not representative of the general population, and all of the golfers were novices, which makes it impossible to draw reliable conclusions regarding the effect of ocular dominance on putting performance.

Sugiyama completed a second golf study looking at the effect of stance (right handed putting stance with the hole on the golfers' left or left handed putting stance with the hole on the golfers' right) in 47 right handed novice golfers with either right or left eye dominance.[105] Dominance was again determined with the Point Test described above.[85] Right-eyed subjects were found to have better performance from a right-handed stance, while left-eyed subjects were found to have better performance from the left-handed stance. Subjective ratings were higher for both groups in the right handed stance, although this was not unexpected as all golfers were right handed.[105] Based on these results, it was suggested that uncrossed dominance may be associated with higher performance on a golfing task, although the authors stated that the results were not conclusive. This study cannot be generalised to the population of golfers either, as it was only conducted on novices, and the fact that performance from a left-handed putting stance was examined in right-handed golfers and compared with their performance in a right-handed putting stance makes this study essentially irrelevant with respect to ocular dominance. The change in stance alone would have significantly affected performance, irrespective of any effects of ocular dominance.

Although there have been a few studies investigating the effect of ocular dominance on golf performance, none of the above mentioned studies have investigated the effect of putting stance on ocular dominance. All of the above studies have measured dominance in a primary gaze position, where individuals were facing the object of interest and looked straight at it. In golf, primary gaze is used when aligning the ball with the hole, but in a putting stance, golfers stand with their heads tilted towards their chests and their line of sight directed either down or laterally depending on the task.

The purpose of this study was to investigate the effects of gaze position (primary gaze versus putting gaze) on ocular dominance in golfers and also to measure the incidence of crossed and uncrossed hand-eye dominance in golfers of different skill levels.

4.3 Methods

4.3.1 Study Design

This study was designed as a retrospective analysis of ocular dominance data collected during optometric examinations, optometric screenings and putting vision assessments of golfers of various skill levels. The optometric examinations and screenings were completed by practitioners at the Michel Guillon Sports Vision Clinic, London UK, either on the premises or in a mobile clinic facility that was transported to various locations around the United Kingdom.

This study received ethics approval from Aston University Audiology/Optometry Research Ethics Committee (AO2010.20). All participants completed an informed consent prior to their full ocular examination, their ocular screening or their putting vision assessment. The informed consent explained whether they were receiving a full ocular examination or an ocular screening which was not a replacement for a regular eye examination. The informed consent also explained that some of the data collected during the ocular examination or screening could be used for research purposes; if the data was used for research purposes identifying information would not be included.

4.3.2 Study Population

31 of a possible 37 golfers were included in this study; 6 of the golfers evaluated had not had their ocular dominance assessed in primary gaze and were removed from the analysis. Golfers' skill level ranged from amateurs to top professionals. Due to the wide variety in skill levels, golfers' were classified into three categories for analysis purposes. These categories were as follows: (1) Top Professionals, including European Tour and Ryder Cup level golfers, (2) Club Professionals, including Challenge Tour (one step below the European Tour) and Australian ladies tour golfers and golf coaches, and (3) Amateurs, which included all levels of amateur golfers (Table 4-1).

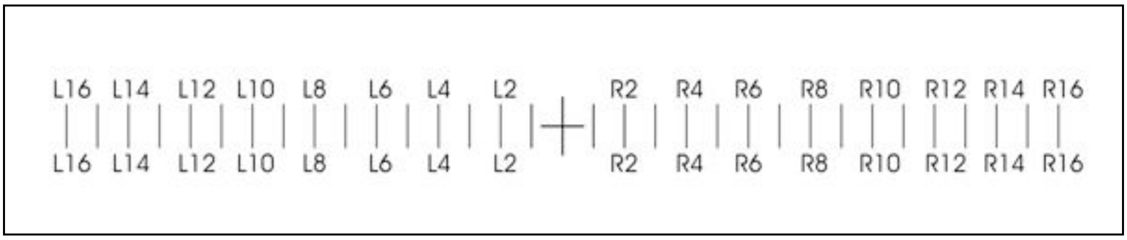
Classification	Level of Play	Men	Women
Top Professionals	Ryder Cup, European Tour,	n=10	n=0
Club Professionals	Challenge Tour, Australian Women's Tour, Coaches	n=6	n=1
Amateurs	Amateurs	n=13	n=1

Table 4-1: Population demographics of golfers in each of the skill groups studied.

4.3.3 Ocular Dominance

Pointing ocular dominance was measured using charts developed at Michel Guillon Sports Vision Clinic (Figure 4-1), which were previously validated in an internal study conducted at the clinic (unpublished data). These charts had been calibrated such that the difference between adjacent whole numbers (i.e. 5 and 6) is equal to one prism dioptre, therefore the charts can be scaled for use at any distance. Golfers were asked to align the index fingers of both hands with the cross in the centre of the chart while keeping both eyes open. The right and left eyes were covered in turn, and players were asked to indicate where their index fingers were aligned when the chart was viewed with the right and left eyes independently.[106]

Figure 4-1: Ocular dominance chart to be used in various gaze positions.



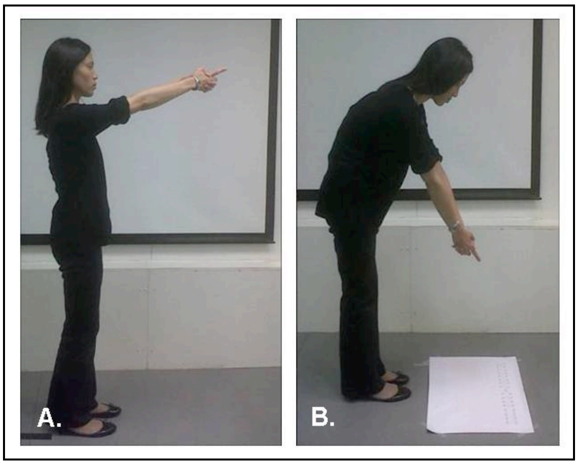
Values to the left of the cross were considered to be negative and values to the right, positive. The individual scores from the right and left eyes were added together to determine the final, quantitative dominance score. Ocular dominance (OD) was then classified as no dominance,, weak dominance or strong dominance as demonstrated in Table 4-2. For example, if the following measurements were recorded: cover right eye +6, cover left eye -2, the ocular dominance would be +4, which would have been classified as a weak right eye dominance.[107]

Ocular Dominance Classification	Calculated Ocular Dominance Value
Strong Left Dominance	OD < -4
Weak Left Dominance	-4 ≥ OD ≤ -2
No Dominance	-2 < OD < 2
Weak Right Dominance	2 ≤ OD ≤ 4
Strong Right Dominance	OD > 4

Table 4-2: Classification of types of ocular dominance.

Ocular dominance was measured in primary gaze and putting gaze on all full optometric examinations, optometric screenings and putting vision assessments (Figure 4-2).

Figure 4-2: Ocular dominance measured in (A) Primary gaze and (B) Putting gaze.



4.3.4 Statistics

Statistical analysis was completed using IBM SPSS 18.0 for Windows (Release 18.0.0, 30 July 2009, http://www.spss.com).

Means and standard deviations of the ocular dominance scores in primary and putting gazes were calculated for each skill group. Additionally, they were calculated for the absolute change in ocular dominance between primary and putting gazes in each skill group.

A students-t test was used to evaluate the mean difference in ocular dominance scores between primary and putting gazes. The Chi-square test was used to compare the distributions of ocular dominance scores in primary and putting gazes and the distribution of handedness between skill groups. Pearson correlations were calculated to examine the relationship between ocular dominance scores in primary and putting gazes and the relationship between ocular dominance and handedness.

4.4 Results

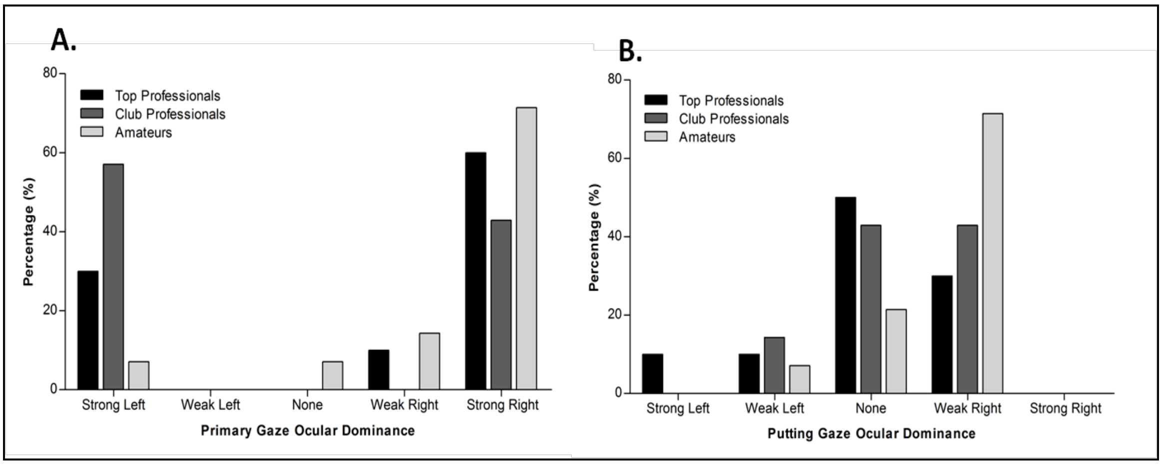
4.4.1 Primary and Putting Gaze Ocular Dominance

Overall, in primary gaze 71% of golfers were right eye dominant (Strong: 61.3%; Weak: 9.7%), 26% (Strong: 25.8%; Weak: 0.0%) were left eye dominant and 3% had no ocular dominance. In putting gaze, 52% of golfers were right eye dominant (Strong: 0.0%; Weak: 51.6%), 13% were left eye dominant (Strong: 3.2%, Weak: 9.7%), and 36% had no ocular dominance. The distribution of golfers' ocular dominance is shown in Table 4-3 and Figure 4-3.

	Strong Left	Weak Left	None	Weak Right	Strong Right
Top Professionals	30.0% **10.0%**	0.0% **10.0%**	0.0% **50.0%**	10.0% **30.0%**	60.0% **0.0%**
Club Professionals	57.1% **0.0%**	0.0% **14.3%**	0.0% **42.9%**	0.0% **42.9%**	42.9% **0.0%**
Amateurs	7.1% **0.0%**	0.0% **7.1%**	7.1% **21.4%**	14.3% **71.4%**	71.4% **0.0%**
Overall	25.8% **3.2%**	0.0% **9.7%**	3.2% **35.5%**	9.7% **51.6%**	61.3% **0.0%**

Table 4-3: Distribution of ocular dominance in primary and putting gazes by skill level and overall; primary gaze results are recorded first, followed by putting gaze results in bold.

Figure 4-3: Ocular dominance distributions in (A) primary gaze and (B) putting gaze.



In primary gaze, the vast majority of all golfers had a strong ocular dominance; in putting gaze most golfers had either no ocular dominance or a weak right ocular dominance. Golfers' ocular dominance decreased from primary to putting gaze in 87.1% of the population and remained unchanged in the remaining 12.9% (Figure 4-4). No golfer demonstrated an increased ocular dominance in putting gaze compared with primary gaze. Overall, and in each skill group, there were significantly fewer individuals with strong ocular dominance in putting gaze than in primary gaze ($p<0.001$). Skill did not affect the distribution of ocular dominance values in primary ($p=0.275$) or putting ($p=0.399$) gazes (Figure 4-3). The distribution of the magnitude of the change in ocular dominance between primary and putting gazes was not affected by skill either ($p=0.113$) (Figure 4-4).

Primary and putting gaze ocular dominances were significantly correlated overall, (Pearson r=0.726, p<0.001) and for both Club Professionals (Pearson r=0.867, p=0.012) and Amateurs (Pearson r=0.762, p=0.002) but not Top Professionals (Pearson r=0.609, p=0.062) as shown in Figure 4-5.

Figure 4-4: Change in ocular dominance distributions magnitude from primary to putting gaze.

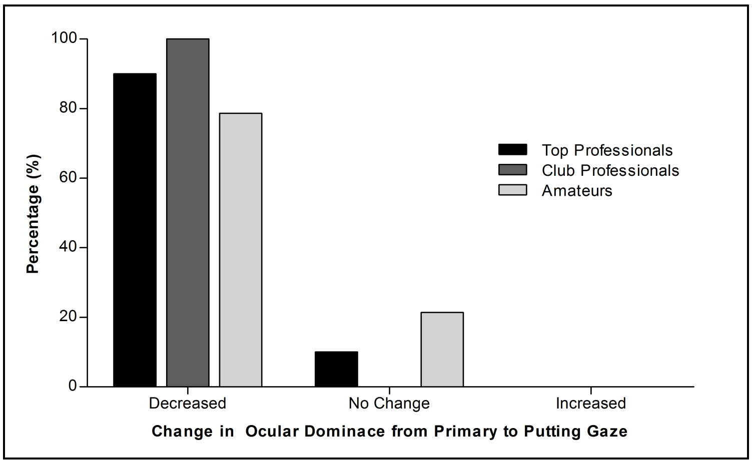
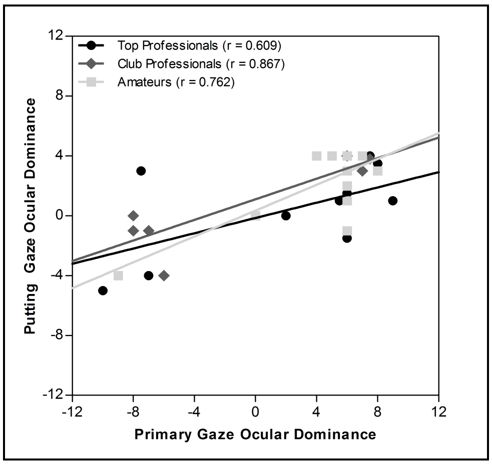


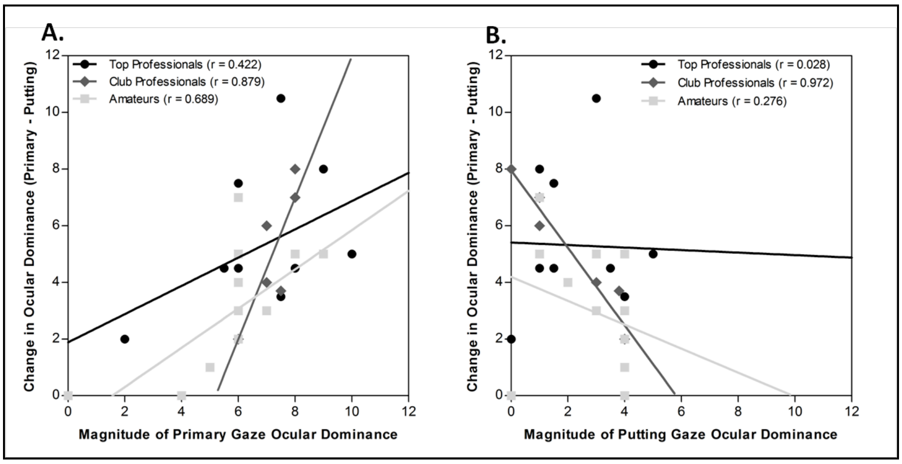
Figure 4-5: Primary gaze ocular dominance compared with putting gaze ocular dominance.



Although the correlation between the primary and putting gaze ocular dominance was fairly strong overall, the predictability of putting gaze ocular dominance from primary gaze ocular dominance was limited. Overall, primary gaze ocular dominance was only predictive of 50% of putting gaze ocular dominance (r^2 = 0.527). Predictability of putting gaze ocular dominance was good for Club Professionals (r^2 = 0.752), average for Amateurs (r^2 = 0.580) and poor for Top Professionals (r^2 = 0.370).

The magnitude of the change in ocular dominance between primary and putting gazes was significantly correlated with the strength of the ocular dominance in primary gaze overall (Pearson r=0.612, p<0.001) and in the Club Professional (Pearson r=0.879, p=0.009) and Amateur (Pearson r=0.689, p=0.006) groups, but not in the Top Professionals (Pearson r=0.423, p=0.224) (Figure 4-6).

Figure 4-6: Magnitude of ocular dominance in (A) primary gaze and (B) putting gaze compared with the magnitude of the change in the ocular dominance strength between primary and putting gazes.



4.4.2 Handedness

Previous studies have examined the relationship of ocular dominance and handedness in golfers with mixed results. In this study handedness was self-reported by the golfers on a 5-point scale of discrete values which ran from -2 to 2. A score of -2 indicated they had a strong left hand dominance, -1 a weak left dominance, 0 was no dominance, 1 a weak right dominance and 2 a strong right dominance. 5 golfers (Top Professional=2, Club Professional=2, Amateur=1) did not report any handedness data and were not included in this particular analysis.

Of the golfers with handedness data, the vast majority (n=23, 88.5%) had a strong right hand dominance (Top Professional=6, Club Professional=5, Amateur=12). One golfer (Top Professional) had weak right hand dominance, one golfer (Amateur) had no hand dominance, and one golfer (Top Professional) reported strong left hand dominance. The distribution of self-reported hand dominance was not different between skill groups (p=0.451).

4.4.3 Eye – Hand Dominance

4.4.3.1 Primary Gaze

Using the self-reported hand dominance and the measured Primary gaze ocular dominance, 15 golfers (58%) had uncrossed hand-eye dominance. Golfers with uncrossed hand-eye dominance were all right eye/right hand dominant. 9 golfers (35%) had crossed dominance and 2 golfers (8%) had no eye-hand dominance. No eye-hand dominance meant that the golfer was ambidextrous or that they did not have a dominant eye (Tables 4-4 and 4-5, Figure 4-7).

	Uncrossed	Crossed	Undefined
Top Professionals	50.0%	50.0%	0.0%
Club Professionals	80.0%	20.0%	0.0%
Amateurs	76.9%	7.7%	15.4%
Overall	57.7%	34.6%	7.69%

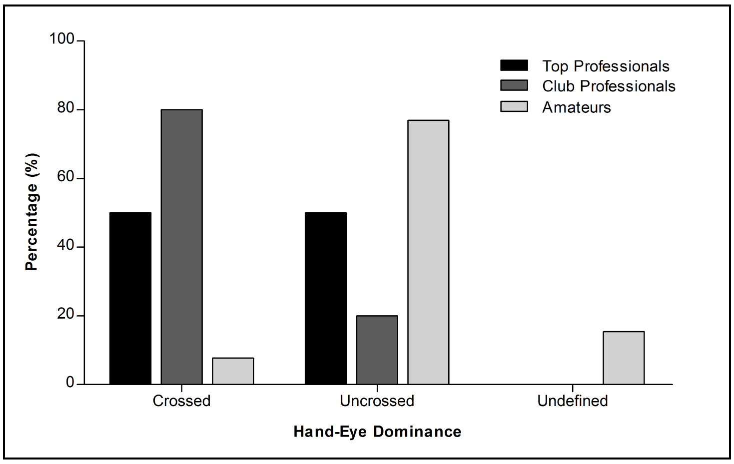
Table 4-4: Distribution of hand-eye dominance in golfers overall and by skill level; hand-eye dominance was determined from a self-reported hand dominance measure and primary gaze ocular dominance.

	Uncrossed		Crossed	
	RE-RH	LE-LH	RE-LH	LE-RH
Overall	100.0%	0.0%	12.5%	87.5%

Table 4-5: Distribution of uncrossed and crossed hand-eye dominance in golfers overall (RE=right eye, LE=left eye, RH=right hand, LH=left hand); hand-eye dominance was determined from a self-reported hand dominance measure and primary gaze ocular dominance.

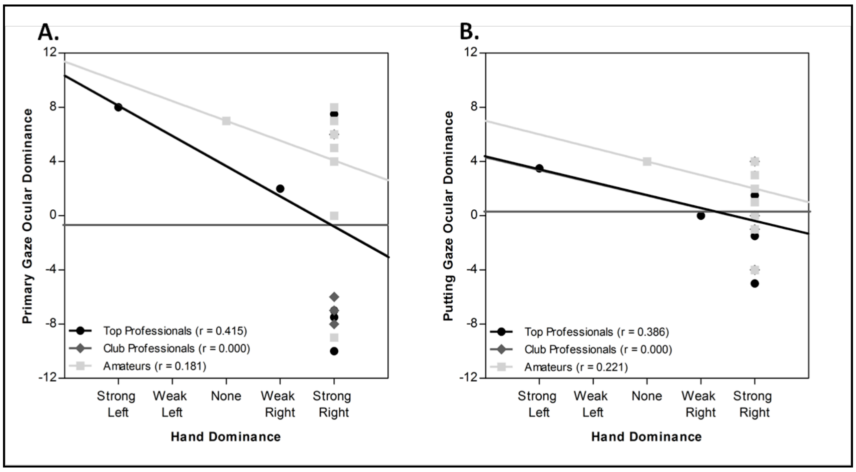
Overall and in the Club Professional group, more individuals had crossed hand-eye dominance, but in the Amateur group more individuals had uncrossed hand-eye dominance and in the Top Professional group there were an equal number of golfers with crossed (50.0%) and uncrossed (50.0%) hand-eye dominance. The difference in the distribution of crossed, uncrossed and no eye-hand dominances were statistically significantly different between the three skill groups (p=0.034). Whether this difference has a practical significance requires further investigation.

Figure 4-7: Distribution of hand-eye dominance in golfers of different skill levels; hand-eye dominance was determined from a self-reported hand dominance measure and primary gaze ocular dominance.



No correlation was found between primary gaze ocular dominance and handedness overall (Pearson r=-0.263, p=0.193) or in Top Professional (Pearson r=-0.415, p=0.306) and Amateur (Pearson r=-0.181, p=0.553) skill groups (Figure 4-8). Pearson correlations between handedness and ocular dominance could not be calculated for the Club Professional group because all of the golfers in this group had strong right hand dominances.

Figure 4-8: Correlation between ocular dominance and handedness in (A) primary gaze and (B) putting gaze.



4.4.3.2 Putting Gaze

When self-reported hand dominance was compared with the measured putting gaze ocular dominance, 11 golfers (42.3%) had uncrossed hand-eye dominance. Golfers with uncrossed hand-eye dominance were all right eye/right hand dominant. 5 golfers (19.2%) had crossed dominance and 10 golfers (38.5%) had no eye-hand dominance (Tables 4-6 and 4.7, Figure 4-9). The shift towards a higher proportion of golfers with no eye-hand dominance in putting gaze was due to the aforementioned decrease in ocular dominance magnitude from primary to putting gaze.

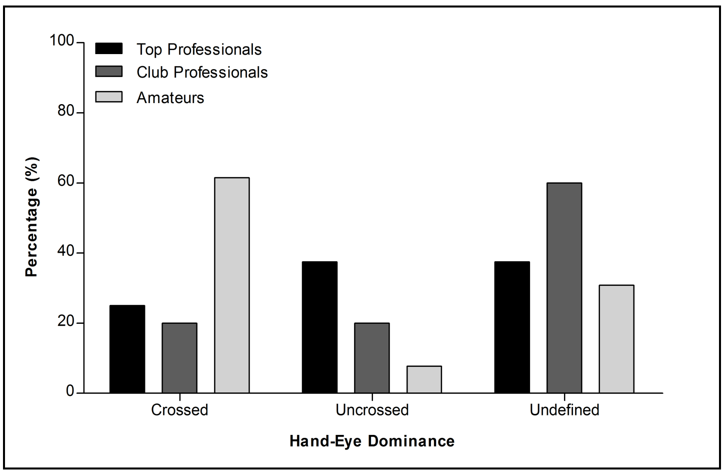
	Uncrossed	**Crossed**	**Undefined**
Top Professionals	25.0%	37.5%	37.5%
Club Professionals	20.0%	20.0%	60.0%
Amateurs	61.5%	7.7%	30.8%
Overall	42.3%	19.2%	38.5%

Table 4-6: Distribution of hand-eye dominance in golfers overall and by skill level; hand-eye dominance was determined from a self-reported hand dominance measure and putting gaze ocular dominance.

	Uncrossed		**Crossed**	
	RE-RH	**LE-LH**	**RE-LH**	**LE-RH**
Overall	100.0%	0.0%	20.0%	80.0%

Table 4-7: Distribution of uncrossed and crossed hand-eye dominance in golfers overall (RE=right eye, LE=left eye, RH=right hand, LH=left hand); hand-eye dominance was determined from a self-reported hand dominance measure and putting gaze ocular dominance.

Figure 4-9: Distribution of hand-eye dominance in golfers of different skill levels; hand-eye dominance was determined from a self-reported hand dominance measure and putting gaze ocular dominance.



The difference in the distribution of crossed, uncrossed and no eye-hand dominances were not statistically significantly different between the three skill groups (p=0.279). However trends were observed overall and in the Amateur group, more individuals had crossed hand-eye dominance, but in the Club Professional group more individuals had no eye-hand dominance. In the Top Professional group there were an equal number of golfers with uncrossed (37.5%) and no (37.5%) eye-hand dominance.

Putting gaze dominance was not correlated with handedness either (Overall, Pearson r=-0.223, p=0.273; Top Professionals, Pearson r=-0.386, p=0.0345; Amateurs, Pearson r=-0.221, p=0.468) (Figure 4-8). Pearson correlations between handedness and ocular dominance could not be calculated for the Club Professional group because all of the golfers in this group had strong right hand dominances.

4.5 Discussion

Ocular dominance is an essential visual component of putting. It is important in the alignment phase of the putt, where golfers' align their ball with the target and in the address phase when they align their club with the ball. It is also important in the putting action phase where it can influence fixation control during the swing and at ball contact. When aligning the ball with the target, golfers tend to use their primary gaze, with their head resting in a natural position. They look directly at the object of interest and they are looking straight ahead. During the putting action phase, when golfers align their club with the ball, they stand in a putting stance and use what has been defined as a putting gaze to look at the ball and the club.

4.5.1 Primary and Putting Gaze Ocular Dominance

The incidence of primary gaze ocular dominance measured in this population of golfers (71% right eye dominance, 26% left eye dominance and 3% no ocular dominance) was similar to what has been previously reported in the general population.[92] The distribution of ocular dominance values measured in both primary and putting gazes was not affected by golfers' skill levels, but ocular dominance in primary gaze was not representative of ocular dominance in putting gaze. In putting gaze the overall strength of golfers' ocular dominance usually decreased in magnitude and sometimes it disappeared entirely.

Ocular dominance, while weaker in putting gaze, was fairly well correlated with ocular dominance in primary gaze. This was especially true in the Club Professional group ($r=0.867$, $p=0.012$). Although the correlations between the primary and putting gaze ocular dominance were fairly strong overall and in each of the skill groups, the predictability of putting gaze ocular dominance from primary gaze ocular dominance was generally poor. Overall and in the Amateur group, primary gaze ocular dominance measures were only capable of predicting approximately 50% of putting gaze ocular dominance. In the Top Professional group, the predictability of putting gaze ocular dominance from primary gaze ocular dominance was even lower at 37%. The Club Professionals were the only group in which predictability of putting gaze ocular dominance from primary gaze ocular dominance was reasonably high (75%). The high correlation between primary and putting gaze ocular dominance in the Club Professionals was not representative of the entire population. It may have been an artefact of the small sample size of this group ($n=7$) compared with the other groups (Top Professional=10, Amateur=14), although all three groups were still relatively small.

The effect of stance on ocular dominance has never been previously investigated.[102, 104, 105, 108] The results of this study show that primary gaze ocular dominance is definitely not a good predictor of putting gaze ocular dominance. For this reason it is important that ocular dominance is measured in both primary and putting positions of gaze.

This conclusion is further supported by comparing the magnitude of the change between primary and putting gaze ocular dominances with the magnitudes of the primary and putting gaze ocular dominances. A weak positive correlation existed between the strength of the primary gaze ocular dominance and the magnitude of the change in dominance between primary and putting gazes (Overall, Pearson $r=0.612$, $p<0.001$), but no relationship existed between the magnitude of the change in ocular dominance between gazes and putting gaze ocular dominance (Overall, Pearson $r=-0.385$, $p=0.033$) even though the correlation was statistically significant. Results in the Top Professional and Amateur skill groups resembled the results in the overall population, but stronger correlations were found in the Club Professional group. Again this was likely an artefact of the small size of the Club Professional group.

4.5.2 Handedness and Eye-Hand Dominance

The majority of the golfers (89%) in this study reported having a strong right-hand dominance. The distribution of hand dominance did not differ between golfers of different skill levels. With respect to primary gaze eye-hand dominance, 58% of the population had an uncrossed (right eye/right hand or left eye/left hand) dominance, while 35% had a crossed dominance. Unlike Coffey *et al.*,[102] the distribution of crossed and uncrossed dominance was statistically significantly different between the different skill groups. The Club Professional group had the highest proportion of crossed dominant golfers (80%) and the Amateur group had the highest proportion of uncrossed dominant golfers (77%), but it is unlikely that the dominance differences were related to skill difference, because the Top Professional group had an equal number of golfers with crossed (50%) and uncrossed (50%) dominance.

In putting gaze, 42% of golfers had uncrossed eye-hand dominance and 19% had crossed eye-hand dominance; there was no eye-hand dominance in 39% of golfers. The increase in the number of golfers with no eye-hand dominance in putting gaze was a direct result of the decrease in the magnitude of golfers' ocular dominance from primary to putting gaze. Crossed eye-hand dominance was more common overall, and in the Amateur group (62%) whereas no eye-hand dominance was more common in Club Professionals (60%). In Top Professionals uncrossed and no eye-hand dominances occurred with equal frequency (Uncrossed 38%, Undefined 38%). Although there appear to be differences in the distribution of eye-hand dominance in putting gaze between the skill groups, the groups were statistically similar.

Ocular dominance and handedness were not correlated with each other in either primary or putting gaze, as expected.[80, 94]

4.5.3 Conclusion

Ocular dominance can be used to manipulate fixation stability during the swing and at ball contact. If golfers are able to maintain steady fixations through contact, it is highly likely they will be able to maintain a stable and consistent head and body position, which in turn should help improve the biomechanics and the consistency of their swing. The role of ocular dominance in fixation control will be explored later in this thesis, as ocular dominance will be included in the multifactorial analysis of golfers' putting visual strategy [Chapter 6, Vision Strategy in Golf Putting: Training, Competition and Ocular Dominance].

Although handedness may be important in the vision strategy of some individual golfers, it does not appear to be correlated with golfers' ocular dominance. Eye-hand dominance does not appear to be strongly associated with golfers' skill levels either, therefore neither factor will be included in the analyses of putting visual strategy conducted in the following chapters.

Measuring golfers' ocular dominance in both primary and putting gaze is essential for coaches who use ocular dominance information to optimise the putting vision strategy. The proper use of the dominant eye can improve accuracy in aligning both the ball with the target and the club with the ball; if there is no dominant eye, the ball position can be adjusted to induce an ocular dominance and increase precision. Improved alignment should ultimately lead to improved performance if all other factors remain equal.

Relying on primary gaze ocular dominance information to optimise the putting vision strategy, as is currently being done by golf coaches, leads to strategy decisions to be based on incorrect information in 87% of cases. As such, incorporation of the measurement of ocular dominance in putting stance in the assessment of golfers is of fundamental importance.

4.6 Summary

Chapter 4, Ocular Dominance and Golf demonstrated that primary gaze ocular dominance is not predictive of putting gaze ocular dominance and that there are no associations between (i) ocular dominance and skill, (ii) hand dominance and skill or (iii) eye-hand dominance and skill. Additionally, ocular dominance and hand dominance are not related. The next chapter, Chapter 5, Vision Strategy in Golf Putting: Skill and Success, will examine the relationships between individual gaze behaviours and both putting skill and success.

Chapter 5

VISION STRATEGY IN GOLF PUTTING: SKILL AND SUCCESS

5.1 Introduction

Understanding the vision strategy of putting[**] requires that knowledge of the sport be combined with objective analysis of the eye movements golfers make while performing. Mobile eye trackers are ideal instruments for this research, as they allow for the measurement of an individual's eye movements in a real-world environment, such as on the putting green.

Traditionally, eye tracking research in golf has focused on the action phase of the putt because gaze behaviours in this phase were thought to be of critical importance in putting success [Chapter 1, Introduction]. Furthermore, measurement of gaze behaviours during this phase of the putt was relatively simple compared with the rest of the putt as golfers maintain a relatively stationary body position throughout and their gaze falls on two primary locations: the ball and the hole. The lack of explosive movement means eye tracking equipment does not have to be wireless, and the limited number of gaze positions simplifies instrumentation calibration.

All previous research investigating putting vision strategy has been summarised in Table 5-1. Unfortunately all of these studies were erroneously conducted when considering established vision science principles. The studies used gaze criteria which were based on the assumption that a fixation measured with an eye tracker was indicative of cognitive attention (fixation was a stable gaze for a minimum of 100ms), and took a 3° visual angle criterion to define a fixation. Moreover they were all completed with monocular eye trackers and binocular aspects of visual system, such as ocular dominance, were not examined. Another drawback of many of the studies completed was that the participants were novice golfers, which has limited the value of these studies in understanding the vision strategy of elite

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[**] The putting vision strategy includes all of the gaze behaviours (fixations, pursuits and saccades) used by a golfer while putting. Both the duration of, and location of these gaze behaviours is important.

golfers. Finally, no single study, apart from the original publication by Vickers,[28] has measured specific gaze behaviours throughout the entire putt, from preparation to post-contact.

The purpose of the current study was to fully characterise the putting vision strategy of golfers, without the limitations of previous studies. In particular the totality of the putting vision strategy was analysed binocularly using gaze criteria which defined a fixation as a stable gaze within 0.5° visual angle with a minimum duration of 16.67 ms (1 movie frame at 60Hz). The study addressed the following outcomes: (i) identification of the parameters of interest in the assessment of the putting vision strategy, (ii) determination of the ideal vision strategy for golf putting, associated with both higher skill and success, (iii) assessment of the relationship between training and competition with respect to the putting vision strategy and (iv) examination of the role of ocular dominance in putting vision strategies.

As this was a comprehensive and exhaustive study of golfers' putting vision strategy, the analysis and report have been divided into two sections. This chapter focuses specifically on the identification of the parameters of interest in the putting vision strategy and the determination of aspects of the strategy identified with higher skill and success. The following chapter examines both the relationship between training and competition, and the impact of ocular dominance on putting vision strategy [Chapter 6, Vision Strategy in Golf Putting: Training, Competition and Ocular Dominance].

Publication	Population	Fixation Definition	Total Putt	Preparation / Address	Swing	Contact	Post Contact	Quiet Eye	Quiet Eye Dwell Time
Vickers 1992[28]	**High Skill:** 5 LH (6.2, range 0-8) **Low Skill:** 7 HH (14.1, range 10-16)	3° visual angle, 99.99ms minimum duration	**# of Gazes:** LH: 14.2; HH 19.4 *[S**, A^{NS}]* **Duration:** LH: 7800ms, HH 8226ms *[S**, A^{NS}]*	**# of Gazes:** LH: 7.3; HH 10.6 *[S**, A^{NS}]* **Duration(ms):** LH: 3704, HH 4813 *[S**, A^{NS}]* **Fix to Ball used:** LH=HH^{NS}; Success > Miss^{NS} **Fix to Ball(ms):** LH: 1442, HH: 926**; Success>Miss^{NS}	**# of Gazes:** **LH: 1.5; HH 2.9** ***[S**, A^{NS}]*** **Duration(ms): LH: 1927, HH 1672** ***[S^{NS}, A^{NS}]*** **Fix to Ball used:** LH=HH* Success > Miss^{NS} **Fix to Ball(ms):** LH: 1788, HH: 911*; Success > Miss**	**# of Gazes:** LH: 1.0; HH 1.0 *[S^{NS}, A^{NS}]* **Duration(ms):** LH: 160, HH 140 *[S^{NS}, A^{NS}]* **Fix to Surface (ms):** LH: 200, HH: 114**; Success > Miss**	**# of Gazes:** LH: 4.5; HH 4.9 *[S^{NS}, A^{NS}]* **Duration(ms):** LH: 2009, HH 1609 *[S**, A^{NS}]* **Ball Tracking(ms):** LH: 1206, HH: 747**; Accuracy not evaluated	>1700ms during swing	>200ms after contact
Fairchild, Johnson, Babcock & Pelz 2001[32]	Novice (No experience)=1 Beginner=1 Intermediate=1 (Hc=15-20) Advanced=1 (Hc=3)	The definition of a fixation was not specified	**# of Fixations:** Advanced: 15.9	**# of Fixations:** Novice: 9.0±3.9 Beginner: 8.0±2.5 Intermediate: 6.4±2.0 Advanced: 7.8±1.2 Accuracy improved with lower standard deviations	**Mean duration of last 4 fixations (s):** Novice: 0.51±0.57 Beginner: 0.57±0.54 Intermediate: 1.19±1.23 Advanced: 0.88±0.45 [A] improved with lower standard deviations **Total duration of last 4 fixations (s):** Novice: 2.1 Beginner: 2.3 Intermediate: 4.7 Advanced: 3.5				
Vickers & Crews 2002[34]	Novice=? LPGA=?	3° visual angle, 99.99ms minimum duration						Novice: 1.5s LPGA: 2.0s (all values are approximate)	
Vickers 2004[35]								Less-skilled: 1-2s Experts: 2-3s	
Naito, Kato & Fukuda 2004[36]	Beginner (rarely played or no experience)=11 Novice=3 (Hc: 2-15) Expert=3 (Hc=0)	Mean % of time gaze was directed at different locations; only gazes to the ball reported		Beginner: 73.6% Intermediate: 89.7% Expert: 18.4%*	**Backswing:** Beginner: 78.9% Intermediate: 85.6% Expert: 24.6% * **Downswing:** Beginner: 92.5% * Intermediate: 66.3% Expert: 33.4%	Beginner: 84.1% * Intermediate: 21.9% Expert: 10.0%	**Rolling Ball:** Beginner: 58.7% Intermediate: 16.3%* Expert: 35.3%		
Van Lier, Van der Kamp, Savelsbergh 2008	Teaching golf professionals (highly skilled)=12	1.5° visual angle, 120ms minimum duration						**Holed (s):** 0%: 1.5; 1%: 1.7; 2%: 1.7 **Missed (s):** 0%: 1.6; 1%: 1.5; 2%: 1.3 [Slope^{NS}, Success^{NS}]	
Wilson & Pearcy 2009[38]	6 University team golfers	1° visual angle, 120ms minimum duration						**Holed (ms):** Sloped: 1620.0 ± 991.4 Flat: 1816.0 ± 1077.1 **Missed (ms):** Sloped: 1176.7 ± 673.6 Flat: 1514.3 ± 941.7 [A*, Slope^{NS}]	

Table 5-1: Summary of all previously published research regarding golf putting vision strategy [Abbreviations used: LH=low handicap, HH=high handicap, HC=handicap, S=skill, A=accuracy, # of Gazes=total number of gaze behaviours (fixations, pursuits, saccades), Fix to Ball=number of fixations to the ball, *=p<0.05, **=p<0.01, NS=not significant].

5.2 Methods

5.2.1 Study Design

This study was designed as a retrospective analysis of putting eye tracking data collected during optometric examinations, optometric screenings and putting vision assessments of golfers of various skill levels. The optometric examinations, optometric screenings and putting vision assessments were completed by practitioners at the Michel Guillon Sports Vision Clinic, London UK, either on the premises or in a mobile clinic facility that was transported to various locations around the United Kingdom.

This study received ethics approval from Aston University Audiology/Optometry Research Ethics Committee (AO2010.20). All participants completed an informed consent prior to their full ocular examination, ocular screening or putting vision assessment. The informed consent explained whether they were receiving a full ocular examination, an ocular screening or a putting vision assessment, and that ocular screenings and putting vision assessments were not replacements for a regular eye examination. The informed consent also explained that some of the data collected during the ocular examination or screening could be used for research purposes; if the data was used for research purposes identifying information would not be included.

5.2.2 Study Population

Golfers of three skill levels were included in this study: (i) Top Professionals: elite highly skilled golfers who were members of the European Tour, (ii) Club Professionals: highly skilled golfers who were either professional coaches or members of the Challenge Tour (which is a satellite of, and feeds into the European Tour) and the Australian Ladies Professional Tour, and (iii) Amateurs: golfers with a wide range of experience, some played once or twice a year and others played once or twice a week, but did not make a living playing golf. 27 of a possible 37 golfers were included in this study; eight of the golfers were excluded because they putting vision assessment took place on a real putting green and they did not take putts from controlled distances on an artificial green and two were excluded because their eye tracking videos were not suitable for analysis. In total, nine Top Professional, six Club Professional and twelve Amateur golfers were included in this study (Table 5-2).

Classification	Level of Play	Men	Women
Top Professionals	Ryder Cup, European Tour,	n=9	n=0
Club Professionals	Challenge Tour, Australian Women's Tour, Coaches	n=5	n=1
Amateurs	Amateurs	n=11	n=1

Table 5-2: Population demographics of golfers in each of the skill groups studied.

Handicap was not used as a measure of skill in this study, as it would not have been helpful in classifying the European Tour Players or the novice Amateurs. Handicap is a good measure for classifying advanced Amateur golfers but novices typically do not play enough rounds in a season to accurately calculate one. Furthermore, handicap rates golfers' overall skill rather than their specific putting skill. The lack of association between handicap and putting skill is illustrated by professional golf tour rankings, whereby the overall rankings and the putting rankings are not the same.

5.2.3 Eye tracking

All golfers had their putting vision strategy assessed with the Arrington Research ViewPoint binocular eye tracker as part of a full golf-specific optometric examination, a golf-specific optometric screening or a putting vision assessment at the Michel Guillon Sports Vision Clinic. The study itself was a retrospective analysis of all eye tracking data collected at these visits.

All data was analysed using GazeDetection [Chapter 2, Software Development]. Fixations were defined as a stable gaze within 0.5° visual angle with a minimum duration of 16.67ms (1 movie frame at 60Hz).

5.2.4 Experimental Routine

Golfers completed a total of 20 putts on a flat artificial putting surface, alternating between 6 foot and 10 foot distances. They were asked to putt as they would on a golf course, and were encouraged to walk around the green and go through their full pre-shot routines. They were given no additional instructions regarding their vision strategy.

5.2.5 Data Reporting

To ensure a complete analysis of the vision strategy results, reporting has been sub-divided into four sections. The first two sections of the analysis are included in this chapter; they identify the parameters of importance in the putting vision strategy and the parameters of this strategy that are associated with higher skill and/or success. The third and fourth sections will be discussed in the following chapter, and are related to examination of the relationship between training and competition scenarios, and evaluation of the impact of ocular dominance.

5.2.6 Parameters of Interest

The initial parameters considered for inclusion in the putting vision strategy analysis were the duration of the first (T_{FA1}) and last (T_{FAQ}) fixations of the Address phase, the first (T_{FS1}) and last (T_{FSQ}) fixations of the Swing phase, the fixation at contact (T_{FCQ}) and the first fixation immediately after contact (T_{FPQ}), as well as when these fixations started and ended relative to ball contact (T_0). These six fixations were thought to be the key fixations in the assessment of putting vision strategy. The Total Number of Fixations made on the ball and the hole, the Mean Duration of ball and hole fixations, and the Total Duration of ball and the hole fixations in each of the Address and Swing phases were included, as were the durations of the entire putt and the Preparation, Address, Swing and Post Contact phases. The six key fixations are described in more detail below; definitions of the putt phases are the same as those used in Chapter 3, Analytic Strategy Development and are included below for reference.

5.2.7 Putt Phases

5.2.7.1 Preparation Phase

The Preparation phase was defined as the portion of the putt that started at Stationary Ball and ended at Address (T_A)[††]. If there was more than one Address in the putt, the Preparation phase ended at the earliest secondary Address.

[††] T_A was a reference for the end of the Preparation phase and the start of the Address phase. T_A was determined by the frame in which the club was first perceived to break any of the horizontal or vertical tangents to the ball during club placement (Tangent Address).

5.2.7.2 Primary Address Phase

The Primary Address phase was the portion of the putt that started at the Primary Address (T_{A1}) and ended at Swing (T_S)‡‡. The Primary Address phase was the Address phase that occurred closest to Ball Contact.

5.2.7.3 Secondary Address Phases

Secondary Address phases refer to the portions of the putt that started at Address (n) and ended at Address (n-1). For example, Secondary Address phase 3 started at Address 3 (T_{A3}) and ended at Address 2 (T_{A2}). There may have been more than one Secondary Address phase per putt, and they were labelled in reverse chronological order from Ball Contact.

Secondary Address parameters were not included in the analysis as there were only 21 putts (3.9%) with Secondary Address phases and the sample size was not considered large enough for analysis. Of the putts with Secondary Address phases, 19 (90.5%) had only one Secondary Address phase and 2 (9.5%) had two Secondary Address phases. Thus, the term Address used throughout the analyses presented in the following chapters refers to the Primary Address phase, which was the Address phase that immediately preceded the Swing phase.

5.2.7.4 Swing Phase

The Swing phase started at Backswing Time (T_S) and continued until Ball Contact (T_0)§§. There was only one Swing phase per putt.

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‡‡ T_S was a reference for the end of the Address phase and the start of the Swing phase. T_S was determined by the first frame where the club face was seen to move away from the ball in the backswing.

§§ Ball Contact (T_0) was used as the zero time reference for every putt. All of the events which occurred during the putt prior to Ball Contact (i.e. Address and Swing) had a negative time value, and all events which occurred after Ball Contact (i.e. Gaze Break) had a positive time value.

5.2.7.5 Post-Contact Phase

The Post-Contact phase was the remainder of the putt that occurred after Ball Contact (T_0). The Post-Contact phase ended at the Gaze Break.

5.2.8 Key Fixations

5.2.8.1 First Fixation of the Preliminary Address (T_{FA1})

The first fixation of the Preliminary Address (T_{FA1}) started immediately before Address (T_A) and included T_A. In the event that there was not a fixation at T_A, T_{FA1} was the first fixation that occurred immediately after $T_{A.}$

5.2.8.2 Last Fixation of the Preliminary Address (T_{FAQ})

The last fixation of the Preliminary Address (T_{FAQ}) was the last fixation during the Address phase that started before the Swing (T_S); this fixation may or may not have included T_S and was equivalent to the 'Quiet Eye' as described by Vickers.[30]

5.2.8.3 First Fixation of the Swing (T_{FS1})

The first fixation of the Swing, T_{FS1}, started immediately before T_S and included T_S. In the event that there was not a fixation at T_S, T_{FS1} was the first fixation that occurred immediately after T_S. In cases where T_{FS1} started before T_S, $T_{FS1}=T_{FAQ}$ and was equivalent to the "quiet eye" as described by Vickers.[30]

5.2.8.4 Last Fixation of the Swing (T_{FSQ})

The last fixation of the Swing (T_{FSQ}) was the last fixation of the Swing phase that started before Contact (T_0); this fixation may or may not have included T_0. If this fixation started before the swing, than $T_{FSQ}=T_{FS1}$, if the fixation included T_0, than $T_{FSQ}=T_{FCQ}$ (or $T_{FS1}=T_{FSQ}=T_{FCQ}$).

5.2.8.5 Contact Fixation (T_{FCQ})

The Contact fixation (T_{FCQ}) was the fixation that started immediately before or at T_0 and included T_0. In the event that there was not a fixation which started before or at T_0 and included T_0, then T_{FCQ}=0.000ms. If T_{FCQ} started before T_0, then T_{FCQ}=T_{FSQ}.

5.2.8.6 Post Contact Fixation (T_{FPQ})

The Post Contact fixation (T_{FPQ}) was the first fixation that started immediately after T_0 but did not include T_0. If there was a T_{FCQ} fixation than T_{FPQ} was the first fixation which started after T_{FCQ} had ended.

5.2.9 Statistical Analysis

5.2.9.1 Descriptive Statistics

Distribution statistics for the population and each skill group were calculated for each of the above parameters. Initially these were calculated with the right and left eye data pooled, but they were also calculated for right and left eyes independently. The descriptive statistics reported were the mean, standard deviation, median, minimum and maximum values, skewness and kurtosis.

Skewness and kurtosis values were used to evaluate the normality of the data distributions to ensure that appropriate statistical methods were used. Skewness values were considered to be representative of a normal Gaussian distribution if the value was within ±twice the standard error of the skewness. Kurtosis values were considered to be representative of a normal Gaussian distribution if the value was within ±twice the standard error of the kurtosis.

5.2.9.2 Parameter Selection

Correlation analyses were conducted on the overall population and each skill group with the right and left eye data pooled initially to identify which parameters were of interest, and which were correlated and therefore could be considered equivalent performance predictors. The vast majority of the parameters measured did not have normal Gaussian distributions, therefore non-parametric Spearman correlations were used. A secondary correlation analysis was conducted to compare the right and left eye data. The results of this analysis are presented in Appendix A.

5.2.9.3 Data Modelling

In choosing a model to assess the putting vision strategy, various aspects of the data were considered. The model needed to be representative of golfer's overall performance and it needed to rely on data that could be collected in a timely and efficient manner.

5.2.9.4 Adaptation Effect

None of the golfers who participated in this study had previously worn eye tracking equipment, therefore it was unknown whether or not their vision strategy would be affected by adaptation to the equipment. To examine the effect of adaptation, a repeated measures multivariate ANOVA was carried out. Skill (Top Professional, Club Professional or Amateur), Putt Length (6 or 10foot) and Putt Result (Success or Failure) were used as between subjects factors. Putt Trial (10 repetitions) and Eye (right or left) were used as a within subjects factors; Eye (right or left) was nested within the Putt Trial term to help control sample size. The effect of Eye was not considered in the results, as Eye cannot be assessed without consideration of ocular dominance (See Chapter 6, Vision Strategy in Golf Putting: Training, Competition and Ocular Dominance). The results of the analysis are given in Appendix B.

5.2.9.5 Data Collection Efficiency

To assess data collection efficiency, the session results (mean of ten putts) were compared with the mean results of the first three and the first five putts taken using Spearman correlations. A high correlation between the three data sets would allow one to simplify the data collection routine in future studies. The two putt distances tested were considered as independent sessions for this analysis. In one golfer (a Club Professional) only eight putts were used to calculate the session mean at each distance; two putts at each distance were not suitable for analysis due to problems with the recording system. The results of the analysis are given in Appendix C.

5.2.9.6 Fixation Identification

GazeDetection measured every fixation made during a putt, not just the key fixations. Each fixation made was identified with a unique fixation identification value, and this enabled the identification of the key fixations (defined in section 5.2.8 Key Fixations).

It was possible for a single fixation made during the putt to be identified as more than one key fixation. For example, if the last fixation of the Address (T_{FAQ}) ended after the Swing phase started, this fixation would be the first fixation of the Swing (T_{FS1}), due to the nature of the key fixation definitions. When this happened T_{FAQ} and T_{FS1} were identified as T_{FAQ}=T_{FS1}.

Following on this concept, T_{FS1} could have been either T_{FS1}, T_{FAQ}=T_{FS1}. Additionally, if T_{FS1} lasted throughout the entire Swing phase $T_{FS!}$ could have been either T_{FS1}=T_{FSQ} or T_{FS1}=T_{FSQ}=T_{FCQ}. T_{FSQ} (the last fixation in the Swing phase) also could have been T_{FSQ}, T_{FSQ}=T_{FS1} (if T_{FS1}/T_{FSQ} lasted throughout the swing), or T_{FSQ}=T_{FCQ} or T_{FS1}=T_{FSQ}=T_{FCQ} (if T_{FSQ} lasted through ball contact).

T_{FCQ} could only be classified as T_{FSQ}=T_{FCQ}, or T_{FCQ}=0.000ms; if a fixation was measured at contact (T_0) had would have had to start at least 1 frame before T_0 in the Swing phase, which would also make it the last fixation of the Swing (T_{FSQ}); if no fixation was recorded than T_{FCQ}=0.000ms. Likewise, if a golfer did not have a fixation which met the definitions of any of the other key fixation, the key fixation was identified as having a 0.000ms duration. T_{FA1} and T_{FPQ} were never classified as any other fixation because they did not occur during phase transitions.

The distributions of the key fixations that overlapped transitions between putt phases (T_{FAQ}, T_{FS1}, T_{FSQ} and T_{FCQ}) were compared between skill groups using Chi-square analysis. The significance value for all analyses was α=0.05.

5.2.9.7 Vision Strategy Analysis

A linear mixed model procedure was chosen to analyse putting vision strategy due to its ability to deal with multiple repeated measures and non-normal data. One of the greatest benefits of linear mixed models is their flexibility, which makes them useful for many different tasks. This flexibility is also one of their greatest drawbacks as it makes the selection of a precise model complicated, as numerous aspects of the model need to be specified.

All of the linear mixed models used in Chapters 5 and 6 have the same basic structure, but the explanatory and repeated measure variables differ. The purpose of the analysis in this chapter was to examine the factors of the putting vision strategy associated with skill and success. Therefore, the principle explanatory variables included were Skill (Top Professional, Club Professional, Amateur), Putt Length (6 foot, 10 foot) and Putt Result (Success, Failure). Subjects were identified by a Player ID variable. The repeated measures variable was Putt Trial, which was identified by the Player ID, Eye and Putt Length variables; Eye and Putt Length were nested within Player ID to precisely identify the repeated measures data. Eye was also included in the model as an explanatory variable, although it will not be discussed in the analysis; Eye will not be examined as it does not account for ocular dominance, but Eye was included simply to account for any variations in this parameter that could affect the final results. An analysis of Eye, which accounts for the influence of ocular dominance, is examined in Chapter 6, Vision Strategy in Golf Putting: Training, Competition and Ocular Dominance.

The specific model used for the assessment putting vision strategy was designed based on various aspects of the data, and the details of the model selection are presented in Appendix D. The specific parameters included in this analysis were chosen based upon the results of the parameter selection correlation analysis discussed above.

Estimated marginal means are sometimes reported in conjunction with the linear mixed model results; these means are in the format of mean ± standard error and are denoted with "†" to differentiate them from results reported as mean ± standard deviation. The graphs presented below display estimated marginal means with mean ± standard error.

5.2.9.8 CHAID Analysis

Chi-Square Automatic Interaction Detection, otherwise known as CHAID analysis, is a method which partitions a data set into decision trees through the determination of how predictor (independent) variables are best combined to explain the outcome of a given target (dependent) variable. CHAID is a stepwise decision tree analysis; each step in the tree is created through the determination of the most significant predictor variable at that level. [109, 110]

CHAID analysis was conducted to determine which aspects of the putting vision strategy were most predictive of putting success. An overview of the CHAID analysis principles can be found in Appendix E. An Exhaustive CHAID model was used; trees were restricted to a maximum of 5 levels. The minimum parent node size was 10 and the minimum child node size was 5. A Bonferroni adjustment of probabilities was used with the alpha probability level for splitting predictors set at 0.01 and the alpha probability level for merging predictors set at 0.05. CHAID analysis was performed on the overall population, as well as on each skill group and for each putt length. Putt Result was used as the outcome variable in all of the CHAID analyses.

5.3 Results

5.3.1 Study Population

Eye tracking videos from 27 golfers (9 (33.3%) Top Professionals, 6 (22.2%) Club Professionals, 12 (44.4%) Amateurs) were used in this study. Every golfer completed ten putts from two distances (6 and 10 feet) on a flat artificial green surface and a total of 540 putts were recorded during the study (270 at each distance). Four putts (two each from 6 and 10 feet) from a Club Professional golfer were not analysed due to poor quality of the recorded video. The very low recording failure rate (4 of 540 putts or 0.7%) is an indication of the feasibility of the application of the technique to the analysis of golf putting. Of the 536 putts analysed, 180 (33.6%) were taken by Top Professionals, 116 (21.6%) by Club Professionals and 240 (44.8%) by Amateurs.

All of the golfers were male except for one Club Professional and one Amateur, who were female. The entire population putt right handed, therefore the hole was always on the golfers' left hand side. The mean age of the golfers was 31.8±9.5 years (range 18.1 to 57.6yrs). Top Professionals had a mean age of 30.4±6.2 years (range 22.8 to 39.9yrs); the mean ages for Club Professionals and Amateurs respectively, were 28.0±2.0 years (range 25.1 to 30.2yrs) and 34.7±12.9 years (range 18.1 to 57.6yrs) respectively. There was no significant difference in age between skill groups (p=0.332).

In terms of putting results, a successful putt was defined as a putt when the ball rolled into the hole and a missed putt was defined as a putt where the ball did not enter the hole. The results of five putts (two at 6 feet and three at 10 feet from one Amateur) were not recorded; these putts were classified as having an unknown result. Putts with an unknown result were included in the preliminary correlation analyses, but were excluded from all of the analyses where Putt Result was a variable (i.e. skill and success analysis, CHAID). Eye tracking data was recorded for the right and left eyes of all golfers.

5.3.2 Descriptive and Distribution Statistics

Table 5-3 displays the descriptive statistics for all parameters measured in the study, including the duration of the six key fixations (T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}), their Start and End Time from T_0 (Ball Contact), and the Total Number of, the Mean Duration of, and the Total Duration of all fixations made to the ball and the hole in the Address and Swing phases. The total duration of the putt and the duration of each of the critical putt phases (Preparation, Address, Swing, Post-Contact) were also examined.

With respect to the key fixations, T_{FAQ} and T_{FS1} had the longest durations. T_{FA1} and T_{FSQ} had durations of similar length. T_{FPQ} and T_{FCQ} had the shortest durations. T_{FA1} started furthest from ball contact followed by T_{FAQ}, T_{FS1}, T_{FSQ} and T_{FCQ}. T_{FPQ} was the only fixation to start after ball contact (T_0). T_{FA1} also ended furthest from ball contact followed by T_{FAQ}, T_{FS1} (-859.5±178.1ms) and T_{FSQ}. T_{FCQ} was stable at contact, and ended just after T_0. T_{FPQ} was the only other fixation to end after ball contact (Table 5-3).

During Address, more fixations were made to the ball than the hole during Address (Table 5-3); ball fixations were longer than hole fixations and accounted for a greater percentage of the total duration of fixations made during Address as well (Ball 90.3%, Hole 9.7%).

During the Swing phase, the vast majority of fixations made were to the ball (Table 5-3). Fixations to the hole were very uncommon, as most golfers did not make any fixations to the hole during the Swing.

On average, putts had a total duration of 20.5±9.5s, and golfers spent approximately 50% of this time in Preparation (Table 5-3). Upon termination of the Preparation phase, Address was the next longest putt phase, followed by the Post Contact and Swing phases.

Parameter	Mean ± Standard Deviation	Median	Minimum	Maximum	Skewness	Standard Error of Skewness	Kurtosis	Standard Error of Kurtosis
T_{FA1} Duration	39.3 ± 44.0	16.7	5.8	383.2	3.552	0.075	16.642	0.149
T_{FAQ} Duration	106.1 ± 150.7	50.0	15.3	1533.0	3.511	0.075	18.622	0.149
T_{FS1} Duration	100.3 ± 150.7	34.3	0.0	1533.0	3.596	0.075	19.146	0.149
T_{FSQ} Duration	33.5 ± 47.0	16.7	0.0	716.8	6.814	0.075	69.281	0.149
T_{FCQ} Duration	15.3 ± 46.0	0.0	0.0	716.8	7.282	0.075	80.521	0.149
T_{FPQ} Duration	24.6 ± 21.7	16.7	0.0	432.5	8.265	0.075	123.614	0.149
T_{FA1} Start from T0	-7465.4 ± 2182.2	-7332.1	-2761.3	-17329.8	-0.941	0.075	1.875	0.149
T_{FAQ} Start from T0	-1204.1 ± 549.5	-1083.4	-590.0	-6013.4	-4.376	0.075	25.138	0.149
T_{FS1} Start from T0	-962.6 ± 230.1	-960.7	-1.4	-2500.6	-0.395	0.076	4.145	0.151
T_{FSQ} Start from T0	-127.8 ± 188.9	-53.5	0.0	-1208.3	-2.655	0.076	7.549	0.151
T_{FCQ} Start from T0	-28.3 ± 57.7	-14.6	0.0	-697.9	-8.569	0.142	89.087	0.283
T_{FPQ} Start from T0	233.5 ± 303.5	103.1	0.2	2276.8	2.243	0.075	6.793	0.149
T_{FA1} End from T0	-7426.1 ± 2186.4	-7292.6	-2502.9	-17313.1	-0.938	0.075	1.884	0.149
T_{FAQ} End from T0	-1097.9 ± 562.9	-958.2	-527.5	-5996.8	-4.399	0.075	24.984	0.149
T_{FS1} End from T0	-859.5 ± 178.1	-861.5	15.3	-1453.2	0.450	0.076	1.958	0.151
T_{FSQ} End from T0	-93.4 ± 191.9	-18.3	36.4	-1158.2	-2.536	0.076	7.191	0.151
T_{FCQ} End from T0	27.4 ± 42.8	13.0	0.2	364.0	3.873	0.142	19.659	0.283
T_{FPQ} End from T0	258.1 ± 302.0	132.0	14.1	2311.6	2.255	0.075	6.912	0.149
Total Number Ball Fixations (A)*	42.5 ± 23.0	42	0	132	0.477	0.075	0.202	0.149
Mean Ball Fixation Duration (A)	42.8 ± 24.5	35.8	0.0	174.4	1.487	0.075	3.235	0.149
Total Ball Fixation Duration (A)	2039.9 ± 1667.1	1616.8	0.0	8647.1	1.058	0.075	0.630	0.149
Total Number Hole Fixations (A)*	6.0 ± 8.5	4	0	55	1.888	0.075	3.853	0.149
Mean Hole Fixation Duration (A)	22.7 ± 17.9	20.8	0.0	199.9	1.910	0.075	12.592	0.149
Total Hole Fixation Duration (A)	222.0 ± 335.5	99.8	0.0	2047.7	2.634	0.075	7.678	0.149
Total Number Ball Fixations (S)*	9.6 ± 5.2	11	0	21	-0.275	0.075	-0.980	0.149
Mean Ball Fixation Duration (S)	44.8 ± 46.5	33.3	0.0	775.0	5.951	0.075	66.593	0.149
Total Ball Fixation Duration (S)	443.7 ± 347.1	384.6	0.0	2282.7	0.784	0.075	0.533	0.149
Total Number Hole Fixations (S)*	0.19 ± 1.14	0	0	11	6.862	0.075	49.143	0.149
Mean Hole Fixation Duration (S)	1.4 ± 10.2	0.0	0.0	149.9	10.346	0.075	123.597	0.149
Total Hole Fixation Duration (S)	9.6 ± 84.2	0.0	0.0	1182.8	11.479	0.075	138.542	0.149
Total Putt Duration	20453.0 ± 9486.4	1771.7	6306.1	57056.4	0.963	0.075	0.437	0.149
Preparation phase Duration	10418.1 ± 9280.1	7006.8	-59.4	48712.2	1.006	0.075	0.431	0.149
Address phase Duration	6620.9 ± 2153.7	6373.0	1636.2	16349.6	1.049	0.075	2.279	0.149
Swing phase Duration	974.7 ± 161.4	967.6	583.9	2178.1	1.419	0.075	7.150	0.149
Post-Contact phase Duration	2439.3 ± 698.6	2335.5	931.2	5538.5	1.075	0.075	1.562	0.149

**Count data without units*

Table 5-3: Summary table displaying mean ± standard deviation, median, minimum and maximum values, skewness, standard error of skewness, kurtosis and standard error of kurtosis for all parameters measured for the overall population (right and left eye data pooled). All values are reported in milliseconds (ms) except for the Total Number of Ball/Hole Fixation parameters in the Address (A) and Swing (S) phases, which are count data and reported without units; negative values represent time before contact.

None of the above parameters had normal Gaussian distributions (Table 5-3), hence the decision to use non-parametric Spearman correlations. This was also one of the reasons a linear mixed model approach was used in preference to multivariate ANOVA to analyse the putting vision strategies; linear mixed models are more robust with data that does not have a normal distribution.

5.3.3 Adaptation Effect

A complete report of the adaptation analysis can be found in Appendix B. Eye was nested within the Putt Trial term, and this factor, Putt Trial*Eye, did not have a significant effect on any of the variables examined except for Total Fixation Duration in Address ($p=0.042$).

Pairwise comparisons for the Total Fixation Duration in Address between putt trials revealed non-significant differences between all putts ($p=0.203$ to 1.000), except for Putt 1 versus Putt 10 ($p=0.030$). The estimated mean values for each putt ranged from a low of $1.839 \pm 0.178^{\dagger}$ on Putt 10 to a high of $2.117 \pm 0.199^{\dagger}$ on Putt 1; the Total Fixation Duration in the Address varied randomly between its minimum and maximum values for Putts 2 – 9. Therefore, it was concluded that there was no specific adaptation or learning effect influencing the Total Duration of Fixation in Address measurement, and that the significance of the multivariate test was a random occurrence.

As no significant effects of Putt Trial*Eye were found for any of the other variables the eye tracking data does not seem to suffer from an adaptation effect.

5.3.4 Data Collection Efficiency

As an analysis of this type had never been done before, it was decided that ten putts would be assessed at each distance as it was thought this would give a good indication of golfers' performance. As no learning effect was detected, it may have been possible to measure a golfer's performance with fewer putts, which would save time and increase efficiency when recording and processing data. A complete report of the data collection efficiency analysis can be found in Appendix C.

The three putt mean results were strongly correlated with the session means, especially overall, at 6 and 10 feet and in the Top Professional group (overall, 6 feet and 10 feet). In these particular groups at least 11 of the 12 parameters were strongly correlated ($r \geq 0.700$).

In the Club Professional group overall and at 6 feet, and in the Amateur group overall and at 6 and 10 feet, at least 9 of the parameters were strongly correlated with each other. The Club Professional group at 10 feet had the lowest number of strong correlations between the three putt and the session results, with only 6 parameters demonstrating strong correlations.

Comparing the five putt mean results with the session mean demonstrated even better results, with all of the groups being strongly correlated on all 12 parameters, except for the Club Professional group at 10 feet, which only demonstrated strong correlations between 9 parameters. Overall and in the Top Professional group, most of the parameters were actually very strongly correlated ($r \geq 0.900$) which highlights the similarity between the five putt and session (ten putt) results

Although the three putt results correlated well with the session means, there were not enough strong and very strong correlations for the three putt results to be representative of golfers' overall performance. The five putts results gave a good representation of golfers' putting performance as the five putt means were strongly to very strongly correlated with the session means (ten putt) on almost every parameter. The analyses presented in this thesis were based on the full data set available for the session mean (ten putts) values. However, the high correlation between five and ten putts indicates that the smaller set could be used without anticipated detrimental effect; hence such approach should be considered in future studies.

5.3.5 Parameter Selection

The results of the Spearman correlation analyses for the overall population were instrumental in the determination of which parameters were included in the analysis of the putting vision strategy and can be found in Appendix A.

With respect to the putt phase duration parameters, putt duration was very strongly correlated with Preparation phase duration ($r=0.919$, $p<0.01$), which supports the earlier observation and demonstrates that the vast majority of golfers' time is spent in Preparation when putting. None of the other putt phase durations were strongly correlated with the total putt duration ($r=-0.131$ to 0.433, $p<0.01$ to $p>0.05$). Additionally, none of the putt phase duration parameters (including total put duration) were strongly correlated with any of the fixation parameters examined in the study (Address Fixations: $r=-0.226$ to 0.276; Swing Fixations: $r=-0.214$ to 0.266). The lack of correlation between these parameters indicated that putting vision strategy was independent of the length of time spent putting and that the simple measurements of putt and phase durations are not indicative of putting vision strategy. For this reason the putt duration parameters were not included in any further analyses.

Within the Address and Swing phases there were a number of parameters that were strongly correlated within each phase and between the phases. T_{FAQ} duration was strongly correlated with the Address Mean Ball Fixation Duration ($r=0.735$, $p<0.01$), which suggests that the duration of T_{FAQ} not only represents a unique fixation, but also represents the overall fixation strategy during the Address phase. T_{FS1} duration strongly correlated with the Swing Mean Ball Fixation Duration ($r=0.800$, $p<0.01$) and the Total Ball Fixation Duration ($r=0.764$, $p<0.01$) indicating, that T_{FS1}, much like T_{FAQ}, is not simply a unique fixation and is representative of the overall fixation strategy in the Swing phase. Additionally, the durations of T_{FAQ} and T_{FS1} were strongly correlated with each other ($r=0.802$, $p<0.001$) with other fixation parameters in both phases, including the Mean Fixation Duration in each phase and the Total Fixation Duration in the Swing. Furthermore, the Address Mean and Total Fixation Durations were strongly correlated with the Swing Mean and Total Fixation Durations ($r=0.711$ to 0.839, $p<0.001$).

The correlations between T_{FAQ} and T_{FS1} and the Address and Swing fixation parameters support the conclusion that T_{FAQ} and T_{FS1} are both unique fixations, representative of their respective phases. These results are of particular importance with respect to training golfers' putting vision strategies; the high correlations between T_{FAQ}, T_{FS1} and various parameters of the Address and Swing phases would suggest that Swing fixation strategy could be improved through training Address fixation strategy and vice versa.

The other key fixations (T_{FA1}, T_{FSQ}, T_{FCQ} or T_{FPQ}) were not correlated with each other, or with the Address and Swing fixation parameters ($r=-0.009$ to 0.420, $p<0.001$ to $p>0.05$). Although they were not highly correlated with other fixation parameters, these fixations were not excluded from the putting vision strategy analysis, as more investigation was needed to determine their relevance and importance.

Interestingly, hole fixation parameters were not correlated with ball fixation parameters in the Address ($r=-0.090$ to 0.130, $p>0.05$) and Swing phases ($r=-0.303$ to -0.233, $p<0.01$). The poor correlations between the hole and ball fixation parameters and the small number of hole fixations made during both the Address (Median=4) and Swing (Median =0) phases, suggests that fixations to the hole, as defined in this study, do not significantly impact putting vision strategy. This may be due, in part to the inherent lack of precision in the measurement of hole fixations in this study, as the eye tracking system used in this study was set up and calibrated to accurately measure ball fixations in putting gaze, rather than hole fixations which occurred in a side gaze position. Consequently, hole fixations were excluded from all further analyses of putting vision strategy.

The start and end times of each of the key fixations from T_0 were strongly correlated for each individual fixation, but they were not related to other key fixations, except for the start and end times of T_{FSQ} and T_{FCQ}. T_{FSQ} and T_{FCQ} were exceptions simply because of the definition of these fixations; when a fixation with a duration greater than 0.00ms occurred at contact it had to have started in the Swing phase, thus $T_{FCQ}=T_{FSQ}$. Despite the strong correlations between the start and end times of the individual key fixations, these parameters did not provide much information about the overall putting vision strategy; rather they simply indicated that the start and end times of each fixation were correlated with each other. For this reason, they were excluded from any further analyses of the putting vision strategy. Had the start and end times of the key fixations correlated with each other they may have been able to provide more information about the overall putting strategy.

Comparison of the right and left eye fixation parameters revealed that only the Total Number of Fixations ($r=0.776$) and the Total Fixation Duration (Spearman $r=0.778$) in Address were strongly correlated. No other parameters demonstrated strong correlations between the right and left eyes. The lack of correlation between right and left eye data indicated that eye needed to be considered as a factor in all further analyses. It also demonstrated that analysis of one eye only, as has been done previously in monocular studies, was based on an incorrect assumption that both eyes are acting in a similar manner.

5.3.6 Vision Strategies Associated with Skill and Success

The individual fixation parameters included in the analysis of the putting vision strategy were the durations of T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, and T_{FPQ}, the Total Number of Fixations made in the Address and Swing Phases, the Mean Fixation Duration in the Address and Swing phases, and the Total Fixation Duration in the Address and Swing phases. All of these parameters were ball fixation parameters. Table 5-4 summarises the parameters for each skill group.

Parameter	Top Professionals	Club Professionals	Amateurs
T_{FA1} Duration	50.4 ± 52.0	46.8 ± 50.6	27.4 ± 28.4
T_{FAQ} Duration	193.5 ± 197.8	69.5 ± 73.7	58.3 ± 100.8
T_{FS1} Duration	188.5 ± 198.9	60.7 ± 70.8	53.3 ± 99.5
T_{FSQ} Duration	52.7 ± 73.4	27.8 ± 24.1	21.8 ± 14.3
T_{FCQ} Duration	33.0 ± 72.2	9.3 ± 24.9	5.0 ± 13.0
T_{FPQ} Duration	29.7 ± 32.3	25.6 ± 17.4	20.2 ± 9.4
Total Number of Fixations (A)*	52.0 ± 16.9	35.2 ± 16.7	39.0 ± 27.0
Mean Fixation Duration (A)	62.2 ± 28.0	37.8 ± 14.7	30.7 ± 14.4
Total Fixation Duration (A)	3312.5 ± 1733.1	1316.7 ± 727.3	1435.1 ± 1368.0
Total Number Fixations (S)*	11.5 ± 4.1	10.2 ± 5.2	7.8 ± 5.4
Mean Fixation Duration (S)	72.3 ± 67.7	35.1 ± 292.7	28.8 ± 19.3
Total Fixation Duration (S)	694.8 ± 319.6	389.7 ± 292.7	281.4 ± 276.3

**Count data without units*

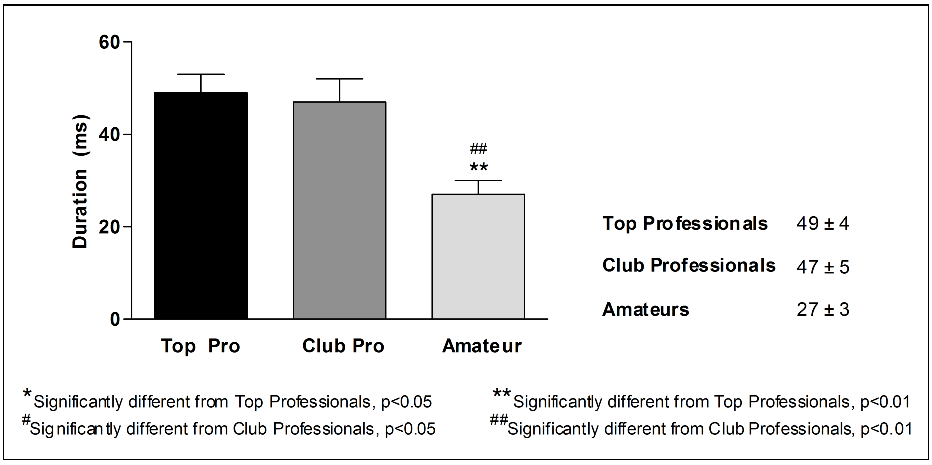
Table 5-4: Summary table displaying mean ± standard deviations of the parameters of importance in each skill group. All values are reported in milliseconds (ms) except for the Total Number of Ball Fixation parameters in the Address (A) and Swing (S) phases, which are reported without any units. Right and left eye data have been pooled for all fixation parameters; values are reported as mean ± standard deviation.

5.3.6.1 T_{FA1}

T_{FA1} was the first fixation made during the Address phase while golfers were in the process of lining their club up with the ball, and every golfer made a T_{FA1} fixation on every putt.

The multivariate analysis demonstrated that overall, skill was a significant factor affecting T_{FA1} duration ($p<0.001$), which was unaffected by putt distance (Skill*Putt Length interaction, $p=0.266$) or putting success (Skill*Putt Result interaction, $p=0.630$). Post-hoc Bonferroni comparisons found that overall T_{FA1} duration was similar in Top and Club Professionals ($p=1.000$), but was significantly shorter in the Amateurs compared with both Top ($p<0.001$) and Club ($p=0.002$) Professionals (Figure 5-1).

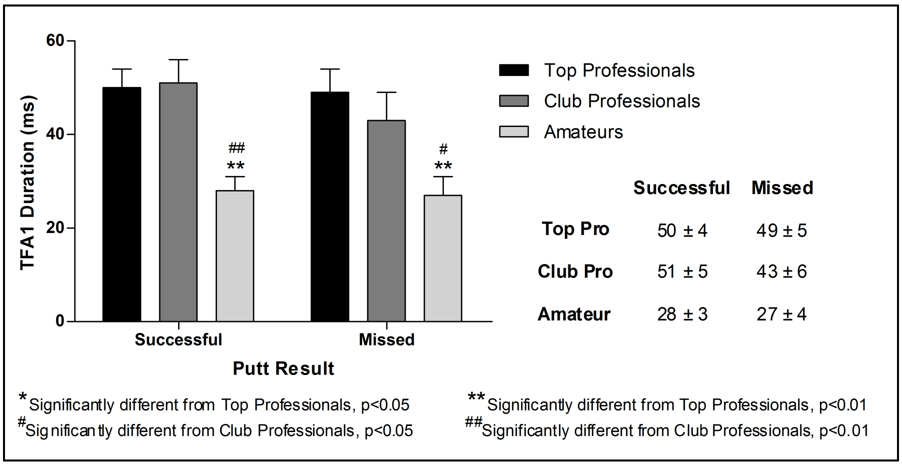
Figure 5-1: T_{FA1} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.



Overall, putt length did not affect the duration of T_{FA1} (p=0.216); putt length was unaffected by skill (Skill*Putt Length interaction, p=0.266) or putt outcome (Putt Length*Putt Result interaction, p=0.799).

Overall, T_{FA1} duration was not different for successful and missed putts (Success, 40±3ms[†]; Missed, 43±2ms[†], p=0.276), and the difference was unaffected by skill (Skill*Putt Result interaction, p=0.630) (Figure 5-2). As could be expected from the absence of a significant interaction between putt outcome and skill, T_{FA1} duration was not different between successful and missed putts in golfers of all skill levels (Top, p=0.851; Club, p=0.216, Amateurs, p=0.778). Hence, T_{FA1} duration is not capable of differentiating successful and missed putts.

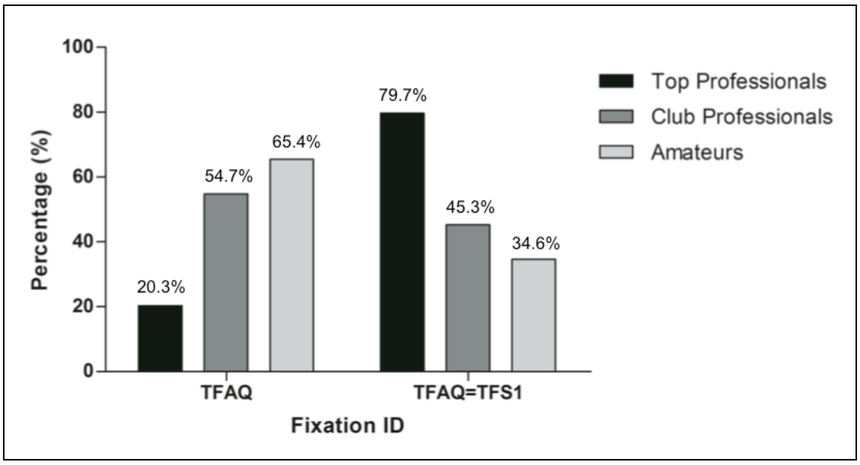
Figure 5-2: T_{FA1} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and missed putts.



5.3.6.2 T_{FAQ}

T_{FAQ} was the last fixation made in the Address phase; when T_{FAQ} lasted into the Swing phase then $T_{FAQ}=T_{FS1}$. $T_{FAQ}=T_{FS1}$ significantly more often in Top Professionals than either of the other groups ($p<0.001$). The difference in $T_{FAQ}=T_{FS1}$ distribution between the Club Professionals and Amateurs was also significant ($p=0.006$) (Figure 5-3).

Figure 5-3: Distribution of fixation IDs for T_{FAQ}.



Overall, skill was a significant factor affecting T_{FAQ} duration ($p<0.01$), which was highly dependent on the putt result (Skill*Putt Result interaction, $p=0.007$) but the difference was unaffected by the putt length (Skill*Putt Length interaction, $p=0.808$). T_{FAQ} was significantly longer in Top Professionals than Club Professionals ($p<0.001$) and Amateurs ($p<0.001$). T_{FAQ} was not different between Club Professionals and Amateurs ($p=1.000$) (Figure 5-4).

Putt length (overall) was not a significant factor for T_{FAQ} duration ($p=0.672$) and was independent of golfers' skill (Skill*Putt Length interaction, $p=0.808$) and putting success (Putt Length*Putt Result interaction, $p=0.577$).

T_{FAQ} fixations were longer on successful putts overall (Success, $113\pm10ms^{\dagger}$; Miss, $94\pm11ms^{\dagger}$, $p=0.023$), however the putt outcome effect was highly skill dependent (Skill*Putt Result interaction $p=0.007$) (Figure 5-5). Examination of the post-hoc Bonferroni comparisons revealed that T_{FAQ} duration was significantly longer in Top Professionals on successful putts compared with missed putts ($p<0.001$); in Club Professionals ($p=0.655$) and Amateurs ($p=0.465$) T_{FAQ} duration was not different on successful and missed putts.

Figure 5-4: T_{FAQ} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.

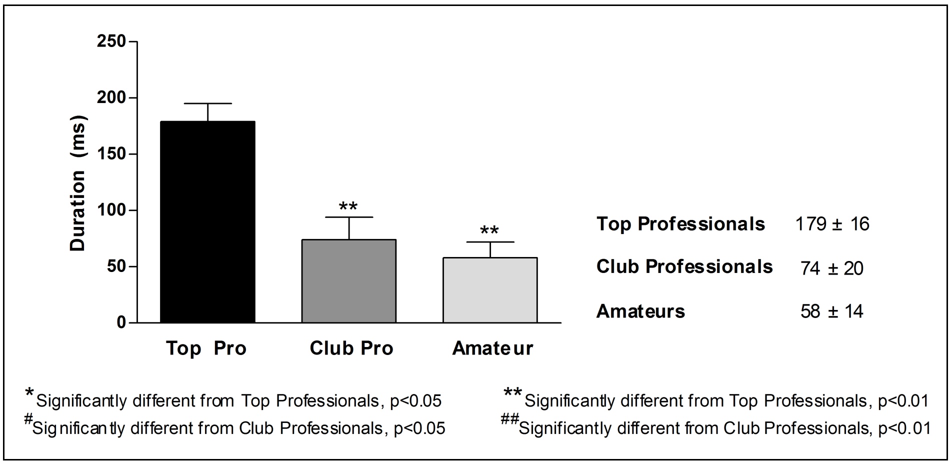
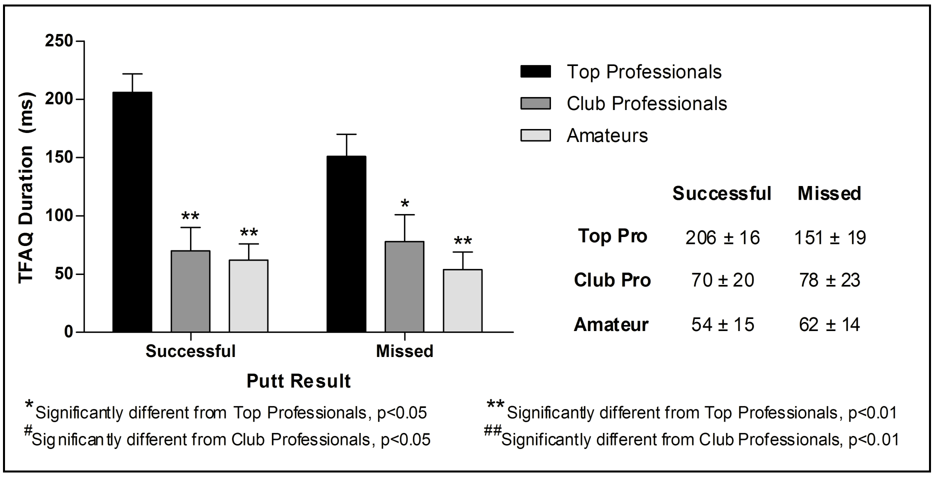


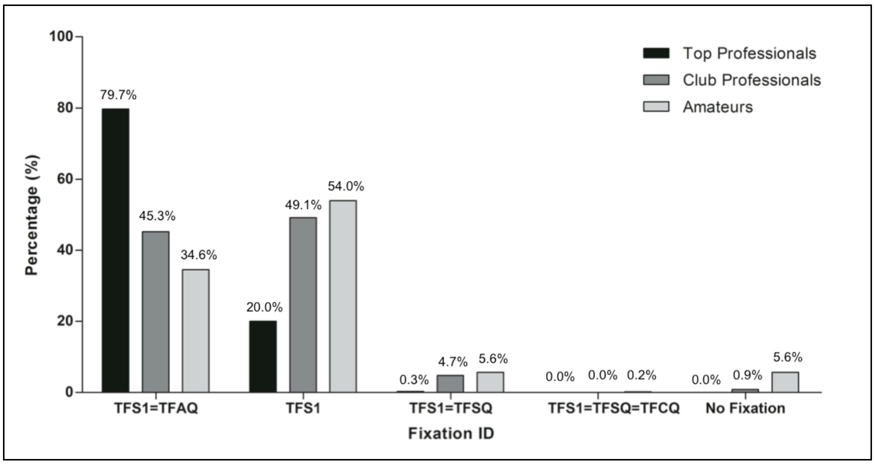
Figure 5-5: T_{FAQ} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and missed putts.



5.3.6.3 T_{FS1}

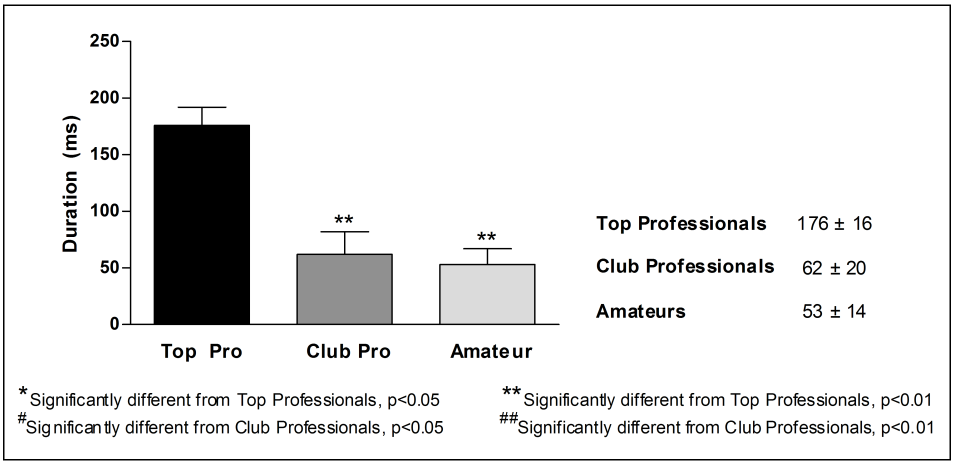
T_{FS1} was the first fixation made in the Swing phase. If it started before the Swing phase, than T_{FS1} was also the last fixation made in the Address (T_{FAQ}=T_{FS1}). If T_{FS1} lasted throughout the Swing phase than it was possible for T_{FS1}=T_{FSQ}, or T_{FS1}=T_{FSQ}=T_{FCQ}. The distribution of T_{FS1} was significantly different between Top and Club Professionals ($p<0.001$), between Top Professionals and Amateurs ($p<0.001$), and between Club Professionals and Amateurs ($p=0.005$) (Figure 5-6).

Figure 5-6: Distribution of fixation IDs for T_{FS1}.



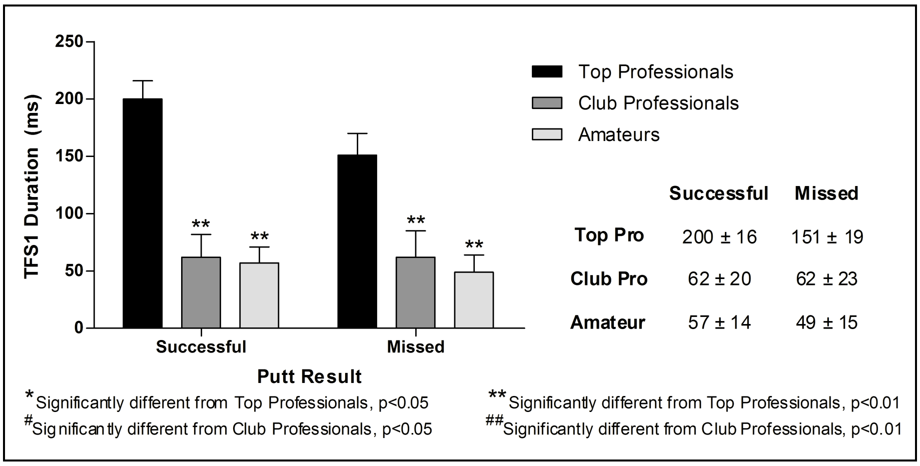
Overall, T_{FS1} duration was significantly affected by Skill (p<0.001); the effect was independent of putt length (Skill*Putt Length interaction, p=0.871) but highly dependent on the putt result (Skill*Putt Result interaction, p=0.032). T_{FS1} was significantly longer in Top Professionals than in Club Professionals (p<0.001) or Amateurs (p<0.001); T_{FS1} duration was similar in Club Professionals and Amateurs (p=1.000) (Figure 5-7).

Figure 5-7: T_{FS1} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.



T_{FS1} duration overall differed depending on the putt outcome (Success, 106±10ms†; Miss, 88±11ms†, p=0.021); the effect of putt outcome on T_{FS1} was highly skill dependent (Skill*Putt Result interaction, p=0.032). In Top Professionals T_{FS1} was significantly longer on successful putts compared with missed putts (p=0.001), but in both Club Professionals (p=0.992) and Amateurs (p=0.478) this difference was not found (Figure 5-8).

Figure 5-8: T_{FS1} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and missed putts.

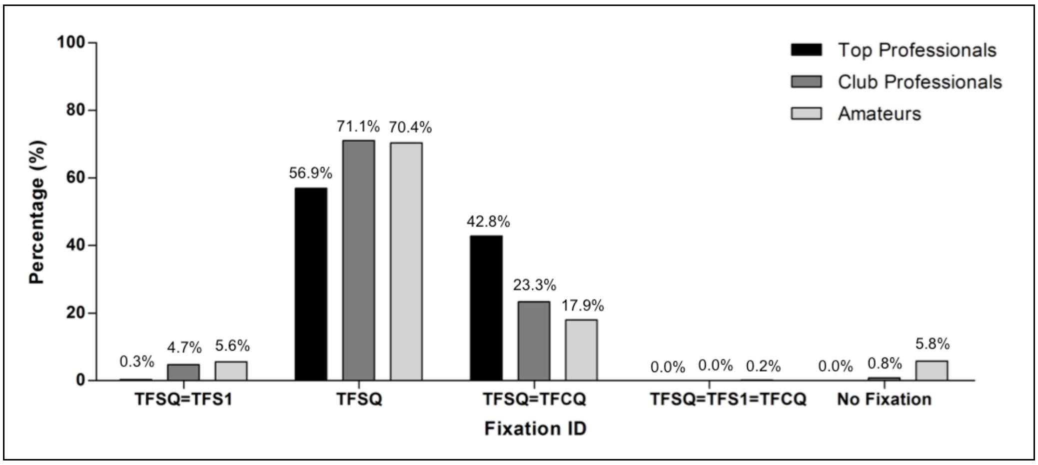


5.3.6.4 T_{FSQ}

T_{FSQ} was the last fixation made in the Swing phase. If T_{FSQ} started early enough in the Swing phase T_{FS1}=T_{FSQ}, and if T_{FSQ} lasted through contact, T_{FSQ}=T_{FCQ}. It was possible for T_{FS1}=T_{FSQ}=T_{FCQ} although this was uncommon. It was also possible for no fixation to be recorded at T_{FSQ} (T_{FSQ}=0.000ms). The distributions of T_{FSQ} were significantly different between Top and Club Professionals (p<0.001), between Top Professionals and Amateurs (p<0.001) and between Club Professionals and Amateurs (p=0.016) (Figure 5-9). Clearly, T_{FSQ}=T_{FS1} was uncommon for all skill groups, but T_{FSQ}=T_{FCQ} was much more common occurrence Top Professional group than either the Club Professionals or Amateurs, and demonstrates that Top Professionals maintained fixations of greater stability at the critical time points just prior to and at contact.

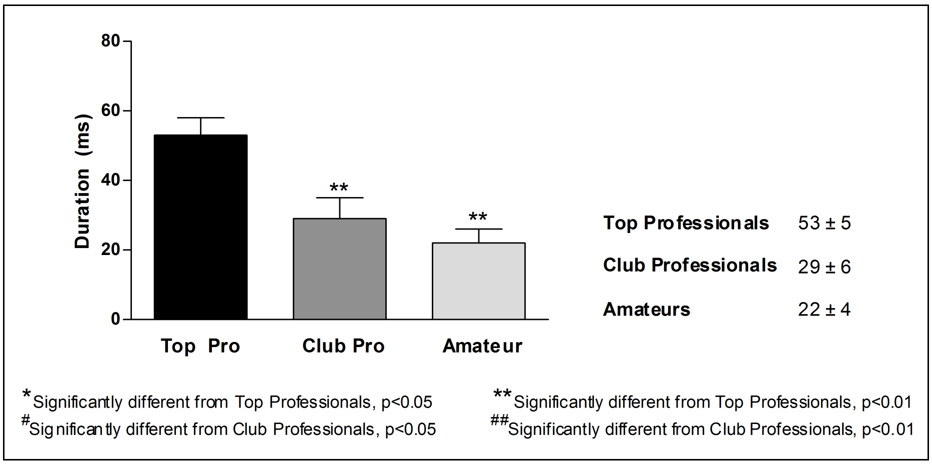
Overall, the duration of T_{FSQ} was significantly different between skill groups; as a factor, skill was independent of putt length (Skill*Putt Length interaction, p=0.814) and putt result (Skill*Putt Result interaction, p=0.858). Post-hoc Bonferroni comparisons demonstrated that Top Professionals had significantly longer T_{FSQ} than both Club Professionals (p=0.006) and Amateurs (p<0.001) and that T_{FSQ} duration was similar for Club Professionals and Amateurs (p=0.882) (Figure 5-10).

Figure 5-9: Distribution of fixation IDs for T_{FSQ}.



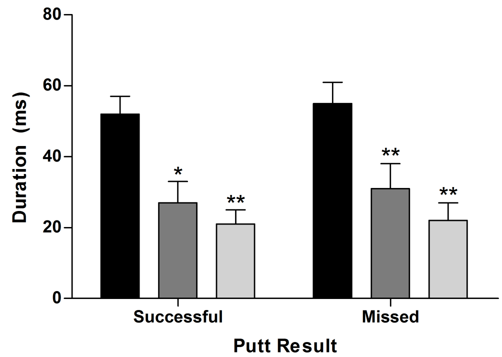
Putt length (overall) was not a significant factor affecting T_{FSQ} duration (p=0.268), irrespective of golfer's skill (Skill*Putt Length interaction, p=0.814) or the putt outcome (Putt Length*Putt Result interaction, p=0.714).

Figure 5-10: T_{FSQ} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.



Putt outcome (overall) was not a significant factor for T_{FSQ} duration either (Success, 33±3ms†; Miss, 36±3ms†; p=0.382), and was independent of golfers' skill (Skill*Putt Result interaction, p=0.858) (Figure 5-11). As could be expected from the absence of a significant interaction between putt outcome and skill within each skill group, T_{FSQ} duration was not different between successful and missed putts in any of the skill groups (Top, p=0.535; Club, p=0.517, Amateurs, p=0.883), and T_{FSQ} was not a differentiating factor between successful and missed putts.

Figure 5-11: T_{FSQ} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and missed putts.



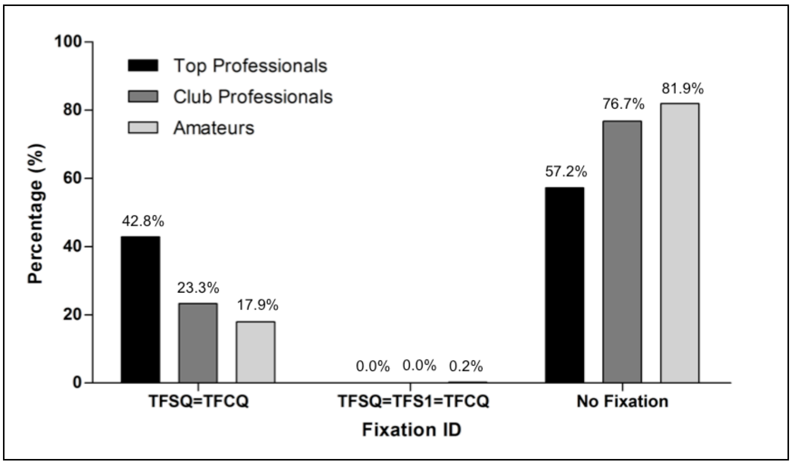
	Successful	Missed
Top Pro	52 ± 5	55 ± 6
Club Pro	27 ± 6	31 ± 7
Amateur	21 ± 4	22 ± 5

*Significantly different from Top Professionals, p<0.05
**Significantly different from Top Professionals, p<0.01
#Significantly different from Club Professionals, p<0.05
##Significantly different from Club Professionals, p<0.01

5.3.6.5 T_{FCQ}

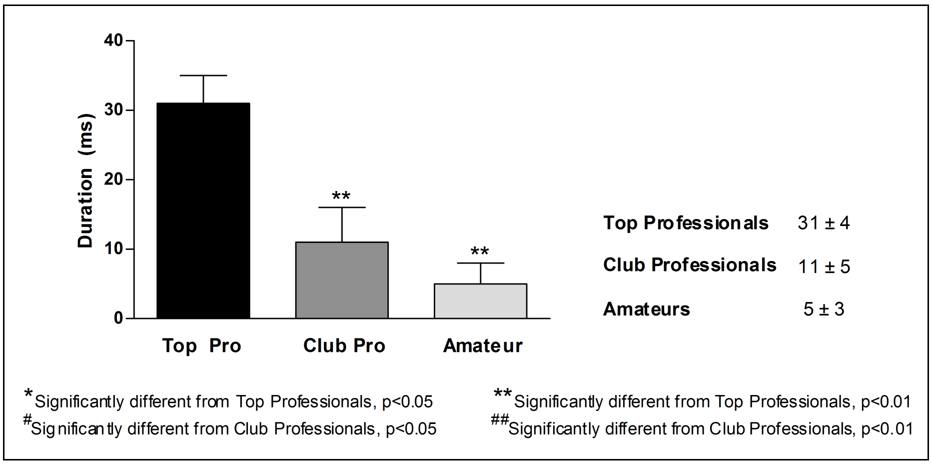
T_{FCQ} was the fixation that occurred at contact (T_0). If a fixation occurred at contact, it needed to start at least one frame before contact, making T_{FCQ}=T_{FSQ}. When a fixation did not occur at contact, T_{FCQ}=0.000ms. Significantly more Top Professionals had fixations at contact than Club Professionals (p=0.000) or Amateurs (p=0.000). There was no difference in the number of T_{FCQ} fixations made by the Club Professionals and Amateurs (p=0.193) (Figure 5-12).

Figure 5-12: Distribution of fixation IDs for T_{FCQ}.



Skill was a significant factor in T_{FCQ} duration (p<0.001), but was unaffected by the putt length (Skill*Putt Length interaction, p=0.885) or the putt outcome (Skill*Putt Result interaction, p=0.209). Top Professionals had the longest duration fixations, which were significantly longer than those of Club Professionals (p=0.009) or Amateurs (p<0.001). No difference in T_{FCQ} fixation duration was recorded between the Club Professionals and the Amateurs (p=0.867) (Figure 5-13).

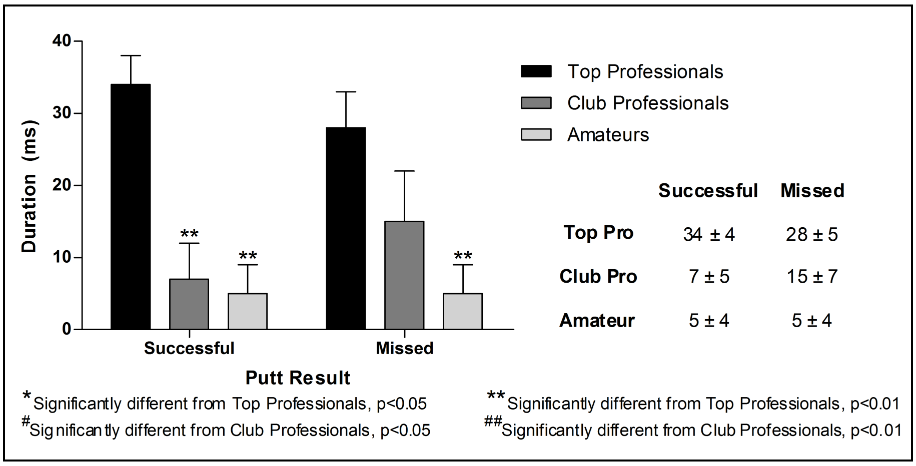
Figure 5-13: T_{FCQ} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.



Overall, putt length was not a significant factor affecting T_{FCQ} duration (p=0.419). Furthermore, the absence of significant interactions confirms an absence of a putt length effect (Skill*Putt Length interaction, p=0.885; Putt Length*Putt Result interaction, p=0.720).

Overall, putt outcome was not a significant factor for T_{FCQ} duration (Success, 15±3ms†; Missed, 16±3ms†, p=0.900) and was independent of skill (Skill*Putt Result interaction, p=0.209) (Figure 5-14). The lack of a significant interaction indicates that T_{FCQ} had a similar duration on successful and missed putts in all skill groups (Top, p=0.220; Club, p=0.201; Amateur, p=0.908) and that T_{FCQ} duration is not a differentiating factor for putting success.

Figure 5-14: T_{FCQ} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and missed putts.



5.3.6.6 T_{FPQ}

T_{FPQ} was the first fixation that started immediately after contact. If there was a fixation at contact (T_{FCQ}) than T_{FPQ} was the first fixation that started immediately after T_{FCQ} ended. All golfers had a T_{FPQ} recorded on every putt, except for one Amateur golfer who did not have a T_{FPQ} fixation recorded on one putt.

Skill was a significant factor affecting T_{FPQ} duration (p<0.001), and the effect was independent of putt distance (Skill*Putt Length interaction, p=0.720) and putt result (Skill*Putt Result interaction, p=0.166). Top and Club Professionals had similar T_{FPQ} durations (p=1.000); T_{FPQ} was significantly longer in both professional groups than in Amateurs (Top, p<0.001; Club, p=0.017) (Figure 5-15).

Putt length (overall) was not a significant factor affecting T_{FPQ} duration (p=0.493) and was independent of the other factors (Skill*Putt Length interaction, p=0.720; Putt Length*Putt Result interaction, p=0.940).

Putt outcome (overall) was not a significant factor for T_{FPQ} (Success, 25±1ms†; Miss, 25±1ms†, p=0.557), and the outcome was independent of golfers' skill (Skill*Putt Result interaction, p=0.166) (Figure 5-16). The lack of a significant interaction indicates that T_{FPQ}, much like T_{FCQ} had a similar duration on successful and missed putts in all skill groups (Top, p=0.067; Club, p=0.355; Amateur, p=0.648), although there was a trend towards T_{FPQ} being longer on successful putts in Top Professionals. Despite this trend, T_{FPQ} is not a differentiating factor for successful and missed putts overall.

Figure 5-15: T_{FPQ} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.

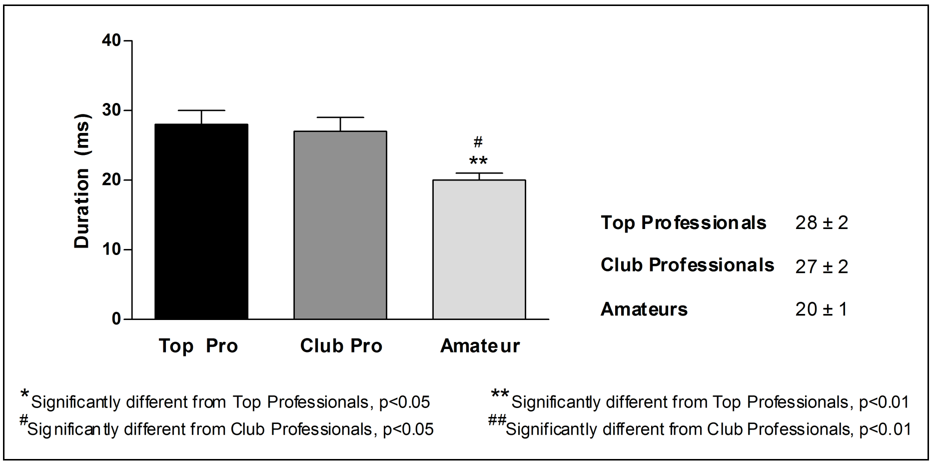
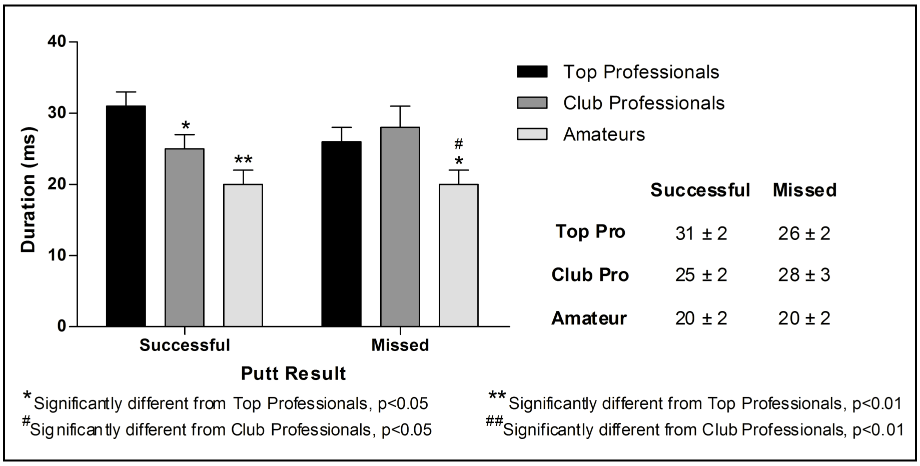


Figure 5-16: T_{FPQ} duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and missed putts.



5.3.6.7 Address Phase

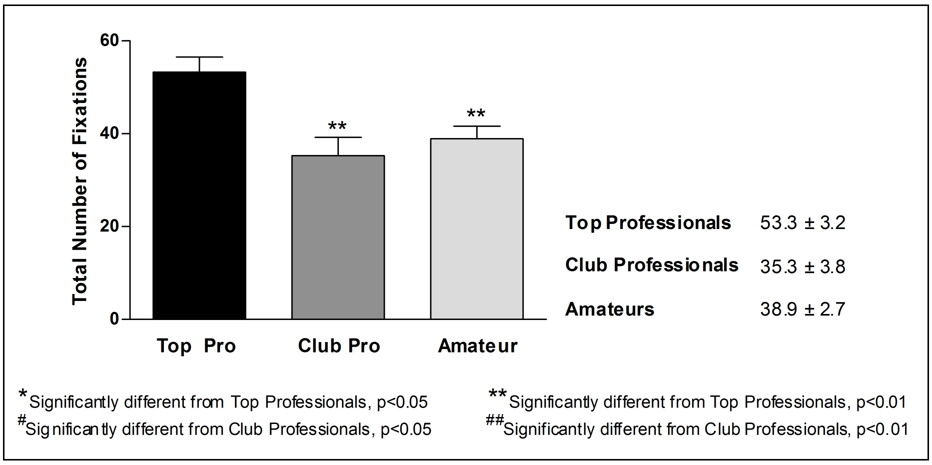
Address is the phase of the putt in which the club is lined up with the ball, prior to the start of the backswing. Skill had a significant overall effect on the length of the phase (p=0.006), which on average had a duration of 6621±2154ms. Amateurs (7174±268ms†) had a significantly longer Address phases than Club Professionals (5530±384ms†; p=0.004) and similar length Address phases as Top Professionals (6623±331ms†; p=0.598). In Top and Club Professionals, the Address phase duration was similar (p=0.160).

5.3.6.7.1 Address Phase Fixation Parameters

Within the Address phase, three specific fixation parameters were considered: the Total Number of Fixations, the Mean Fixation Duration and the Total Fixation Duration of fixations made to the ball. Overall, all three of these fixation parameters were significantly affected by skill (Total Number, $p<0.001$; Mean Duration, $p<0.001$; Total Duration, $p<0.001$). The skill effect was independent of putt length for all three parameters (Skill*Putt Length interaction: Total Number, p=0.916; Mean Duration, p=0.999; Total Duration, p=0.982), but dependent on the putt outcome for the Total Number of Fixations (Skill*Putt Result interaction, $p<0.001$) and the Total Fixation Duration (Skill*Putt Result interaction, p=0.009). There was a trend towards the skill effect being dependent on putt outcome for the Mean Fixation Duration (Skill*Putt Result interaction, p=0.057) as well.

Top Professionals made significantly more fixations during Address than Club Professionals (p=0.001) or Amateurs (p=0.002), yet Club Professionals and Amateurs made a similar number of fixations (p=1.000) (Figure 5-17). Despite the Amateur group having the longest Address phase, they did not make the most number of fixations, which indicates that the number of fixations made during Address is not the only factor influencing the Total Fixation Duration in Address, at least in Amateurs.

Figure 5-17: Total Number of Fixations in Address (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.



Top Professionals also had significantly longer Mean and Total Fixation Durations than both Club Professionals (Mean, p<0.001; Total, p<0.001) and Amateurs (Mean, p<0.001; Total, p<0.001). Mean (p=0.242) and Total (p=1.000) Fixation Durations were similar in Club Professionals and Amateurs (Figures 5-18 and 5-19).

Overall, putt length was not significant for the Total Number of Fixations (p=0.565), Mean Fixation Duration (p=0.912) or Total Fixation Duration (p=0.715) and putt length was independent of other effects (Skill*Putt Length interaction: Total Number, p=0.916; Mean Duration, p=0.999; Total Duration, p=0.982; Putt Length*Putt Result interaction: Total Number, p=0.420; Mean Duration, p=0.830; Total Duration, p=0.159).

Figure 5-18: Mean Duration of Address Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.

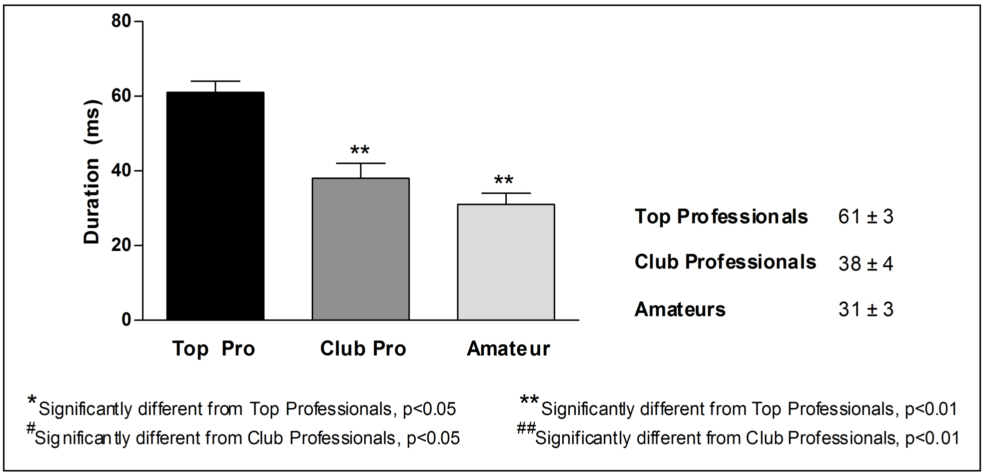
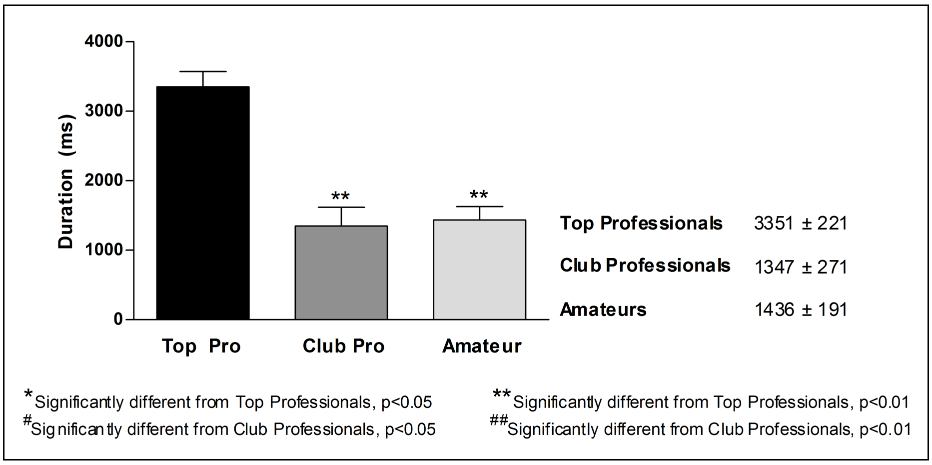


Figure 5-19: Total Duration of Address Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.



Putt outcome (overall) was not a significant factor in the Total Number of Fixations (p=0.130), however the effect of skill on putt outcome was significant (Skill*Putt Result interaction, p<0.001). Post-hoc Bonferroni comparisons found that Top Professionals made significantly fewer total fixations on successful putts than on missed putts (p<0.001), whereas Club Professionals (p=0.182) and Amateurs (p=0.802) made a similar number of fixations on successful and missed putts (Figure 5-20). Additionally, Top Professionals made significantly more fixations on both successful and missed putts than either Club Professionals (Success, p=0.009; Missed, p<0.001) or Amateurs (Success, p=0.011; Missed, p<0.001). Making more fixations during the Address is associated with higher skill, but more fixations are also associated with missed putts. Therefore there appears to be a limit to the number of fixations in Address that are beneficial.

Putt outcome (overall) was a significant factor for the Mean Fixation Duration (Success, 44±2†; Miss, 43±2†; p=0.019) and there was a trend towards the effect being dependent upon skill (Skill*Putt Result interaction, p<0.057). Examination of the post-hoc Bonferroni comparisons revealed that Top Professionals had significantly longer Mean Fixation Durations on both successful and missed putts compared with Club Professionals (Success and Missed, p<0.001) and Amateurs (Success and Missed, p<0.001). Top Professionals made significantly longer fixations on successful putts as well (Success, 69±3ms†; Missed, 59±3ms†, p=0.002); Mean Fixation Duration was similar in Club Professionals (p=0.558) and Amateurs (p=0.800) regardless of the outcome (Figure 5-21).

Figure 5-20: Total Number of Fixations in Address (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on Successful and Missed putts.

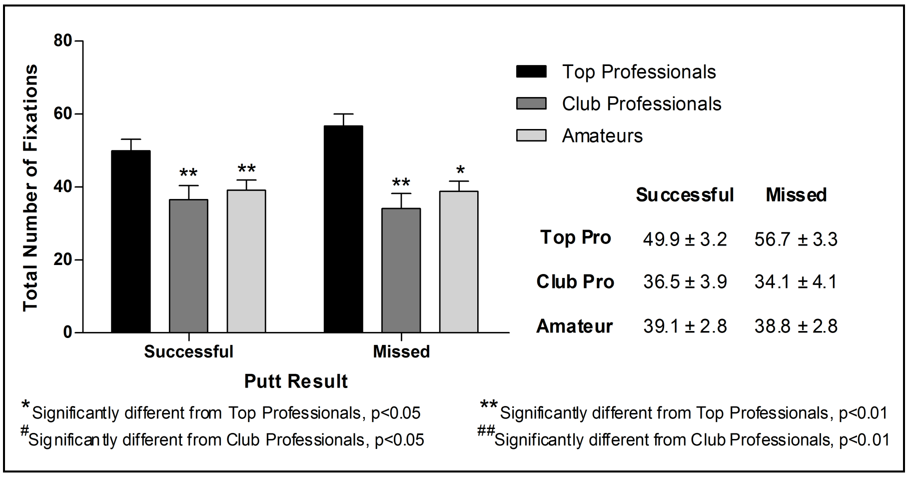
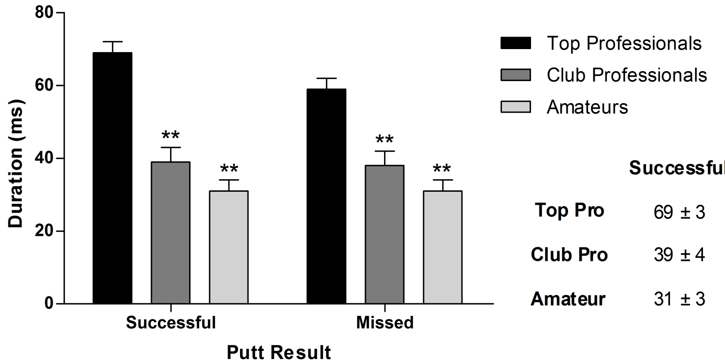


Figure 5-21: Mean Duration of Address Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on Successful and Missed putts.

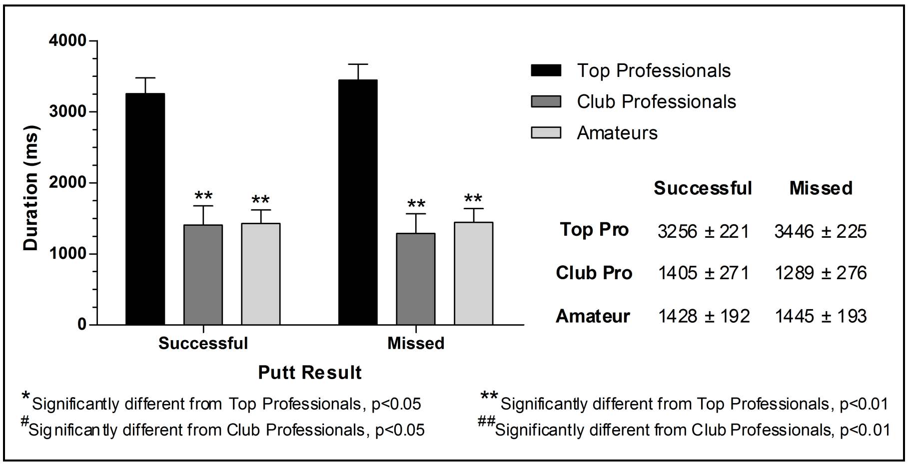


	Successful	Missed
Top Pro	69 ± 3	59 ± 3
Club Pro	39 ± 4	38 ± 4
Amateur	31 ± 3	31 ± 3

*Significantly different from Top Professionals, p<0.05
**Significantly different from Top Professionals, p<0.01
#Significantly different from Club Professionals, p<0.05
##Significantly different from Club Professionals, p<0.01

Putting success (overall, p=0.421) was not a significant factor for Total Fixation Duration either (Success, 2030±133ms†; Miss, 2060±135ms†) although the effect on Total Fixation Duration was highly dependent upon golfers' skill (Skill*Putt Result interaction, p=0.009). Total Fixation Duration was significantly shorter on successful putts in Top Professionals (p=0.005); in Club Professionals and Amateurs Total Fixation Duration was similar on successful and missed putts (Club, p=0.129; Amateurs, p=0.727). In addition, Total Fixation Duration was significantly longer in Top Professionals than both Club Professionals (Success and Missed, p<0.001) and Amateurs (Success and Missed, p<0.001), irrespective of the putt outcome; in Club Professionals and Amateurs Total Fixation Duration was similar (Success, p=0.945; Missed, p=0.645) (Figure 5-22). Once again there appears to be a limit to the amount of time that should be spent fixating the ball during the Address. A longer Total Fixation Duration is associated with higher skill, but it is also associated with missed putts in highly skilled golfers.

Figure 5-22: Total Duration of Address Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on Successful and Missed putts.



5.3.6.8 Swing Phase

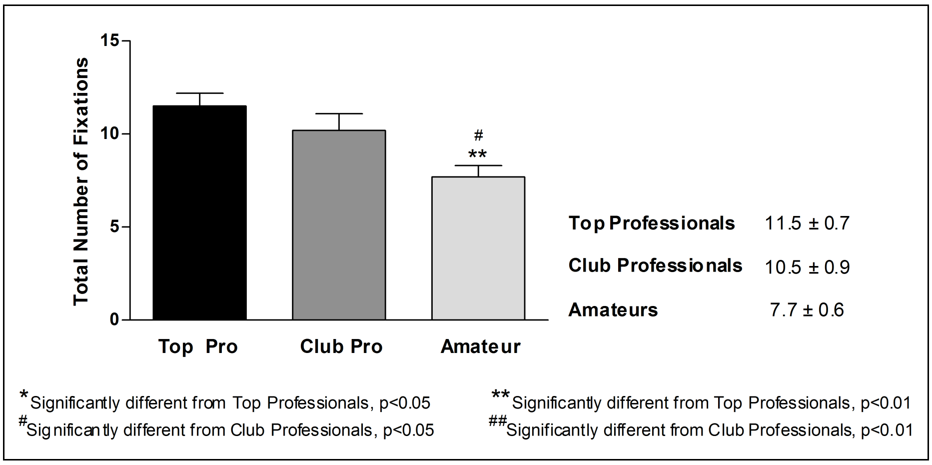
The Swing phase of the putt starts with the initiation of the backswing and ends with ball contact. On average the length of the Swing phase was 975±161ms. Overall, skill had a significant effect on the length of the Swing phase (p=0.049) but the post-hoc Bonferroni comparisons between skill levels were not significant. The Swing phase duration of Top Professionals (935±33ms†) was similar to Club Professionals (951±38ms†, p=1.000). The Swing phase duration in Amateurs (1031±26ms†) was similar to both Club (p=0.255) and Top Professionals (p=0.073), although there was a trend towards the Swing phase being shorter in Top Professionals.

5.3.6.8.1 Swing Phase Fixation Parameters

The same three fixation parameters (Total Number of Fixations, Mean Fixation Duration, Total Fixation Duration) analysed in the Address phase were examined in the Swing phase. Overall, skill was a significant factor or all three of the parameters (Total Number, p<0.001; Mean Duration, p<0.001, Total Duration, p<0.001). This effect was independent of putt length (Skill*Putt Length interaction: Total Number, p=0.937; Mean Duration, p=0.990; Total Duration, p=0.911) for all three parameters. The effect was also independent of putt outcome for Mean Fixation Duration (Skill*Putt Result interaction, p=0.702) and Total Fixation Duration (Skill*Putt Result interaction, p=0.203), but the effect of skill was highly dependent on putt outcome for the Total Number of Fixations (Skill*Putt Result interaction, p=0.010).

Unlike in the Address phase, both Top and Club Professionals made a similar number of fixations (p=1.000) in the Swing phase, and both groups made significantly more fixations than Amateurs (Top, p<0.001; Club, p=0.033) (Figure 5-23).

Figure 5-23: Total Number of Fixations in the Swing (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.



Despite the similarity between Top and Club Professionals for the Total Number of Fixations, Top Professionals recorded significantly longer Mean and Total Fixation Durations than Club Professionals (Mean, p<0.001; Total, p<0.001). For Top Professionals, Mean and Total Fixation Durations were also significantly longer than Amateurs (Mean, p<0.001; Total, p<0.001). Furthermore, Mean (p=1.000) and Total (p=0.153) Fixation Durations were similar in Club Professionals and Amateurs (Figures 5-24 and 5-25).

Putt length (overall) was not significant for the Total Number of Fixations (p=0.725), Mean Fixation Duration (p=0.941) or Total Fixation Duration (p=0.881) in the Swing phase. The effect of putt length was independent of skill (Skill*Putt Length interaction: Total Number, p=0.937; Mean Duration, p=0.990; Total Duration, p=0.911) and putt outcome (Putt Length*Putt Result interaction: Total Number, p=0.498; Mean Duration, p=0.610; Total Duration, p=0.559).

Figure 5-24 Mean Duration of Swing Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.

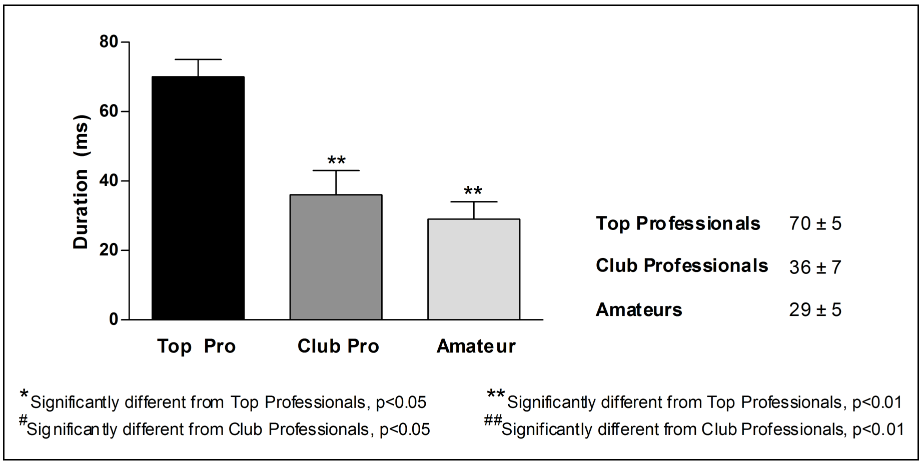
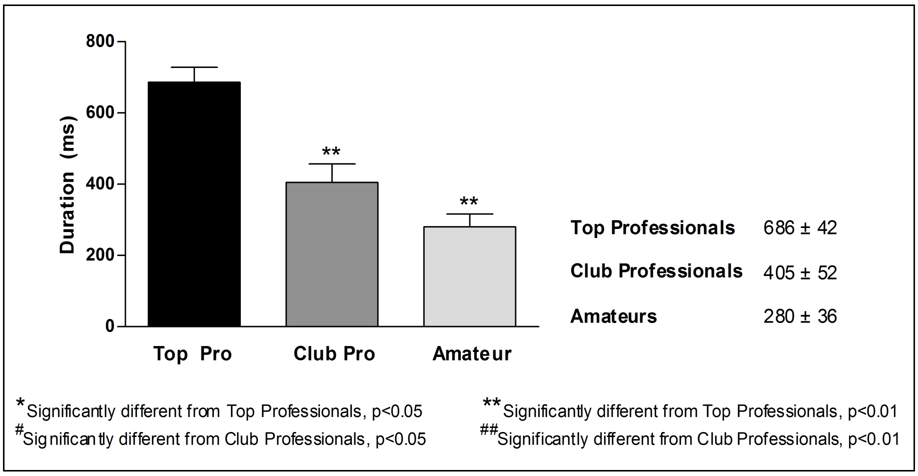
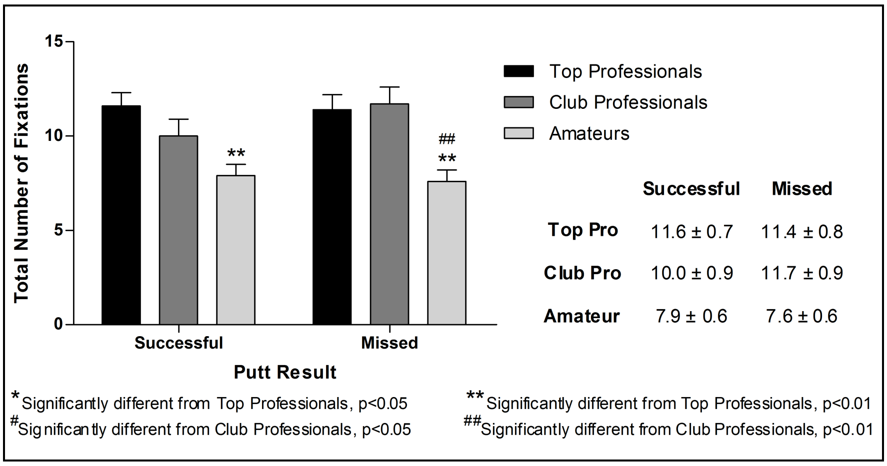


Figure 5-25: Total Duration of Swing Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs.



Putt outcome (overall) was not significant for the Total Number of Fixations in the Swing (p=0.317) but the effect was dependent on golfer's skill (Skill*Putt Result interaction, p=0.010). Examination of the post-hoc Bonferroni comparisons demonstrated that Amateurs made significantly fewer fixations than both Top (Success and Missed, p<0.001) and Club Professionals (Success, p=0.055; Missed, p=0.002) although the difference from Club Professionals only trended towards significance on successful putts (Figure 5-26). Top and Club Professionals made a similar number of fixations (Success, p=0.144; Missed, p=0.802). Additionally, Club Professionals made significantly fewer fixations on successful putts (p=0.006); no difference in the number of fixations made on successful and missed putts was found in Top Professionals (p=0.453) or Amateurs (p=0.313).

Figure 5-26: Total Number of Fixations in the Swing (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and missed putts.



Putt outcome (overall) was not significant for the Mean (Success, 46±3ms†; Miss, 44±4ms†; p=0.372) or Total (Success, 460±26ms†; Miss, 454±27ms†; p=0.676) Fixation Durations, and the effects of putt outcome were independent of skill (Skill*Putt Result interaction: Mean Duration, p=0.702; Total Duration, p=0.203) (Figures 5-27 and 5-28). The lack of significant interaction was confirmed by examination of the post-hoc comparisons, which demonstrated that both Mean Fixation Duration (Top, p=0.250; Club, p=0.873; Amateur, p=0.817) and Total Fixation Duration (Top, p=0.166; Club, p=0.264; Amateur, p=0.405) were similar between successful and missed putts in all skill groups.

Figure 5-27: Mean Duration of Swing Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and missed putts.

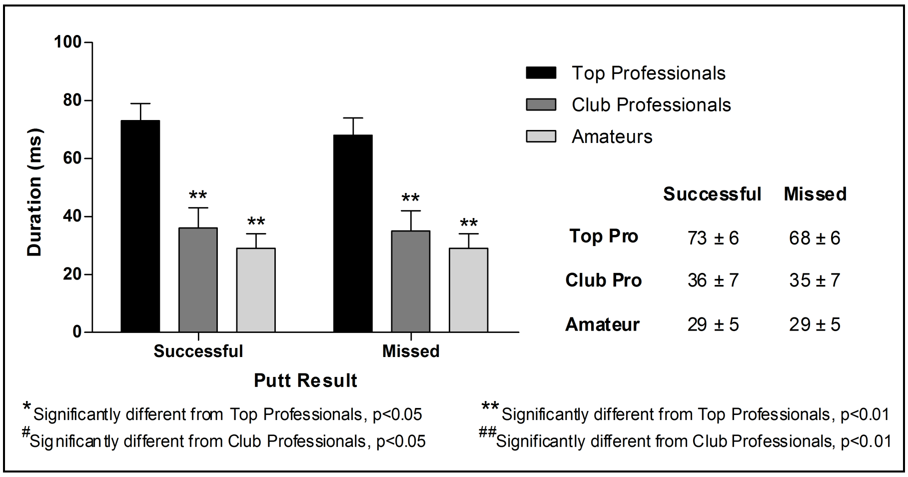
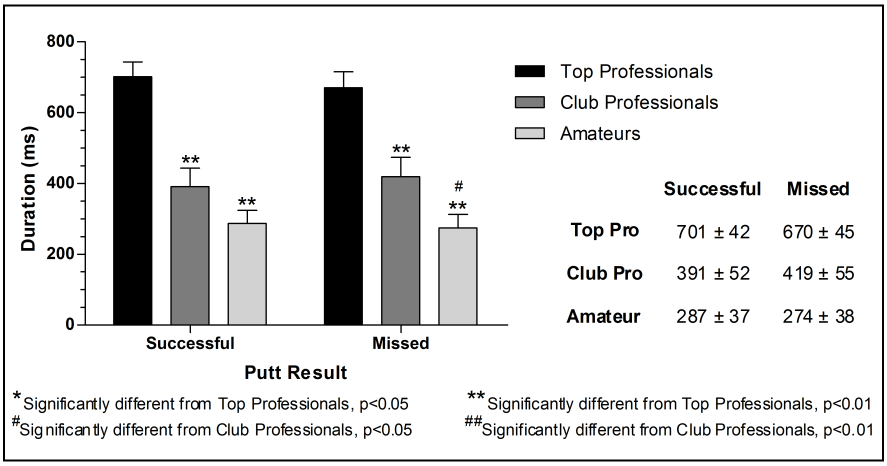


Figure 5-28: Total Duration of Swing Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs on successful and unsuccessful putts.



One important conclusion that was drawn from these preliminary results was that fixations measured with a 0.5° visual angle, minimum gaze time 16.67ms fixation criteria were much shorter than those measured with a 3.0° visual angle, minimum gaze time 100ms fixation criteria. T_{FAQ}, which was similar to the Quiet Eye defined by Vickers (1992), had a mean duration in the Top Professional group of 193.5ms. Vickers found the Quiet Eye to be 1788ms in Low Handicap (higher skilled) golfers.[28] Moreover, golfers in this study made significantly more fixations during the Address (Top Professionals 52.0, Club Professionals 35.2, Amateurs 39.0) and Swing (Top Professionals 11.5, Club Professionals 10.2, Amateurs 7.8) phases than they did in Vickers study (Address: Low Handicap 7.3, High Handicap 10.6; Swing: Low Handicap 1.5, High Handicap 2.9).[28] Hence, the revised fixation criteria used in this study has allowed for the capture of significantly more short fixations which have never before been investigated.

5.3.7 CHAID Analysis

Chi-squared automatic interaction detection (CHAID) analysis was the final analysis used in the examination of putting vision strategies. CHAID is a predictive type of analysis that allows for the combination of gaze behaviour factors with population and environmental factors such as skill level, ocular dominance and putt length. The purpose of this analysis was to explore which characteristics of the population would be most highly associated with putting success. Initially, an exhaustive CHAID was conducted on the entire population; afterwards each skill group was looked at individually to see if associations with success differed in the three populations and each putt length was examined to determine if the vision strategy associated with success was different on short and long putts.

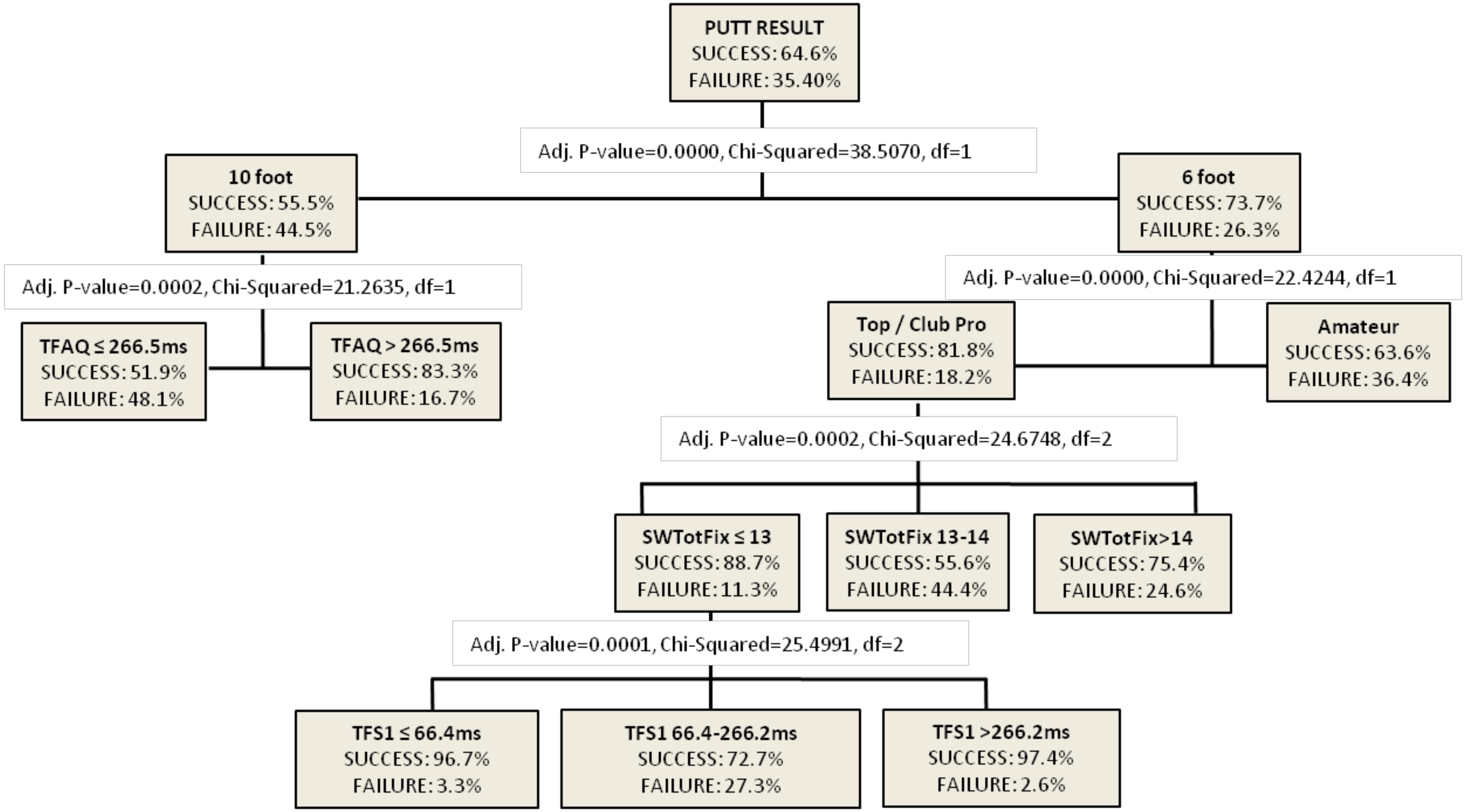
Overall, the most significant factor in putting success was the length of the putt. Golfers had a significantly higher success rate on 6 foot putts than they did on 10 foot putts ($p<0.0001$) (Figure 5-29).

On 10 foot putts, the next differentiating factor in determining putting success was the length of the last fixation of the Address (T_{FAQ}). T_{FAQ} durations of greater than 267ms were associated with a significantly higher success rate than shorter T_{FAQ} durations ($p=0.0002$). In golfers with T_{FAQ} fixation durations greater than 267ms, the success rate was over 80% versus 50% success in golfers with for T_{FAQ} fixation durations shorter than 267ms.

On 6 foot putts, the second most significant factor in determining success was a golfer's skill. Professionals (Top and Club) had higher success rates as expected and Amateurs were significantly less successful ($p<0.0001$). For Amateur golfers, no additional factors were identified. For Professional golfers, the next factor associated with higher success was the Total Number of Fixations made during the Swing. Making 13 or fewer fixations slightly increased the success rate of golfers. For golfers who made 13 or fewer fixations, the duration of the first fixation in the Swing (T_{FS1}) was highly influential in success. T_{FS1} durations of ≤66.4ms and >266.2ms were almost equally associated with success (>95%), whereas T_{FS1} durations of 66.4-266.2ms were associated with significantly lower rates of success ($p=0.0001$). Both T_{FS1} strategies (T_{FS1}<67ms and T_{FS1}>267ms) were found to improve success.

In considering the population as a whole, these results clearly demonstrate that the factors that improve success on 6 and 10 foot putts are different. For 10 foot putts, the factor associated with the greatest success in golfers of all skill levels, and which should be focused on in training, is the duration of the last Address fixation (T_{FAQ}). For 6 foot putts, the factors associated with success are not universal, therefore training is dependent on golfers' skill level. For professional golfers, making fewer fixations in the Swing phase appears to be beneficial. Additionally training for either a short (66ms or less) or long (267ms or greater) fixation at the beginning of the Swing phase would produce the best results. For Amateur golfers, no specific parameters were identified which should be trained to improve efficiency.

Figure 5-29: CHAID tree displaying results of CHAID analysis on the entire population of golfers (ADTotDur = Address Total Fixation Duration; SWTotFix = Swing Total Number of Fixations).



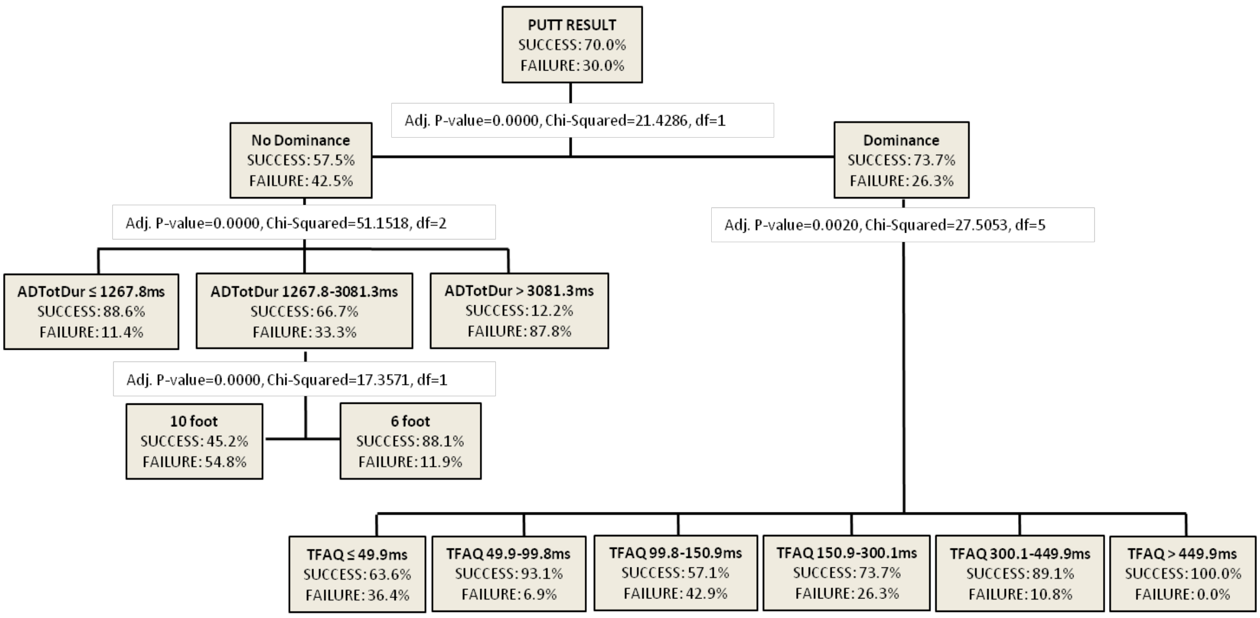
5.3.7.1 Top Professionals

In Top Professionals, the most significant factor determining putting success was ocular dominance (Figure 5-30). Top Professionals with a dominant eye had significantly higher success rates than Top Professionals without an ocular dominance ($p<0.0001$). For golfers with a dominant eye, the second most significant factor in their success was the duration of the last fixation of Address (T_{FAQ}) ($p=0.0020$). The greatest success was found when golfers had a very long T_{FAQ} >449.9ms, followed by a relatively short T_{FAQ} of 49.9-99.8ms.

In Top Professional golfers without ocular dominance, the Total Fixation Duration in Address ($p<0.0001$) was highly significant factor for success. A long Total Fixation Duration (>3081.3ms) was associated with the lowest success rates overall ($p<0.001$).

Therefore, when considering the putting vision strategy in Top Professionals, the primary characteristic to consider is ocular dominance. Golfers' ocular dominance can be used to ensure that the training conditions are optimised for success. From a fixation training viewpoint, the general aim should be to lengthen the duration of the key fixations of the Address (T_{FA1}, T_{FAQ}, Mean Fixation Duration) and minimize the amount of additional time spent fixating during this phase.

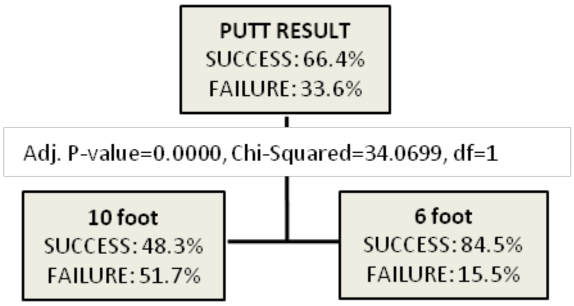
Figure 5-30: CHAID tree displaying results of CHAID analysis on the Top Professional golfers (ADTotDur = Address Total Fixation Duration).



5.3.7.2 Club Professionals

For Club Professionals, only Putt Length was significantly associated with success in the CHAID analysis. Club Professionals had a significantly higher success rate on shorter, 6 foot putts than on longer, 10 foot putts ($p<0.0001$) (Figure 5-31).

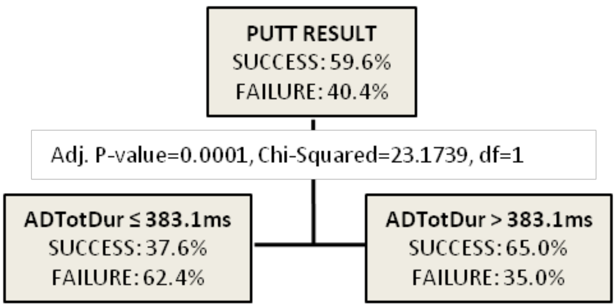
Figure 5-31: CHAID tree displaying results of CHAID analysis on the Club Professional golfers.



5.3.7.3 Amateurs

For Amateur golfers, Total Fixation Duration in the Address was again significantly associated with putting success. A longer Total Fixation Duration (>383.1ms) was associated with the highest success rate, whereas a shorter Total Fixation Duration ≤383.1ms was associated with a much lower success rate ($p<0.001$) (Figure 5-32).

Figure 5-32: CHAID tree displaying results of CHAID analysis on the Amateur golfers (ADTotDur = Address Total Fixation Duration).

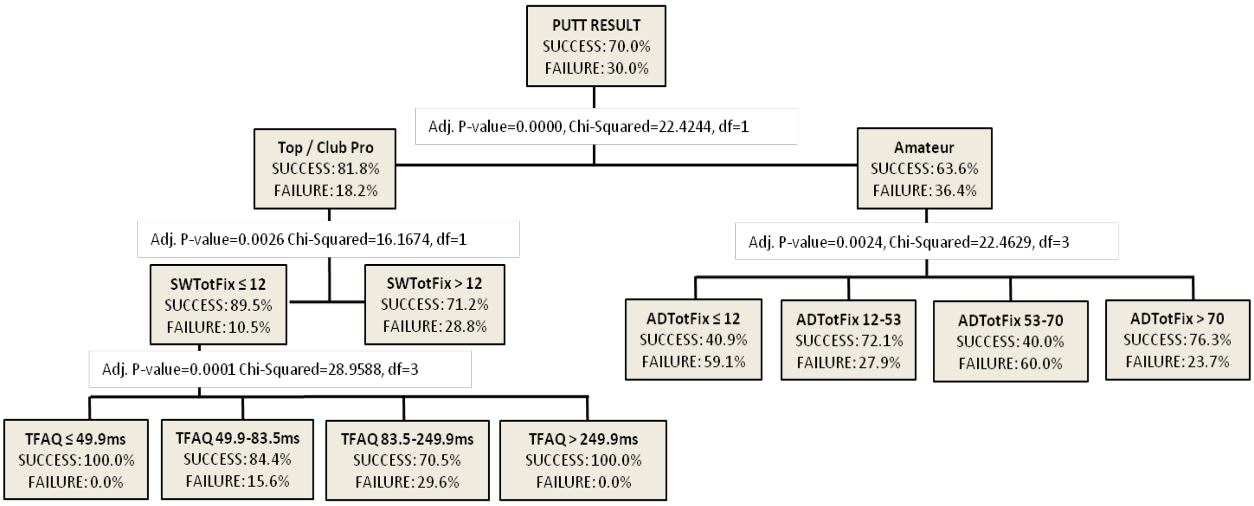


5.3.7.4 Short (6 foot) Putts

On 6 foot putts, the most significant predictive factor for putting success was a golfers' skill level. Professional golfers (Top and Club Professionals) had significantly higher success rates than Amateur golfers ($p<0.0001$). Address fixations again played a role in Amateur golfers' success, although on 6 foot putts, it was the Total Number of Fixations made in the Address rather than the Total Fixation Duration which was significant. Making >70 fixations and making between 12-53 fixations were associated with the highest success rates, while. making ≤12 fixations and making between 53-70 fixations was associated with lower success rates (p=0.0024) (Figure 5-33).

In Professional golfers success on 6 foot putts was significantly associated with the Total Number of Fixations made in the Swing (p=0.0026). Making fewer fixations (≤12) was associated with greater success than making more fixations (>12, p=0.0026). In Top Professionals making ≤12 fixations, the duration of T_{FAQ} (p=0.0001) was an additional factor in success. T_{FAQ} durations of ≤49.9ms and >249.9ms were both associated with the greatest success. T_{FAQ} durations of 49.9-83.5ms and 83.5-249.9ms were both associated with significantly lower success rates.

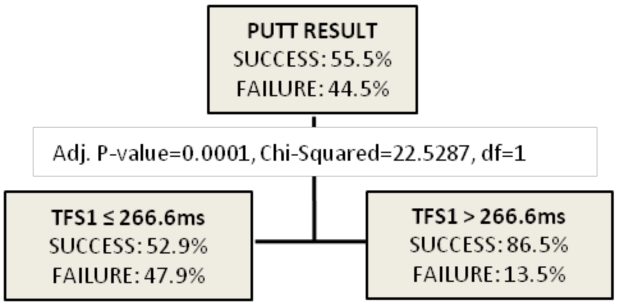
Figure 5-33: CHAID tree displaying results of CHAID analysis on 6 foot putts (SWTotFix = Swing Total Number of Fixations; ADTotFix = Address Total Number of Fixations).



5.3.7.5 Long (10 foot) Putts

On longer, 10 foot putts only T_{FS1} duration was significantly associated with success, irrespective of skill level (p=0.0001). T_{FS1} durations >266.6ms were associated with a high success rate (>85%) whereas T_{FS1} durations ≤266.6ms had a much lower success rate (50%) (Figure 5-34).

Figure 5-34: CHAID tree displaying results of CHAID analysis on 10 foot putts.



T_{FA1}, T_{FSQ}, T_{FCQ} T_{FPQ} were not significant factors in the CHAID analyses conducted, nor were the Mean Fixation Durations in the Address or Swing phases or the Total Fixation Duration in the Swing. T_{FAQ} and T_{FS1} durations, the Total Number of Fixations made in the Address and the Swing phases and the Total Fixation Duration in the Address phase were significant predictors of success in the results presented above, which suggest that these parameters are of particular importance in putting vision strategy. Other factors that appear to influence putting success include a golfer's skill level, the presence of ocular dominance and the length of the putt. Skill and putt length may be, to some extents, self-explanatory factors, but ocular dominance is a unique factor that has never been measured before and will be examined in more detail in the following chapter.

5.4 Discussion

The results presented above address limitations of earlier putting vision strategy research whereby fixations were defined as gazes which remained stable within 3.0° visual angle for a minimum of 100ms[28] and measurements were made under monocular conditions. In keeping with other vision science research, fixations were re-defined as gazes which remained stable within 0.5° visual angle[67] for a minimum of 16.67ms (one movie frame at 60Hz). This definition does not assume fixations are indicative of cognitive attention and measurements were conducted under binocular conditions. This study was conducted on golfers of three skill levels, including highly elite Top Professionals, and has been designed to re-examine the entirety of the putt from preparation to post-contact in order to determine which aspects of the putting vision strategy were associated with both higher skill and success.

In addition to information regarding golfers skill, putting success and ocular dominance, various gaze behaviour parameters were collected for each putt, including the duration of the six key fixations (T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}), their Start and End Time from T_0, the Total Number of Fixations made to the ball and the hole, the Mean Duration of the ball and hole fixations and the Total Duration of all Fixations made to the ball and the hole in Address and Swing phases, the duration of the entire putt and the duration of each of the putt phases (Preparation, Address, Swing, Post-Contact). All of these parameters were examined to determine their relevance to the putting vision strategy and their associations with higher levels of skill and success.

5.4.1 Parameter Selection

Spearman correlation analyses were conducted to determine which parameters to include in the detailed examination of golfers' putting vision strategy. As a result of the preliminary correlation investigation, 12 fixation parameters were selected for inclusion in the analysis of putting vision strategy: T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}, Total Number of Fixations in the Address and Swing, Mean Fixation Duration in the Address and Swing and Total Duration of ball fixations in the Address and Swing.

The putt duration parameters, hole fixation parameters from the Address and Swing, and the start and end of each of the key fixations were not included in any subsequent analyses of the putting vision strategy as they were deemed to have little or no relationship with the fixation parameters chosen for analysis, and as such they were determined to be unimportant in this particular investigation of putting vision strategy.

Right and left eye results were poorly correlated, therefore eye needed to be included as a factor in all of the subsequent analyses. Unfortunately the effect of eye cannot be interpreted unless ocular dominance is also considered and the effect of eye was not specifically examined. The analysis of ocular dominance and its impact on putting vision strategy is reported in Chapter 6: Vision Strategy in Golf Putting: Training, Competition and Ocular Dominance.

Apart from the identification of parameters to include in the analysis of the putting vision strategy, the Spearman correlation results provided some very interesting information with respect to the relationship between Address and Swing fixations. The durations of the last fixation in the Address (T_{FAQ}) and the first fixation in the Swing (T_{FS1}), the Mean Fixation Duration in the Address and the Mean and Total Fixation Durations in the Swing were strongly correlated with each other. These results are of particular importance, because they indicate that gaze behaviours between the two principle phases of the putt are closely related to each other.

Address and Swing fixations are both essential components of the putting vision strategy, associated with higher skill and success (discussed below). Improvement of these fixation behaviours should improve putting performance; the close relationship between Address and Swing fixations indicate that improvements in the fixation behaviours in one phase will transfer to the other. From a simple mechanical perspective, training fixation behaviours in the Address is less complicated than in the Swing because the golfer is standing relatively still in the Address, and the biomechanics of swinging the putter do not interfere. Training Address fixations in general will increase the duration of T_{FAQ} because the Mean Fixation Duration in Address fixations was strongly correlated with T_{FAQ} duration. T_{FAQ} duration was correlated with various fixation behaviours in the Swing phase as well, therefore training Address fixations in general will also improve Swing fixations. Finally, the duration of T_{FS1} was strongly correlated with the Swing fixation parameters, hence the duration of T_{FS1} can be improved through training the Swing phase fixations, which ultimately means that the duration of T_{FS1} can be improved through training Address fixations. Although it would not be advisable to train only Address fixations, the efficiency of vision training programs can be maximised by dedicating more time to training Address fixation behaviours, as this will positively impact the Swing fixation behaviours. Specific examples of putting vision strategy training will be discussed in greater detail in Chapter 7, Case Reports: Vision Training in Golf Putting.

5.4.2 Putt Length

The effect of putt length has never before been examined with respect to its impact on the putting vision strategy. The prevailing hypothesis regarding the quiet eye in golf was that it would be longer on more difficult tasks.[38] This hypothesis was based on work done in by William, Singer and Frehlich, whereby participants in a billiards task had longer quiet eye periods for more difficult shots compared with easy shots.[39] Both Van Lier, Van der Kamp and Savelsbergh and Wilson and Pearcy compared final fixation/quiet eye duration on flat (easy) and sloped (difficult) putts and found that quiet eye duration was not different between flat and sloped putts, although it had been expected it to be.[37, 38]

In this particular study, the gaze behaviours used on both 6 foot (easy) and 10 foot (difficult) putts were compared. None of the gaze behaviours examined differed between the two putt lengths overall or in golfers of any skill level. This result, when taken in conjunction with Wilson and Pearcy's findings would suggest that putting vision strategy is independent of the putting task and consistent across different putting conditions. This finding has important implications with respect to training vision strategies in golfers because it means that that vision strategy training undertaken in one particular condition would be transferable to other putting conditions.

5.4.3 Vision Strategies Associated with Skill and Success

In 1992, Vickers published the hallmark study on putting vision strategy. This study found that higher skilled golfers made longer quiet eye fixations to the ball and the target, shifted their gaze between targets faster and maintained their gaze on the putting surface longer after contact. The quiet eye, a fixation similar to T_{FAQ}, was found to be the only gaze behaviour associated with both higher skill and success. These results lead Vickers to propose that the ideal vision strategy for golf putting would be one in which express saccades to the putter were used in the preparation phase, along with a single fixation of greater than 1700ms directed to the ball during the back/forward swing phase and a stable fixation on the green for over 200ms after ball contact. It was thought that this particular strategy would improve golfers performance by reducing the amount of distracting information collected throughout the movement of the club and increasing the precision of the visual-motor coordination of the hands when the putter contacted the ball.[28]

Since the publication of Vickers' original work, the quiet eye in golf putting has been studied with similar results. To date all quiet eye researchers have agreed that this fixation is associated with both higher skill and success in golf putting, and should have a duration of approximately two seconds.[30, 34, 35, 38] Regrettably, all of these studies have significant limitations, as discussed previously,.

One of the more striking results of the current study, which used a the 0.5° fixation criterion, was that golfers' fixations were significantly shorter than those measured in previous studies, and golfers' made significantly more fixations than had ever been previously recorded.[28] Using a smaller, more accurate fixation criterion (0.5° visual angle) permitted the capture of significantly more, short fixations which had never before been investigated, and this has resulted in many more gaze behaviours having been found to be associated with higher skill and success. The details of these new findings will be discussed presently.

5.4.3.1 Skill

The effect of skill on the putting vision strategy was examined using Chi-square analysis to compare distributions of the key fixations and linear mixed model analysis to examine the twelve parameters of interest.

Skill was found to be a significant factor for the duration of all six key fixations (T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}). All of the key fixations were significantly longer in golfers of higher skill (Top Professionals) than Amateurs, and most of the fixations (except T_{FA1} and T_{FPQ}) were longer in Top Professionals than Club Professionals. Skill was also a significant factor for the distributions of the key fixations.

The last fixation of the Address (T_{FAQ}) most closely resembled the quiet eye fixation,[28, 30, 34, 35, 38, 51, 52] and had an average duration of 195ms in Top Professionals, 70ms in Club Professionals and 60ms in Amateurs.

The first fixation of the Swing (T_{FS1}) had an average duration of 190ms in Top Professionals, 60ms in Club Professionals and 53ms in Amateurs. T_{FAQ} and T_{FS1} were very similar fixations due to the nature of their definitions, and their distributions were also significantly affected by skill. In Top Professionals T_{FAQ}=T_{FS1} in 80% of putts, while in Club Professionals and Amateurs T_{FAQ}=T_{FS1} in 45% and 35% of putts respectively. The last fixation of the Swing (T_{FSQ}) had an average duration of 55ms in Top Professionals, 30ms in Club Professionals and 20ms in Amateurs.

The duration of the contact fixation (T_{FCQ}) was 30ms in Top Professionals, 10ms in Club Professionals and 5ms in Amateurs. When there was a fixation at contact, T_{FSQ} = T_{FCQ}, whereas when there was not a fixation at contact, T_{FCQ}=0.000ms. The distributions of T_{FSQ} and T_{FCQ} were significantly affected by skill, much like the distributions of T_{FAQ} and T_{FS1}. Top Professionals had more stable fixations at contact, as demonstrated by their relatively high proportion of $T_{FSQ}=T_{FCQ}$ fixations (43% of putts). In Club Professionals and Amateurs $T_{FSQ}=T_{FCQ}$ in 23% and 18% respectively. The short average duration of T_{FCQ} fixation was due to the large number of T_{FCQ}=0.000ms fixations that were recorded at contact (Top, 57%; Club, 77%; Amateur, 83%).

The duration of first and last fixations measured during the putt (T_{FA1} and T_{FPQ}) were also significantly affected by skill. T_{FA1} (the first fixation of the Address) had a duration of 50ms in Top and Club Professionals, compared with 30ms in Amateurs, while T_{FPQ} (the post-contact fixation) duration was 30ms in Top Professionals, 25ms in Club Professionals and 20ms in Amateurs.

In addition to the key fixation durations, skill was a significant factor for all of the Address and Swing phase fixation parameters. In the Address phase, Top Professionals made more fixations, which were of longer Mean Duration than Club Professionals or Amateurs. Top Professionals also had the longest Total Fixation Duration in the Address. In the Swing phase, Top and Club Professionals made significantly more fixations than Amateurs, but Mean and Total Fixation Durations were significantly longer in Top Professionals compared with Club Professionals and Amateurs.

Unlike in Vickers work,[28] all of the fixation parameters examined in this study were significantly affected by skill, not just the quiet eye (T_{FAQ}). Using 0.5° visual angle as a fixation criterion, with a minimum gaze time of 16.67ms has revealed that there are many more aspects of the putting vision strategy which are associated with higher skill than has ever before been measured. These results highlight the need for accurate fixation criterion to be used in this type of research, as the criterion used in previous research appears to have masked important parameters of the putting vision strategy.

Moreover, the results of this study demonstrate the need to examine golfers of all skill levels, especially the highly elite, as the vision strategies of these groups are not equal. The results clearly demonstrate that the putting vision strategies of Top Professional and Amateur golfers are different as would be expected, but they also demonstrate that the vision strategy of Top Professionals differs from that of Club Professionals. This is a new and important finding from this study, as differences in the vision strategies of skilled and highly skilled golfers has never been previously observed. The current fixation criterion (0.5° visual angle, minimum 16.67ms) has the precision to differentiate golfers with good putting vision strategies from golfers with excellent putting vision strategies.

5.4.3.2 Success

The relationship between putting success and the putting vision strategy was examined using linear mixed model analysis to examine the 12 fixation parameters and CHAID analysis to determine which characteristics of the population were of the greatest importance.

Of the 12 fixation parameters analysed in the mixed model analysis, T_{FAQ} and T_{FS1} durations, the Total Number of Address Fixations, the Mean and Total Address Fixation Durations and the Total Number of Swing Fixations were all found to be significantly associated with putting success.

Longer T_{FAQ} durations were found to be significantly associated with putting success overall and in Top Professionals, although there was no difference in T_{FAQ} duration on successful and missed putts in Club Professionals or Amateurs. These results were further supported by the CHAID analysis, which found longer T_{FAQ} durations to be significant predictors of putting success overall, in Top Professionals and on 6 foot putts .

Much like T_{FAQ}, T_{FS1} was longer on successful putts, particularly in Top Professionals. Additionally, T_{FS1} stood out as a significant factor in putting success in the CHAID analyses, especially overall and on 10 foot putts where T_{FS1} fixations lasting >266.2ms were predictive of high rates of success. As T_{FAQ} and T_{FS1} closely resemble the quiet eye fixation of Vickers,[28] the results of this study support the Vickers findings, in that longer durations of both T_{FAQ} and T_{FS1} are associated with both higher success and higher skill.

Unlike Vickers original work,[28] the Total Number of Address Fixations, the Mean and Total Address Fixation Durations and the Total Number of Fixations made during the Swing were found to be significantly associated with putting success. Longer Mean Address Fixation Durations were associated with higher success overall, and in Top Professionals. The Total

Number of Fixations made by golfers overall on successful and missed putts were not different, but Top Professionals were found to make significantly fewer Address fixations on successful putts and to have significantly shorter Total Fixation Durations on successful putts. Therefore, Top Professionals made fewer fixations of longer Mean Duration for a shorter Total Fixation Duration in the Address on successful putts.

These results suggest that there is a limit to how much performance can be improved simply by making more fixations in the Address. The CHAID results further support the idea that there is a limit to how much longer fixations in the Address contribute to success; in Top Professionals with no ocular dominance Total Fixation Durations of ≤1267.8ms was associated with higher success rates than Total Fixation Durations >1267.8ms.

Although not significantly associated with putting success in the linear mixed model analysis, the Total Number of Fixations in the Swing was predictive of success on 6 foot putts in Professional golfers (Top and Club combined) in the CHAID analysis. Professional golfers who made fewer than 12 total fixations during the Swing phase were found to have greater success. This would suggest that fixation control in the swing phase is important to golfers' overall success, and is an important part of the putting vision strategy.

Decreasing the number of fixations made in the Swing would either increase the Mean Fixation Duration or decrease the Total Fixation Duration. As Mean Fixation Duration appears to be longer in Top Professionals, it is more likely that the decrease in Total Number of Fixations was associated more strongly with an increase in the Mean Fixation Duration rather than a decrease in the Total Fixation Duration.

The new, novel fixation parameters associated with both putting skill and success described above are a direct result of the use of the new fixation criterion (0.5° visual angle, 16.67ms minimum gaze time) and the examination of highly elite professional golfers in addition to lesser skilled professional and amateur golfers. The criterion used in previous research, unfortunately, appears to have masked the importance of these parameters in the putting vision strategy, and again demonstrates the need to measure fundamental gaze behaviours accurately, without the prior assumption of cognitive attention.

Furthermore, the research presented here demonstrates that the vision strategy attributes associated with the highest success are different in golfers of different skill levels. This interaction between skill and putting success has never before been demonstrated. In Top Professional golfers having a dominant eye was the strongest predictor of putting success, followed by either longer T_{FAQ} durations in golfers with ocular dominance or shorter Total Address Fixation Durations in golfers with no ocular dominance. In Club Professionals, the most significant factor predicting their success was the length of the putt, and success was higher on shorter putts. This suggests that there may be other factors influencing their success such as their ability to read the green and align the ball or their stroke mechanics in addition to their fundamental putting vision strategy. In Amateurs, the Total Fixation Duration in the Address was the only factor predictive of success. This parameter gives some indication of the overall quality of Amateurs gaze behaviours, with longer Total Fixation Durations likely associated with more stable fixations in general.

Traditionally, putting vision strategy training programs have tried to achieve a singular result, which was a longer duration of the quiet eye fixation, but the results presented here indicate that it is now possible to tailor vision strategy training programs to golfer's specific needs and skill level. Further research is needed to determine how this individualised approach will ultimately impact performance in golfers of all skill levels.

5.4.4 Conclusion: The Optimal Putting Vision Strategy

Based on the results presented above, the author proposes that an optimal putting vision strategy include the following parameters: T_{FAQ}=T_{FS1} with a duration of 200-300ms, T_{FSQ}=T_{FCQ} with a minimum duration similar to other fixations in the Swing phase (70ms), no more than 12 fixations during the swing phase for a total Swing phase fixation duration of 1000-1200ms. In the Address, fixations should have a mean duration of 70ms, and the total amount of time spent fixating the ball during the Address should be less than 1300ms.

T_{FAQ}=T_{FS1} is an important fixation in the vision strategy of golfers, associated with both higher skill and success. Previous researchers have suggested that the quiet eye, or the T_{FAQ}=T_{FS1} fixation is associated with cognitive pre-programming of the backswing movement and minimising distraction from internal and external cues.[29, 31] Although the author does not agree with the suppositions of previous researchers, and the findings here do not discredit these findings, the author would like to suggest an alternative possibility for the purpose of $T_{FAQ}=T_{FS1}$. In the Top Professional population, $T_{FAQ}=T_{FSQ}$ in 80% of putts, which was significantly higher than in either Club Professionals (45%) or Amateurs (35%), therefore $T_{FAQ}=T_{FS1}$ likely has a biomechanical advantage as well. A precise, concentrated fixation that lasts through the initiation of the backswing movement may help control head and body position in the swing making the swing mechanics more consistent and repeatable.

As T_{FSQ} was the last fixation in the Swing, it had the potential to continue through contact ($T_{FSQ}=T_{FCQ}$). In Top Professionals $T_{FSQ}=T_{FCQ}$ in almost half (43%) of all putts undertaken, whereas in Club Professionals this occurred on only 1 in 4 putts (25%); in Amateurs it was 1 in 5 (18%). The significantly higher distribution of $T_{FSQ}=T_{FCQ}$ fixations in Top Professionals would suggest that a contact fixation is associated with higher skill, and is likely associated with higher success rates despite putt result not being a significant factor in T_{FSQ} or T_{FCQ} durations.

$T_{FSQ}=T_{FCQ}$ likely plays an important role in stabilising the head and body positions at ball contact, just as $T_{FAQ}=T_{FS1}$ does in the swing. $T_{FSQ}=T_{FCQ}$ did not last as long after contact as has been found previously (quiet eye dwell time=200ms),[28] nor was it a long fixation; this is likely due to the stricter fixation criterion of 0.5° visual angle used in this study. Not only is this criterion intolerant of pursuit and saccadic gaze behaviours, it is intolerant of head and body movement. As the arms, and to some extent the shoulders and torsos of golfers are rotating throughout the backswing and contact of the ball, the body movement may have been enough to limit the length of fixations measured. When fixations were not measured, $T_{FSQ}=T_{FCQ}$ was 0.000ms; as this result was recorded on most putts, this significantly lowered the mean duration of this particular fixation. It would be interesting to re-visit the analysis of $T_{FSQ}=T_{FCQ}$ fixations using a binocular eye tracker and a head tracker in a future study.

The Address and Swing fixation parameters appear to be significant factors in the putting vision strategy of their own accord, but higher performance on these parameters is associated with more stable fixation behaviours overall. All of the Address and Swing fixation parameters found to be significantly associated with putting success were included in the optimal putting vision strategy except for the Total Number of Fixations in Address. This parameter is likely less important to the vision strategy of golfers because it is associated with both the Mean and Total Fixation Durations of this phase; as Mean Address Fixation Duration improves, the Total Number of Address fixations will inherently decrease in order to attain an optimal Total Address Fixation Duration.

T_{FA1} was not included in the optimal vision strategy, because it was not found to be significantly associated with increased putting success, either in the mixed model or the CHAID analyses, despite its significant association with skill.

T_{FA1} was the first fixation in the visually dynamic process of aligning the club with the ball, relative to a chosen target. While one might expect golfers to make a long concentrated fixation on this aiming task, this is unlikely. Aligning the club and the ball involves various gaze behaviours including fixations on the ball, the club, the hole and/or the target, pursuits and saccades. The method through which golfers align the club and the ball will be highly individual and strongly associated with the particular aspects of a single putt. It is likely the quality of the alignment of the ball and the club and the aim line that plays a greater role in putting success than the duration of a single fixation measured in this stage, which is only one of a number of fixations made during the process.

T_{FPQ} is an interesting fixation, in that it was either the first fixation after contact (if there was no fixation at contact) or it was the first fixation that started after the contact fixation. Depending on the length of the contact fixation, T_{FPQ} could have started at very different time points after contact. With this in mind, it makes conclusions about T_{FPQ} difficult to draw. Overall, it does not appear to be significantly associated with putting success, although there is an association with skill. In golfers who did not have a T_{FCQ} fixation, T_{FPQ} may play a different role than it does in golfers with a T_{FPQ} fixation. T_{FPQ} in golfers without a contact fixation may represent a golfers' attempt to keep his eyes steady on the ball after contact. Unfortunately many golfers, even at the Top Professional level did not have stable gazes at contact; therefore more investigation of T_{FPQ} is needed to understand the role it plays in the putting vision strategy. This research would need to be conducted using both eye and head tracking equipment as eye tracking equipment alone is not sufficient due to the dynamic nature of ball contact. Based on the results presented here, T_{FPQ} does not appear to be a significant fixation in golfers' putting vision strategy, but further investigation may reveal it to be so.

5.5 Summary

Chapter 5, Vision Strategy in Golf Putting: Skill and Success demonstrated that there are many fixation behaviours that are strongly associated with putting skill and success. This chapter also introduced a novel optimised vision strategy for putting success, based on the experimental results. The next chapter, Chapter 6, Vision Strategy in Golf Putting: Training, Competition and Ocular Dominance, will examine the effect of condition (training or competition) and ocular dominance on the putting vision strategy.

Chapter 6

VISION STRATEGY IN GOLF PUTTING: TRAINING, COMPETITION AND OCULAR DOMINANCE

6.1 Introduction

As discussed in the previous chapter, the purpose of this study is to evaluate the relationship between training and competition on the putting vision strategy of golfers, and to examine the effect of ocular dominance on golfers' gaze behaviours.

6.1.1 Training and Competition

Golfers putt under essentially two conditions in golf: training or practice putting and competitive putting in scored rounds of golf. Two main differences exist between these conditions: i.) under training conditions, golfers can re-take the same putt many times for practice, but in competitive conditions golfers only have one opportunity to take a putt and ii.) under competitive conditions the pressure to perform is much greater. All previous putting vision strategy research, including that presented in the previous chapter is based on the paradigm of assessing multiple putts which are taken under a strict set of conditions, which are for all intents and purposes intended to be the same. While this paradigm produces a good assessment of golfers' performance overall, it provides only indirect information about golfers' performance as it would occur during a scored round of golf.

Vine and Wilson were the first research group to publish a study on effect of stress and pressure on the quiet eye, which was conducted as part of a study designed to investigate the effectiveness of putting vision strategy training methods. During this study, golfers participated in pressure tests requiring 40 putts to be completed under cognitive stress in a competitive environment (cognitive stress is stress induced by the anticipation of a consequence and can be created through the use of performance incentives in a competitive task). Cognitive stress in the pressure tests was found to significantly decrease the duration of the quiet eye compared with tests in non-pressurised situations, regardless of whether or not golfers had had additional quiet eye training.[52] While this type of testing scenario undoubtedly creates a stressful environment in which to putt, it does not mimic the situation in a competitive round of golf, because golfers took 40 putts under the same conditions.

In an attempt to better understand the effectiveness of quiet eye training on competitive golfer performance, Vine, Moore and Wilson (2011) conducted another study in which elite golfers were asked to record their overall scores and putting statistics on 10 consecutive rounds of golf before having a vision strategy assessment (20 putts) and vision strategy training. After the training golfers were asked to record their scores and the same putting statistics on an additional 10 rounds of golf before returning for a final assessment of their putting vision strategy which consisted of a retention test (20 putts) and a pressure test (15 putts). Quiet eye-specific vision training was found to improve putting performance outside of the laboratory, as golfers who received this particular training improved their putting performance by an average of 1.9 putts per round.[51] Whilst this study did allow for the assessment of putting performance in realistic, competitive environment, no assessment of vision strategy in the natural environment was undertaken.

The most significant limitation of both of these studies was that putting vision strategy was measured in a repeated situation, and they failed to analyse golfer's vision strategy when only one attempt was made at each putt. Therefore the purpose of the study presented below was to assess the effect of repeating the same putt on the putting vision strategy by comparing the first putt golfers made from the distances of 6 and 10 feet, with their overall habitual (training) performance at these distances.

6.1.2 Ocular Dominance and Putting Vision Strategy

Although some studies have tried to examine the relationship between ocular dominance and putting success (see Chapter 4, Ocular Dominance and Golf for a review),[102-105] they had several limitations, the most significant being that they all measured ocular dominance in a primary gaze position. The results of the study presented in Chapter 4, Ocular Dominance and Golf demonstrated that primary gaze ocular dominance and putting gaze ocular dominance are different and that primary gaze ocular dominance is not predictive of putting gaze ocular dominance. Assessments of putting performance in relation to primary gaze ocular dominance then, is essentially ineffective as the dominance information is irrelevant.

Additionally, none of these studies were designed to evaluate the effect of ocular dominance on the gaze behaviours used by golfers when putting.

Of the studies that have assessed golfers' gaze behaviours when putting,[28, 32, 34-36, 38, 51, 52] none have collected binocular data. Therefore an assessment of ocular dominance and the effect it has on the gaze behaviours used by golfers has never before been carried out. The purpose of this particular study was to address this limitation, and assess for the first time, the effect of ocular dominance on golfers' putting vision strategy and its relationship with putting success.

6.2 Methods

6.2.1 Eye Tracking

The results presented below are a continuation of the study presented in Chapter 5: Vision Strategy in Golf Putting: Skill and Success, which was a retrospective analysis of eye tracking data collected in golf-specific optometric assessments at the Michel Guillon Sports Vision Clinic. 27 golfers (9 Top Professionals, 6 Club Professionals and 12 Amateurs) participated in this study, in which a total of 10 x 6 foot and 10 x 10 foot putts were completed by each golfer while wearing the Arrington Research ViewPoint binocular eye tracker. Golfers were asked to putt as they would naturally, and they were encouraged to go through their full pre-shot routines. Ethics approval for this study was obtained from the Aston University Audiology/Optometry Research Ethics Committee (AO2010.20) and all golfers signed an informed consent.

Data analysis was completed with GazeDetection software [Chapter 2, Software Development], and fixations were defined as a stable gaze within 0.5° visual angle with a minimum duration of 16.67ms (1 movie frame at 60Hz).

6.2.2 Statistical Analysis

The two analyses presented in this chapter examine the relationship between training and competition scenarios and evaluate the impact of ocular dominance on the putting vision strategy using the linear mixed model described in Appendix D. The fixation parameters included in these analyses were the same twelve parameters examined in Chapter 5, Vision

Strategy in Golf Putting: Skill and Success: T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}, Total Number of Fixations in the Address and Swing, Mean Fixation Duration in the Address and Swing and Total Duration of Fixations in the Address and Swing. The significance value for all of these analyses was α=0.05 unless otherwise stated.

Estimated marginal means are sometimes reported in conjunction with the linear mixed model results; these means are in the format of mean ± standard error and are denoted with "†" to differentiate them from results reported as mean ± standard deviation. The graphs presented below display estimated marginal means with mean ± standard error.

6.2.2.1 Training and Competition

In this analysis, two theoretical models (Training and Competition) were compared. The training model was based upon the session means, which were calculated for the 10 putts taken at each putting distance. Session means were thought to give a good representation of golfers overall putting performance. The competition model was based upon the first putt made by each golfer at each distance. The first putt was chosen for this model, as golfers are only allowed one attempt at each putt on a golf course. The competition model was compared with the training model to determine if the putting vision strategy differed between the two conditions.

Spearman correlations were used to assess the relationship between training and competition, as was a linear mixed model analysis. The strength of the correlations was defined as follows: 0.0 to 0.199 very weak (negligible), 0.2 to 0.399 weak, low correlation (not significant), 0.4 to 0.699 moderate correlation, 0.7 to 0.899 strong, high correlation, and 0.9 to 1.000 very strong correlation.[111-113]

The basic structure of the linear mixed model used in this analysis was the same as the model described in Chapter 5 [Vision Strategy in Golf Putting: Skill and Success] and Appendix D, although the explanatory variables were different. The principle explanatory variables in the linear mixed model were Condition, Skill, Putt Length and Eye. The repeated measures variable was Condition, which was identified by the Player ID, Eye and Putt Length variables; Eye and Putt Length were nested within Player ID to precisely identify the repeated measures data. The effect of Eye was not examined in this specific analysis, as there were no provisions made for ocular dominance; Eye was included in this analysis to account for any variations in this parameter that could affect the final results.

6.2.2.2 Ocular Dominance

Golfers' ocular dominance was measured in putting gaze and distribution statistics, including means and standard deviations, were calculated for the parameters of interest. In golfers with a putting gaze ocular dominance, distribution statistics were calculated for the dominant and non-dominant eyes independently; in golfers who did not have a putting gaze ocular dominance distribution statistics were calculated for the right and left eyes independently. Spearman correlations were used to assess the relationship between the dominant and non-dominant eyes in golfers with ocular dominance and between the right and left eyes of golfers who did not have ocular dominance. The strength of the correlations was defined as follows: 0.0 to 0.199 very weak (negligible), 0.2 to 0.399 weak, low correlation (not significant), 0.4 to 0.699 moderate correlation, 0.7 to 0.899 strong, high correlation, and 0.9 to 1.000 very strong correlation.[111-113]

A linear mixed model analysis was conducted to assess the effect of ocular dominance on the putting vision strategy. For this analysis, the population was split into two sub-groups: one subgroup contained golfers with ocular dominance and the other contained golfers who did not have any ocular dominance. These two sub-groups were made up of Top and Club Professional golfers, as there was an equal distribution of ocular dominance and no ocular dominance in these groups. Amateurs were not included in this analysis, as most of the Amateurs had a dominant eye, and this would have created an unbalanced sample with almost twice as many individuals in the dominant eye population.

The basic structure of the linear mixed model used in this analysis was the same as the model described in Chapter 5 [Vision Strategy in Golf Putting: Skill and Success] and Appendix D, although the explanatory variables differed. The principle explanatory variables in this analysis were Ocular Dominance, Putt Type and Putt Result. The repeated measures variable was Putt Trial, which was identified by the Player ID and Putt Type; Putt Type was nested within Player ID to precisely identify the repeated measures data. Only the results of the dominant eye from golfers with ocular dominance were included in the analysis; when there was no ocular dominance present, one eye (right or left) was randomly selected to be included in the analysis from each golfer. Skill was not considered as a factor in this analysis, as all golfers were professionals and it was felt the sample size of the dominance and no dominance subgroups were too small to allow for an accurate assessment of the effect of skill.

6.3 Results

6.3.1 Training and Competition

6.3.1.1 Spearman Correlation Analysis

The results of the Spearman correlation analysis used to assess the relationship between training and competition are presented in Table 6-1.

In Top Professionals, training and competition were strongly correlated overall (both distances pooled), and at both 6 and 10 feet (Table 6-1). In particular, there were strong to very strong correlations between the models on T_{FAQ},T_{FS1} and T_{FSQ} fixation durations. The Total Number of Fixations in the Address was strongly correlated at 6 feet, and strong to very strong correlations were found between training and competition for the Mean Fixation Duration and the Total Fixation Duration in Address. Strong to very strong correlations were found between training and competition for all of the Swing phase fixation parameters as well except for the Total Number of fixations made during the Swing on 6 foot putts. The correlation results demonstrate that Top Professional golfers have a vision strategy that is very consistent between putts, especially for T_{FAQ}, T_{FS1}, T_{FSQ} and the majority of the Address and Swing fixation parameters.

	Overall	Top Pro	Club Pro	Amateurs	6 foot	10 foot	Top Pro, 6 foot	Top Pro, 10 foot	Club Pro, 6 foot	Club Pro, 10 foot	Amateurs, 6 foot	Amateurs, 10 foot
Putt 1	**Session Mean**											
T_{FA1} Duration	0.537** (n=108)	0.486* (n=36)	0.282 (n=24)	0.540** (n=48)	0.572** (n=54)	0.499** (n=54)	0.414 (n=18)	0.530* (n=18)	0.561 (n=12)	0.100 (n=12)	0.559** (n=24)	0.513** (n=24)
T_{FAQ} Duration	0.672** (n=108)	0.711** (n=36)	-0.044 (n=24)	0.553** (n=48)	0.754** (n=54)	0.602** (n=54)	0.742** (n=18)	0.788** (n=18)	0.545 (n=12)	-0.377 (n=12)	0.497* (n=24)	0.549** (n=24)
T_{FS1} Duration	0.739** (n=108)	0.793** (n=36)	0.451* (n=24)	0.656** (n=48)	0.813** (n=54)	0.698** (n=54)	0.905** (n=18)	0.842** (n=18)	0.719** (n=12)	0.207 (n=12)	0.671** (n=24)	0.629** (n=24)
T_{FSQ} Duration	0.554** (n=108)	0.714** (n=36)	0.741** (n=24)	0.331* (n=48)	0.638** (n=54)	0.453** (n=54)	0.816** (n=18)	0.538* (n=18)	0.783** (n=12)	0.633* (n=12)	0.439* (n=24)	0.198 (n=24)
T_{FCQ} Duration	0.474** (n=108)	0.586** (n=36)	0.359 (n=24)	0.396** (n=48)	0.471** (n=54)	0.468** (n=54)	0.566* (n=18)	0.590** (n=18)	0.462 (n=12)	0.146 (n=12)	0.254 (n=24)	0.568** (n=24)
T_{FPQ} Duration	0.273** (n=108)	0.251 (n=36)	0.240 (n=24)	0.316* (n=48)	0.002 (n=54)	0.526** (n=54)	0.022 (n=18)	0.503* (n=18)	0.212 (n=12)	0.392 (n=12)	-0.069 (n=24)	0.592** (n=24)
Address Total Fixations	0.820** (n=108)	0.609** (n=36)	0.508* (n=24)	0.788** (n=48)	0.817** (n=54)	0.817** (n=54)	0.751** (n=18)	0.476* (n=18)	0.140 (n=12)	0.543 (n=12)	0.788** (n=24)	0.813** (n=24)
Address Mean Fixation Duration	0.937** (n=108)	0.872** (n=36)	0.789** (n=24)	0.906** (n=48)	0.927** (n=54)	0.948** (n=54)	0.783** (n=18)	0.901** (n=18)	0.769** (n=12)	0.783** (n=12)	0.874** (n=24)	0.931** (n=24)
Address Total Fixation Duration	0.941** (n=108)	0.926** (n=36)	0.819** (n=24)	0.875** (n=48)	0.929** (n=54)	0.954** (n=54)	0.955** (n=18)	0.938** (n=18)	0.678* (n=12)	0.881** (n=12)	0.879** (n=24)	0.892** (n=24)
Swing Total Fixations	0.908** (n=108)	0.743** (n=36)	0.893** (n=24)	0.943** (n=48)	0.881** (n=54)	0.933** (n=54)	0.645** (n=18)	0.784** (n=18)	0.910** (n=12)	0.936** (n=12)	0.933** (n=24)	0.969** (n=24)
Swing Mean Fixation Duration	0.876** (n=108)	0.902** (n=36)	0.688** (n=24)	0.817** (n=48)	0.921** (n=54)	0.828** (n=54)	0.878** (n=18)	0.909** (n=18)	0.916** (n=12)	0.357 (n=12)	0.852** (n=24)	0.759** (n=24)
Swing Total Fixation Duration	0.940** (n=108)	0.786** (n=36)	0.923** (n=24)	0.926** (n=48)	0.949** (n=54)	0.934** (n=54)	0.833** (n=18)	0.818** (n=18)	0.965** (n=12)	0.895** (n=12)	0.930** (n=24)	0.929** (n=24)

**Correlation significant at p<0.05 level; **Correlation significant at p<0.01*

Table 6-1: Spearman correlations comparing the Training (Session Mean) and Competition (1st Putt) Models for T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ} and the Address and Swing phase parameters; Session means are in the vertical columns and the 1st Putt results are in the horizontal rows; the parameters compared are listed horizontally and the groups compared are listed vertically; strong (r = 0.7 to 0.9) and very strong (r >0.9) correlations are highlighted.

In Club Professionals, the only fixation durations that demonstrated strong correlations between the training and competition models were T_{FS1} and T_{FSQ} (Table 6-1). Additionally, the training and competition models were reasonably consistent for the Address and Swing phase fixation parameters; strong to very strong correlations were found for all parameters except for the Total Number of Fixations in the Address, the Total Fixation Duration in Address and the Mean Fixation Duration in the Swing. The high correlations of T_{FSQ} and T_{FS1} likely contributed to the high correlation found between conditions for the Mean Swing Fixation Duration at 6 feet only. When the 6 and 10 foot correlation results were compared, more parameters were correlated on 6 foot putts, which would suggest that Club Professionals are more consistent on shorter putts, and their vision strategy may be influenced by the length of the putt.

In Amateurs, none of the individual fixation durations (T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}) were strongly correlated between the training and competition models (Table 6-1). In contrast, the Address and Swing phase fixation parameters were strongly correlated. These results suggest that Amateurs have a relatively consistent vision strategy for each phase but exhibit some variability in their individual fixation durations.

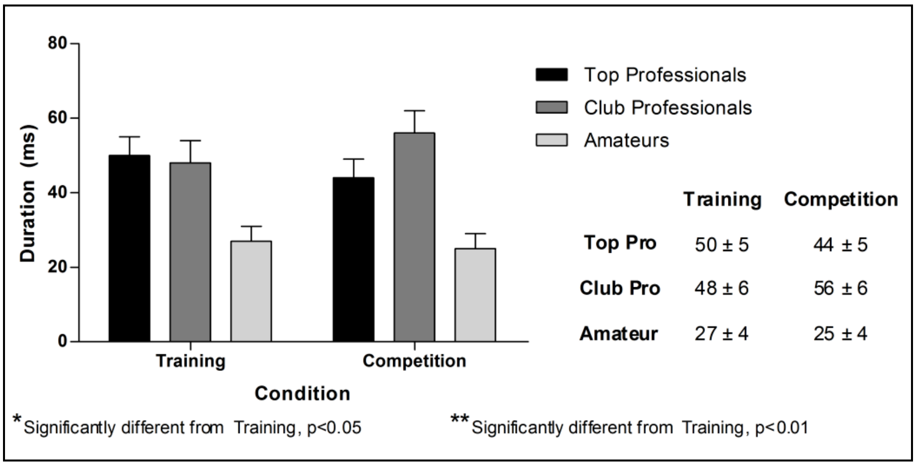
Overall, and in the three skill groups, there were weak to no correlations between the training and competition models for T_{FA1}, T_{FCQ} and T_{FPQ} durations, irrespective of distance. T_{FAQ}, T_{FS1} and T_{FSQ} demonstrated strong to very strong correlations, especially in Top Professionals, while the Address and Swing phase fixation parameters were generally found to be strongly or very strongly correlated in all skill groups. The training and competition models demonstrated more strong and very strong correlations on the fixation parameters in the Top Professional group which supports the hypothesis that Top Professionals had much greater consistency in their putting vision strategies compared with Club Professionals and Amateurs.

6.3.1.2 Mixed Model Analysis

6.3.1.2.1 T_{FA1}

The multivariate analysis demonstrated that overall, condition was not a significant factor affecting T_{FA1} duration (p=0.981), and that condition was unaffected by skill (Skill*Condition interaction, p=0.148) (Figure 6-1). The condition effect was dependent upon putting distance though (Putt Length*Condition interaction, p=0.006). Post-hoc Bonferroni comparisons found that T_{FA1} duration on 6 foot putts was longer in competition than in training (Competition, 48±4ms†; Training, 40±4ms†, p=0.047) but on 10 foot putts T_{FA1} was found to be longer in training (Competition, 36±4ms†; Training, 44±4ms†; p=0.050).

Figure 6-1: T_{FA1} Duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.



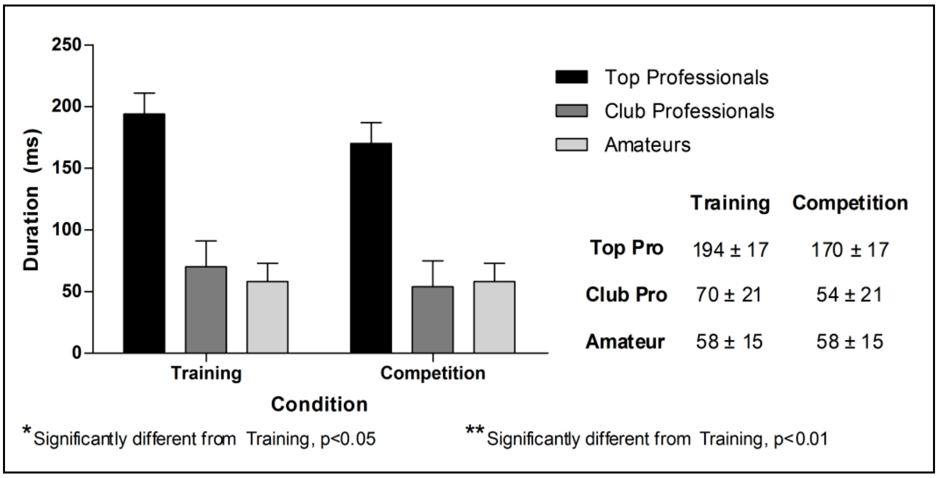
Overall, T_{FA1} duration was not different on 6 foot and 10 foot putts (6 foot, 44±3ms†; 10 foot, 43±2ms†, p=0.276), and the difference was unaffected by skill (Skill*Putt Length interaction, p=0.234). Skill was a significant factor for T_{FA1} duration overall (p<0.001), as demonstrated previously; T_{FA1} duration was similar in Top and Club Professionals (p=1.000), but was significantly shorter in the Amateurs compared with both Top (p<0.001) and Club (p<0.001) Professionals.

Although the interaction of condition and putt length was significant for T_{FA1} duration, the results are difficult to interpret because T_{FA1} was longer under competition conditions on 6 foot putts, but shorter under competition conditions on 10 foot putts. The inconsistency in the results again suggests that T_{FA1} may not be an important influential parameter of the putting vision strategy.

6.3.1.2.2 T_{FAQ}

Overall, condition was not a significant factor affecting T_{FAQ} duration ($p=0.120$) (Figure 6-2). Condition was unaffected by skill (Skill*Condition interaction, $p=0.463$) and putt length (Putt Length*Condition interaction, $p=0.979$).

Figure 6-2: T_{FAQ} Duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.



Skill was a significant factor for T_{FAQ} duration overall ($p<0.001$), and T_{FAQ} was longer in Top Professionals than both Club Professionals ($p<0.001$) and Amateurs ($p<0.001$). Club Professionals and Amateurs had similar T_{FAQ} durations ($p=1.000$).

Putt length overall was not a significant factor for T_{FAQ} duration ($p=0.898$) and was independent of golfers' skill (Skill*Putt Length interaction, $p=0.819$) and the putting condition (Putt Length*Condition, $p=0.979$).

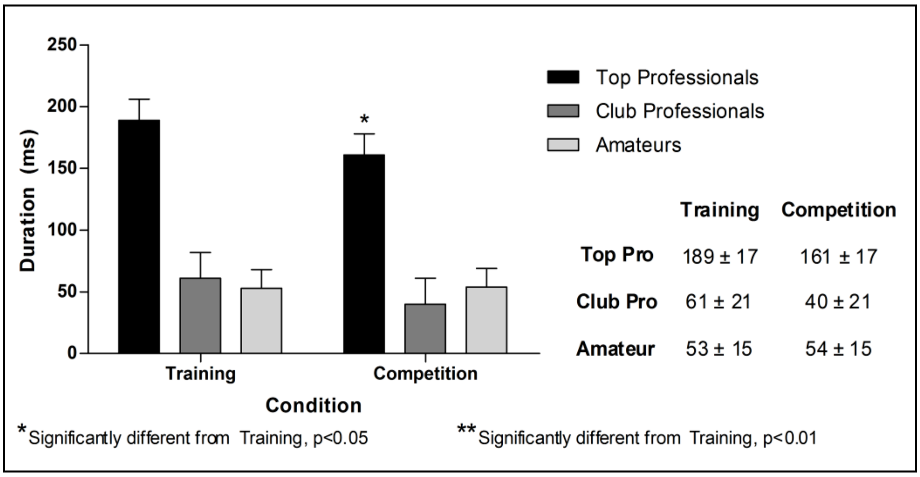
These results suggest that T_{FAQ} duration is an important part of the putting vision strategy, as it is unchanged between the training and competition models.

6.3.1.2.3 T_{FS1}

Overall, there was a trend towards condition being a significant factor affecting T_{FS1} duration ($p=0.054$) (Figure 6-3); this trend was independent of golfers' skill (Skill*Condition interaction, $p=0.268$) and the putting distance (Putt Length*Condition interaction, $p=0.657$). Examination of the post-hoc Bonferroni comparisons revealed that for Top Professionals T_{FS1} was significantly longer in training than in competition (p=0.049). In both Club Professionals (p=0.201) and Amateurs (p=0.955) T_{FS1} duration was similar in both conditions.

Skill was a significant factor for T_{FS1} duration overall (p<0.001); Top Professionals had significantly longer T_{FS1} durations than Club Professionals (p<0.001) and Amateurs (p<0.001). The effect of skill was independent of the putt length (Skill*Putt Length interaction, p=0.848). Putt length itself was not a significant factor affecting T_{FS1} duration (p=0.718).

Figure 6-3: T_{FS1} Duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.

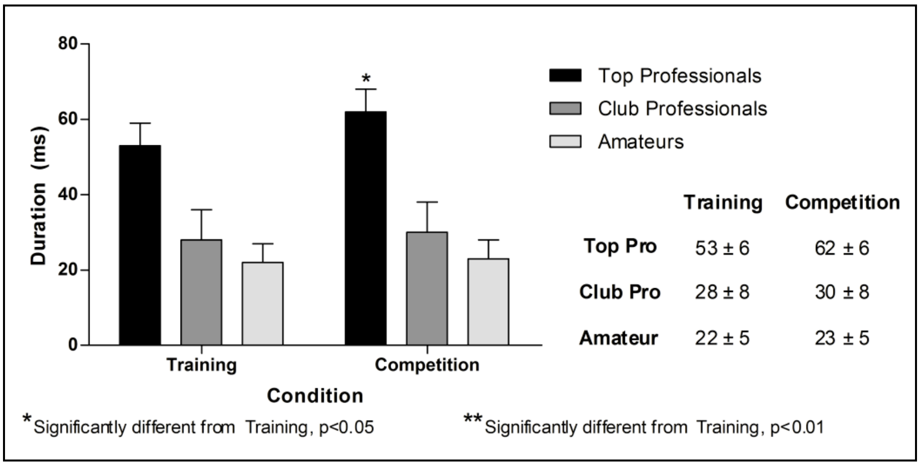


6.3.1.2.4 T_{FSQ}

Overall, condition was not a significant factor affecting T_{FSQ} duration (p=0.149) (Figure 6-4), and the effect of condition was unaffected by skill (Skill*Condition interaction, p=0.357) and the putting distance (Putt Length*Condition interaction, p=0.637).

Skill was a significant factor for T_{FSQ} duration overall (p<0.001); Top Professionals had significantly longer T_{FSQ} durations than Club Professionals (p=0.009) and Amateurs (p<0.001); T_{FSQ} duration was similar in Club Professionals and Amateurs (p=1.000). The effect of skill was independent of the putt length (Skill*Putt Length interaction, p=0.400). Putt length itself was not a significant factor affecting T_{FS1} duration (p=0.357).

Figure 6-4: T_{FSQ} Duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.

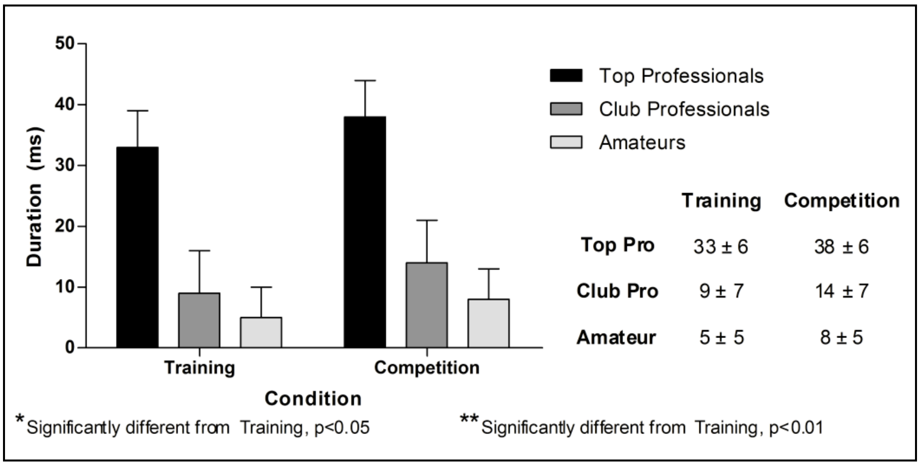


6.3.1.2.5 T_{FCQ}

Condition was not a significant factor affecting T_{FCQ} duration overall (p=0.217) (Figure 6-5); the effect of condition was unaffected by skill (Skill*Condition interaction, p=0.946) and putt length (Putt Length*Condition interaction, p=0.852).

Putt length itself was not a significant factor for T_{FCQ} duration overall (p=0.609) and was independent of skill (Skill*Putt Length interaction, p=0.623). Skill was a significant factor for T_{FCQ} duration overall (p<0.001); Top Professionals had significantly longer T_{FSQ} durations than Club Professionals (p=0.010) and Amateurs (p<0.001); T_{FSQ} duration was similar in Club Professionals and Amateurs (p=1.000).

Figure 6-5: T_{FCQ} Duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.

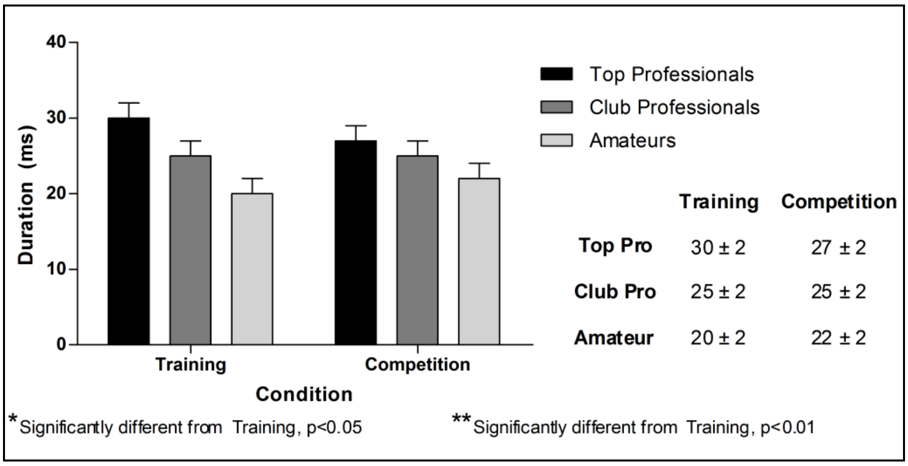


6.3.1.2.6 T_{FPQ}

Overall, condition was not a significant factor affecting T_{FPQ} duration (p=0.560) (Figure 6-6); condition was independent of skill (Skill*Condition interaction, p=0.267) but dependent on putt length (Putt Length*Condition interaction, p=0.028). Post-hoc Bonferroni comparisons found that T_{FPQ} was longer in training (26±2ms†) than competition (22±2ms†, p=0.049) on 6 foot putts. On 10 foot putts T_{FPQ} was similar in training (26±2ms†) and competition (24±2ms†, p=0.249). Despite the statistical significance of the difference in T_{FPQ} duration between training and competition on 6 foot putts, the difference is very small (4ms), and unlikely to be of any clinical significance.

Putt length was not a significant factor for T_{FPQ} duration overall (p=0.449) and was independent of skill (Skill*Putt Length interaction, p=0.194). On the other hand, skill was a significant factor for T_{FPQ} duration (p=0.001) overall. Top and Club (p=0.635) Professionals had similar T_{FPQ} durations. In Amateurs T_{FPQ} was significantly shorter than both Top Professionals (p=0.001) and similar to Club Professionals (p=0.154).

Figure 6-6: T_{FPQ} Duration (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.

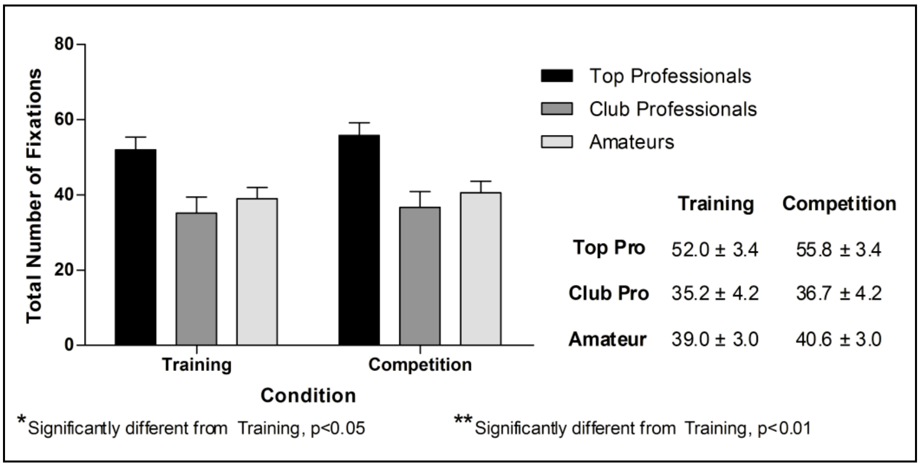


6.3.1.2.7 Total Number of Fixations in Address

There was an overall trend towards the Total Number of Fixations made in the Address phase being greater in competition (44.4±2.1†) than in training (42.1±2.1†, p=0.092), which was independent of skill (Skill*Condition interaction, p=0.737) and putt length (Putt Length*Condition interaction, p=0.928). Post-hoc Bonferroni comparisons showed that there was a trend towards Top Professionals making more fixations in competition than in training (p=0.098). Furthermore, Top Professionals made more fixations than Club Professionals (Training, p=0.002; Competition, p=0.001) and Amateurs (Training, p=0.005; Competition, p=0.001) under both conditions (Figure 6-7).

Skill was a significant overall factor for the Total Number of Fixations in Address (p=0.001); Top Professionals made significantly more fixations than both Club Professionals (p=0.002) and Amateurs (p=0.004). The effect of skill was independent of the putt length (Skill*Putt Length interaction, p=0.705); putt length itself was not a significant overall factor affecting the Total Number of Fixations (p=0.494).

Figure 6-7: Total Number of Fixations in Address (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.



6.3.1.2.8 Mean Fixation Duration in Address

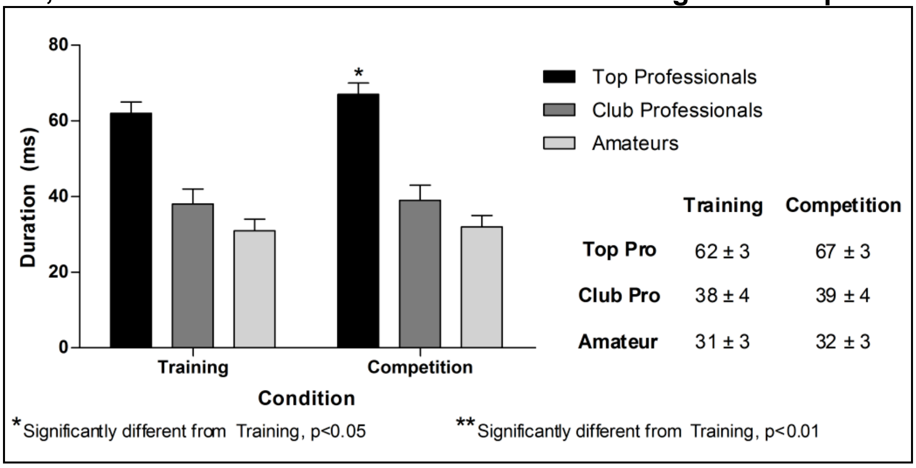
Mean Fixation Duration was significantly affected by condition overall (p=0.045); the effect was independent of skill (Skill*Condition interaction, p=0.266) and putt length (Putt Length*Condition interaction, p=0.114). The Mean Fixation Duration was statistically significantly longer in competition ($46 \pm 2ms^{\dagger}$) than in training ($44 \pm 2ms^{\dagger-}$), however the small magnitude of the difference (2ms) is below the clinical significance threshold and without practical consequence (Figure 6-8).

Skill was once again a significant overall factor affecting the Mean Fixation Duration, and the effect was independent of the putt length (Skill*Putt Length interaction, p=0.945). Top

Professionals had significantly longer Mean Fixation Durations than both Club Professionals (p<0.001) and Amateurs (p<0.001). Mean Fixation Durations in the Address were similar between Club Professionals and Amateurs (p=0.324).

Putt length was not a significant factor affecting the Mean Fixation Duration overall (p=0.647).

Figure 6-8: Mean Duration of Address Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.

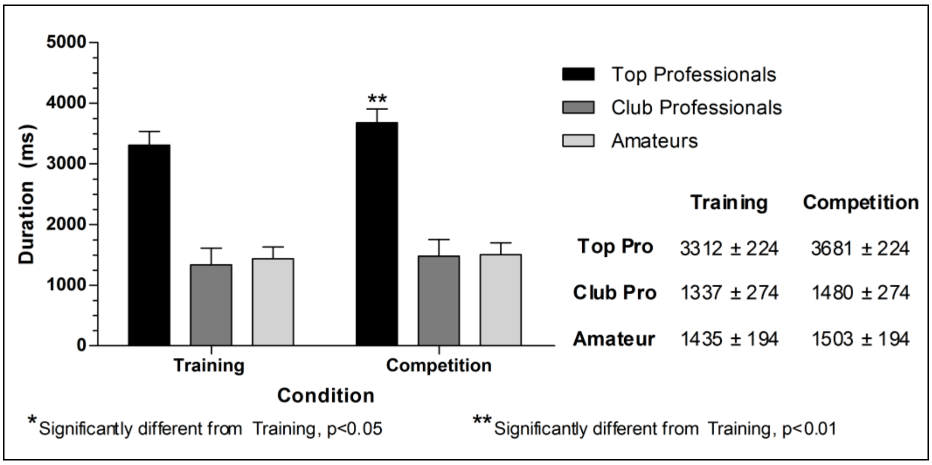


6.3.1.2.9 Total Fixation Duration in Address

Condition was a highly significant factor affecting the Total Fixation Duration in the Address (p<0.001) and more time was spent fixating the ball during competition (2221±134ms†) than during training (2203±134ms†). The effect of condition was highly dependent on skill (Skill*Condition interaction, p=0.039) but was independent of putt length (Putt Length*Condition interaction, p=0.367). Post-hoc Bonferroni comparisons demonstrated that Top Professionals had significantly longer Total Fixation Durations under both conditions than Club Professionals (Training, p<0.001; Competition, p<0.001) and Amateurs (Training, p<0.001; Competition, p<0.001). Top Professionals also had significantly longer Total Fixation Durations in competition compared with training (p<0.001). Total Fixation Durations between Club Professionals and Amateurs were similar for both the competition (p=0.945) and training (p=0.771) conditions. Training and competition Total Fixation Durations were also similar in Club Professionals (p=0.192) and Amateurs (p=0.377) (Figure 6-9).

Overall skill was a significant factor for Total Fixation Duration (p<0.001); this effect was dependent on condition as discussed above (Skill*Condition interaction, p=0.039) and independent of the putt length (Skill*Putt Length interaction, p=0.920). Total Fixation Duration was significantly longer in Top Professionals than both Club Professionals (p<0.001) and Amateurs (p<0.001); Total Fixation Duration was similar in Club Professionals and Amateurs (p=1.000). Putt length (overall) was not a significant factor for Total Fixation Duration (0.804).

Figure 6-9: Total Duration of Address Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.



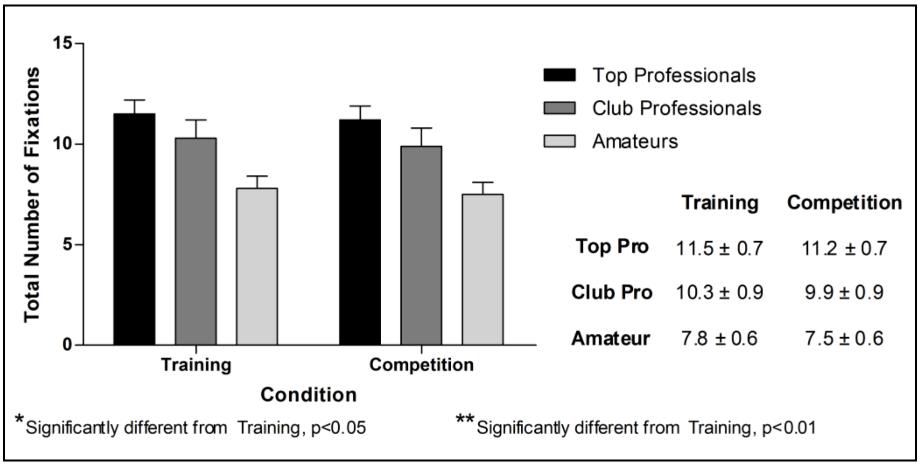
These results clearly indicate that Top Professional golfers spend more time fixating the ball during Address in competition than they do in training. Under competition conditions, golfers only have one attempt at each putt whereas under training conditions golfers can make the same putt many times. The decreased amount of time spent fixating the ball under training conditions compared with competition is likely a result of an increased familiarity with the specific putt, which resulted from repetition. This is important for future studies, and needs to be considered when designing studies of the putting vision strategy, as it is important to differentiate between training and competition conditions.

6.3.1.2.10 Total Number of Fixations in the Swing

Overall, condition was not a significant factor for the Total Number of Fixations made during the Swing phase (p=0.123) (Figure 6-10); the effect of condition was independent of both skill (Skill*Condition interaction, p=0.988) and putting distance (Putt Length*Condition interaction, p=0.345). Putting distance (overall) was not a significant factor for the Total Number of Fixations in the Swing (p=0.748).

On the other hand, skill (overall) was a significant factor affecting the Total Number of Fixations in the Swing; this effect was independent of putting distance (Skill*Putt Length interaction, p=0.964). Top Professionals and Club Professionals made similar numbers of fixations (p=0.828); Amateurs made fewer swing fixations than both professional skill groups (Top, p=0.001; Club, p=0.077) although the difference from Club Professionals only trended towards significance.

Figure 6-10: Total Number of Fixations in the Swing (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.

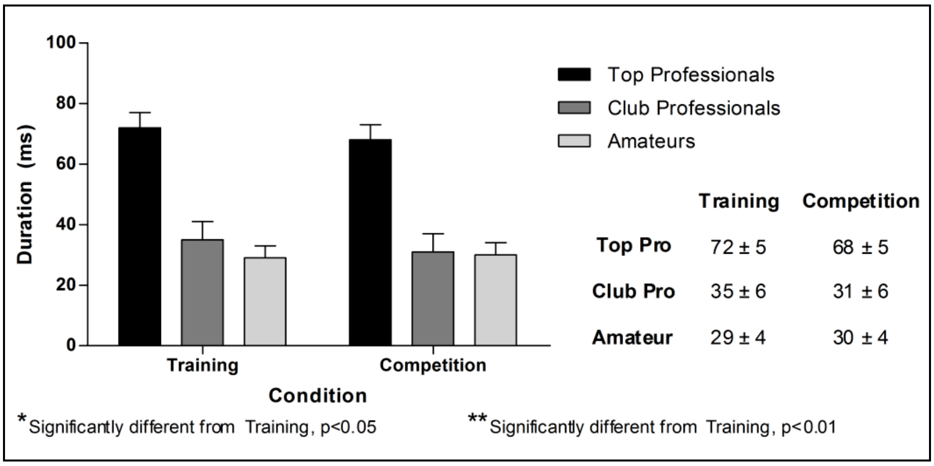


6.3.1.2.11 Mean Fixation Duration in the Swing

Mean Fixation Duration was not significantly affected by condition overall (p=0.229) and the effect of condition was independent of skill (Skill*Condition interaction, p=0.335) and putt length (Putt Length*Condition interaction, p=0.211) (Figure 6-11). Putt length overall was not a significant factor for Mean Fixation Duration in the Swing either (0.873).

Skill overall was a significant factor affecting Mean Fixation Duration (p<0.001); Top Professionals had significantly longer Mean Fixation Durations than both Club Professionals (p<0.001) and Amateurs (p<0.001); Mean Fixation Duration was similar in Club Professionals and Amateurs (p=1.000). The effect of skill was independent of putt length (Skill*Putt Length interaction, p=0.989).

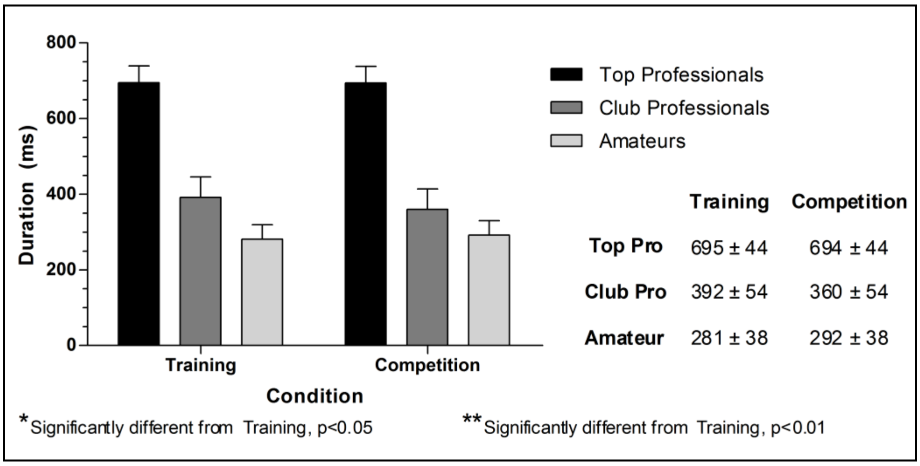
Figure 6-11: Mean Duration of Swing Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.



6.3.1.2.12 Total Fixation Duration in the Swing

Overall, the Total Fixation Duration was not affected by condition (p=0.576) and condition was independent of both skill (Skill*Condition interaction, p=0.437) and putt length (Putt Length*Condition, p=0.820) (Figure 6-12). Putt length overall was not a significant factor for Total Fixation Duration (p=0.788) and was independent of skill (Skill*Putt Length interaction, p=0.996).

Figure 6-12: Total Duration of Swing Fixations (mean ± standard error) for Top Professionals, Club Professionals and Amateurs in Training and Competition models.



Skill was a significant overall factor for Total Fixation Duration; Total Fixation Duration was significantly longer in Top Professionals than in Club Professionals (p<0.001) and Amateurs

($p<0.001$). Total Fixation Duration was similar in Club Professionals and Amateurs ($p=0.510$).

These results demonstrate that the Swing phase fixation parameters are consistent irrespective of the conditions a golfer is putting under. This has important implications with regards to training the putting vision strategy, as it suggests that changes made to the putting vision strategy under training conditions will transfer to the putting vision strategy in competition.

6.3.2 Ocular Dominance

6.3.2.1 Overall Population

17 golfers (Top Professionals, 5; Club Professionals, 3; Amateurs, 9) had a dominant eye in putting gaze. The remaining 10 golfers did not have any ocular dominance in putting gaze (Top Professionals, 4; Club Professionals, 3; Amateurs, 3). The distribution of ocular dominance was similar in the Top and Club Professional groups with approximately half the population having a dominant eye (Top Professionals, 55.6%; Club Professionals, 50.0%) and half the population having no ocular dominance (Top Professionals 44.4%; Club Professionals, 50.0%). In the Amateur group, the vast majority (75.0%) of golfers had a dominant eye.

Table 6-2 displays the results of the Spearman correlation analysis for the dominant and non-dominant eye fixation parameters that was conducted on golfers with ocular dominance. With the exception of T_{FPQ}, which was not correlated between the dominant and non-dominant eyes, the durations of the key fixations demonstrated statistically significant weak to moderate correlations. The Address phase fixation parameters demonstrated significant moderate to strong correlations between the dominant and non-dominant eyes; the Swing phase the fixation parameters were moderately correlated and statistically significant.

Table 6-3 displays the results of the Spearman correlation analysis for the right and left eyes of golfers with no ocular dominance. The durations of T_{FA1}, T_{FAQ} and T_{FS1} demonstrated significant but weak correlations between the right and left eyes of golfers with no ocular dominance, but the durations of T_{FSQ}, T_{FCQ} and T_{FPQ} were not correlated. In golfers with no ocular dominance, weak to moderate correlations were observed between the right and left eyes for all of the Address and Swing phase fixation parameters.

Parameter	Dominant Eye	Non-Dominant Eye	Spearman r-value
T_{FA1} Duration	39.3 ± 39.5	39.9 ± 42.1	0.280**
T_{FAQ} Duration	126.7 ± 168.9	117.8 ± 163.6	0.447**
T_{FS1} Duration	123.5 ± 169.3	108.1 ± 162.9	0.511**
T_{FSQ} Duration	40.4 ± 70.8	29.0 ± 24.9	0.190**
T_{FCQ} Duration	21.2 ± 66.9	13.0 ± 28.0	0.281**
T_{FPQ} Duration	27.3 ± 30.1	23.4 ± 13.4	0.088
Total Number Ball Fixations (A)*	47.4 ± 25.8	44.3 ± 24.7	0.786**
Average Ball Fixation Duration (A)	43.6 ± 27.0	42.9 ± 25.0	0.675**
Total Ball Fixation Duration (A)	2322.2 ± 1829.4	2240.6 ± 1945.6	0.836**
Total Number Ball Fixations (S)*	9.0 ± 5.2	8.8 ± 5.2	0.502**
Average Ball Fixation Duration (S)	55.2 ± 69.5	44.0 ± 35.9	0.612**
Total Ball Fixation Duration (S)	475.7 ± 383.8	431.7 ± 365.1	0.693**

**Count data without unit; **Correlation is significant at p < 0.01*

Table 6-2: Mean ± standard deviations and Spearman correlation values for the comparison of dominant and non-dominant eye gaze data in the sub-group of the population with ocular dominance (skill groups pooled). Mean ± standard deviations are reported in milliseconds (ms) except for the Total Number of Ball Fixations in the Address (A) and Swing (S) which are count data and do not have units.

Parameter	Right Eye	Left Eye	Spearman r-value
T_{FA1} Duration	36.0 ± 41.0	41.7 ± 56.1	0.236**
T_{FAQ} Duration	55.7 ± 48.5	100.6 ± 150.5	0.286**
T_{FS1} Duration	51.3 ± 46.8	95.7 ± 151.9	0.371**
T_{FSQ} Duration	27.2 ± 21.2	35.5 ± 41.8	0.063
T_{FCQ} Duration	7.5 ± 20.1	17.0 ± 44.3	0.060
T_{FPQ} Duration	21.7 ± 12.8	24.8 ± 22.6	-0.081
Total Number Ball Fixations (A)*	37.8 ± 17.7	35.7 ± 16.1	0.687**
Average Ball Fixation Duration (A)	38.0 ± 16.4	46.0 ± 25.5	0.466**
Total Ball Fixation Duration (A)	1538.7 ± 1045.7	1703.4 ± 1094.2	0.620**
Total Number Ball Fixations (S)*	11.5 ± 4.9	10.4 ± 5.3	0.655**
Average Ball Fixation Duration (S)	33.7 ± 13.2	39.1 ± 26.4	0.423**
Total Ball Fixation Duration (S)	400.6 ± 246.1	451.9 ± 330.8	0.595**

**Count data without unit; **Correlation is significant at p < 0.01*

Table 6-3: Mean ± standard deviations and Spearman correlation values for the comparison of right and left eye gaze data in the sub-group of the population with no ocular dominance (skill groups pooled). Mean ± standard deviations are reported in milliseconds (ms) except for the Total Number of Ball Fixations in the Address (A) and Swing (S) which are count data and do not have units.

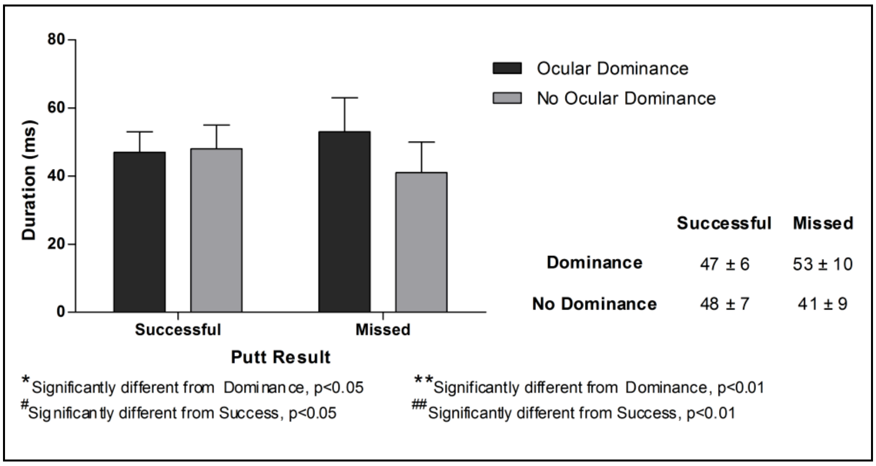
6.3.2.2 Professional Golfers: Dominance versus No Dominance

These results are based upon an analysis of the two sub-groups of Professional golfers with and without ocular dominance. Amateurs were not included in this analysis, as most of the Amateurs had a dominant eye, and this would have created an unbalanced sample with almost twice as many individuals in the dominant eye group.

6.3.2.2.1 T_{FA1}

The presence or absence of ocular dominance was not a significant factor for the duration of the first fixation of the Address (T_{FA1}) (Dominance, 50±7ms†; No Dominance, 45±7ms†; p=0.580) (Figure 6-13). The absence of an effect was independent of the length of the putt (Dominance*Putt Length interaction, p=0.607) and the putt outcome (Dominance*Putt Result interaction, p=0.320). Overall, neither putt outcome (p=0.607) nor putt length (p=0.969) were significant factors for T_{FA1} duration in this group of professional golfers.

Figure 6-13: T_{FA1} Duration (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.

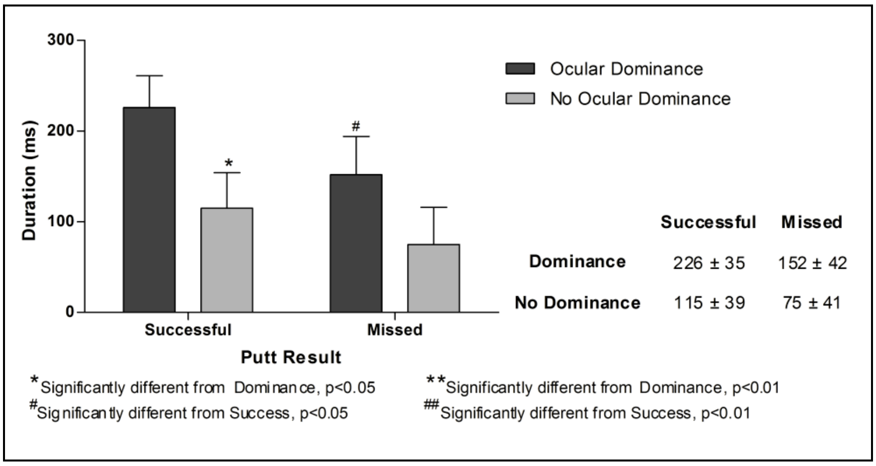


6.3.2.2.2 T_{FAQ}

The duration of T_{FAQ} was 189±35ms† in golfers with ocular dominance and 95±37ms† in golfers without ocular dominance. There was a trend towards the presence of ocular dominance being a significant factor for the duration of T_{FAQ} (p=0.078); this trend was independent of putt length (Dominance*Putt Length interaction, p=0.544) and putt outcome (Dominance*Putt Result interaction, p=0.422).

T_{FAQ} fixations were longer on successful putts overall (Success, 170±26ms†; Missed, 114±29ms†) and putt outcome was a significant factor for T_{FAQ} duration (p=0.008). This effect was independent of the presence of ocular dominance (Dominance*Putt Result interaction, p=0.422), yet it was highly dependent on the length of the putt (Putt Length*Putt Result interaction, p=0.036). Examination of the post-hoc Bonferroni comparisons revealed that T_{FAQ} fixations were significantly longer on successful putts (6 foot, 226±35ms†; 10 foot, 115±39ms†) than on missed putts (6 foot, 152±42ms†; 10 foot, 75±41ms†) but the difference was only significant on shorter putts (6 foot, p=0.016; 10 foot, p=0.181) (Figure 6-14). Putt length (overall) was not a significant factor for T_{FAQ} duration (p=0.738).

Figure 6-14: T_{FAQ} Duration (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



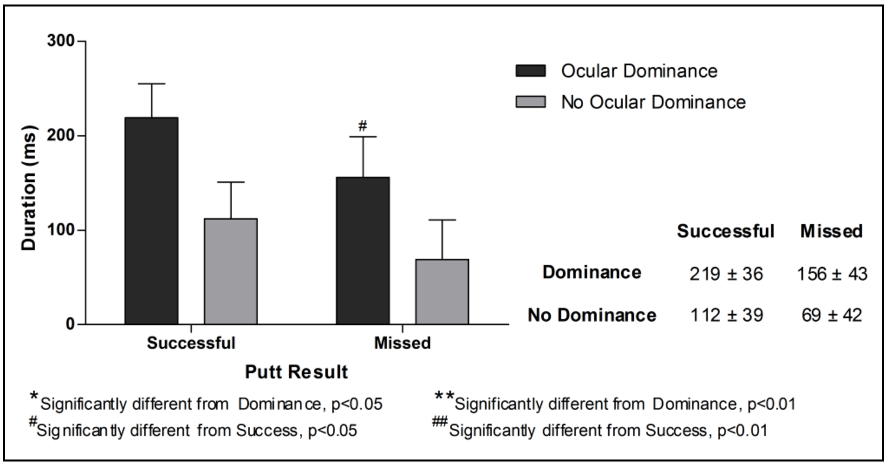
The results presented above clearly demonstrate that longer T_{FAQ} fixations are associated with putting success; the results also demonstrate that there is a trend towards T_{FAQ} fixations being longer in golfers with ocular dominance. Therefore the presence of ocular dominance appears to be advantageous when putting.

6.3.2.2.3 T_{FS1}

The duration of the first fixation in the Swing (T_{FS1}) was 187±36ms† in golfers with ocular dominance and 90±38ms† in golfers without ocular dominance. Much like with T_{FAQ}, there was a trend towards the presence of ocular dominance being a significant factor for the duration of T_{FS1} (p=0.073), which was independent of putt length (Dominance*Putt Length interaction, p=0.614) and putt outcome (Dominance*Putt Result interaction, p=0.624) (Figure 6-15).

Putt outcome was a significant factor for T_{FS1} duration, and T_{FS1} fixations were longer on successful putts overall (Success, 165±26ms†; Missed, 113±30ms†, p=0.013). The effect of putt outcome was independent of the presence of ocular dominance (Dominance*Putt Result interaction, p=0.624) and there was a trend towards the effect of putt outcome being dependent on putt length (Putt Length*Putt Result interaction, p=0.057). Examination of the post-hoc Bonferroni comparisons revealed that T_{Fs1} fixations were significantly longer on successful putts from 6 feet (Success, 178±37ms†; Missed, 85±45ms†; p=0.005) although there was no difference in T_{FS1} duration on successful and missed putts from 10 feet (Success, 152±38ms†; Missed, 140±39ms†; p=649) (Figure 6-15). Putt length (overall) was not a significant factor for T_{FS1} duration (p=0.776).

Figure 6-15: T_{FS1} Duration (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



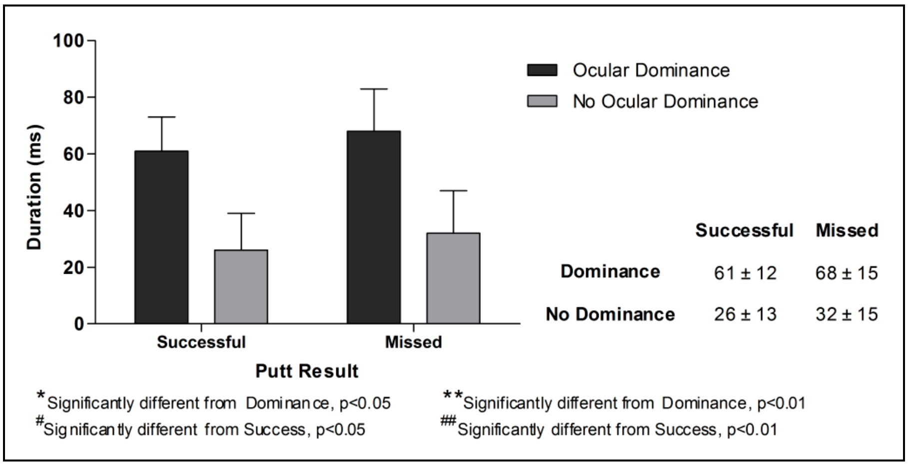
These results suggest that longer T_{FS1} fixations are associated with putting success, especially on shorter putts. The results also demonstrate that there is a trend towards T_{FS1} fixations being longer in golfers with ocular dominance. Therefore the presence of ocular dominance again appears to be advantageous when putting.

6.3.2.2.4 T_{FSQ}

T_{FSQ} duration was significantly longer (p=0.046) in golfers with ocular dominance (Dominance, 65±12ms†; No Dominance 29±12ms†); the effect was independent of both putt length (Dominance*Putt Length interaction, p=0.657) and putt outcome (Dominance*Putt Result, p=0.987) (Figure 6-16).

Overall, T_{FSQ} fixations were similar on successful (43±9ms†) and missed (50±11ms†) and putt outcome was not a significant factor in T_{FSQ} duration (p=0.487). Putt length was not a significant factor for T_{FSQ} duration either (p=0.396) and the effects of putt outcome and putt length were independent (Putt Length*Putt Result interaction, p=0.679) (Figure 6-16).

Figure 6-16: T_{FSQ} Duration (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



The duration of T_{FSQ} was approximately twice as long in golfers with ocular dominance compared to golfers without ocular dominance. This difference is consistent with the findings for both T_{FAQ} and T_{FS1}, and suggests that golfers with ocular dominance have more stable gaze behaviours, which persist throughout the entire Swing phase.

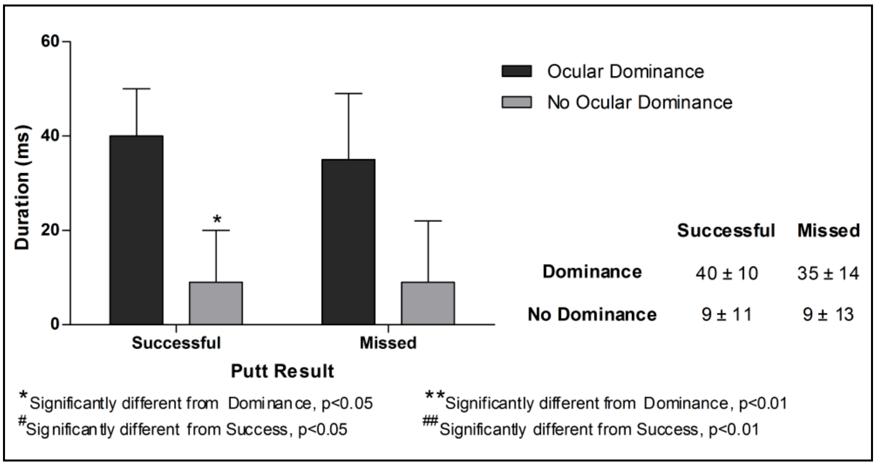
6.3.2.2.5 T_{FCQ}

There was a trend towards the T_{FCQ} fixation being longer (p=0.055) in golfers with ocular dominance (38±10ms†) than in golfers with no ocular dominance (9±10ms†). The effect of ocular dominance was independent of putt length (Dominance*Putt Length interaction, p=0.715) and putting success (Dominance*Putt Result, p=0.782) (Figure 6-17).

Overall, putt outcome was not a significant factor in T_{FCQ} fixation duration (Success, 25±7ms†; Missed, 22±10ms†, p=0.802). Putt length was also not a significant factor for T_{FCQ} duration (p=0.539) and the effects of putt outcome and putt length were independent (Putt Length*Putt Result interaction, p=0.982) (Figure 6-17).

The duration of T_{FCQ} was approximately four times as long in golfers with ocular dominance compared to golfers without ocular dominance, which again suggests that golfers with ocular dominance have more stable gaze behaviours, which are maintained throughout the Swing phase.

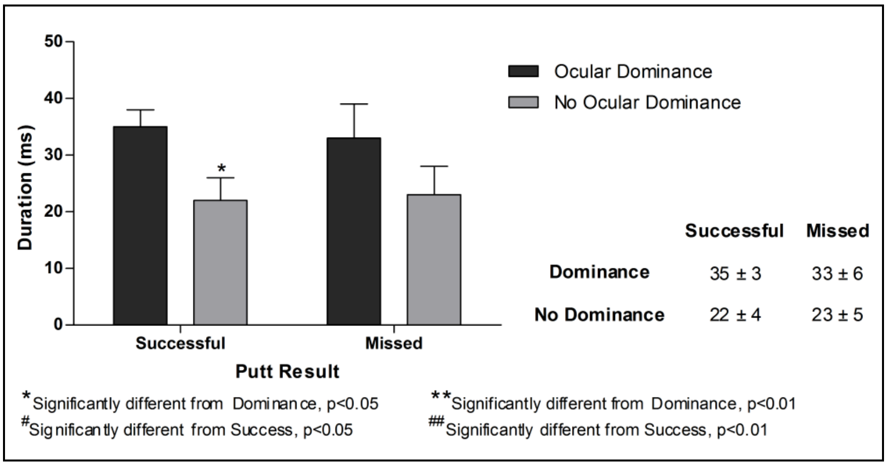
Figure 6-17: T_{FCQ} Duration (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



6.3.2.2.6 T_{FPQ}

T_{FPQ} fixations were significantly longer (p=0.031) in golfers with ocular dominance (34±4ms†) than in golfers with no ocular dominance (23±4ms†); the effect was independent of putt length (Dominance*Putt Length interaction, p=0.253) and putting success (Dominance*Putt Result, p=0.766) (Figure 6-18).

Figure 6-18: T_{FPQ} Duration (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



Overall, putt outcome (p=0.993) and putt length (p=0.230) were not a significant factors for T_{FPQ} duration and their effects were independent (Putt Length* Putt Result interaction, p=0.794) (Figure 6-18).

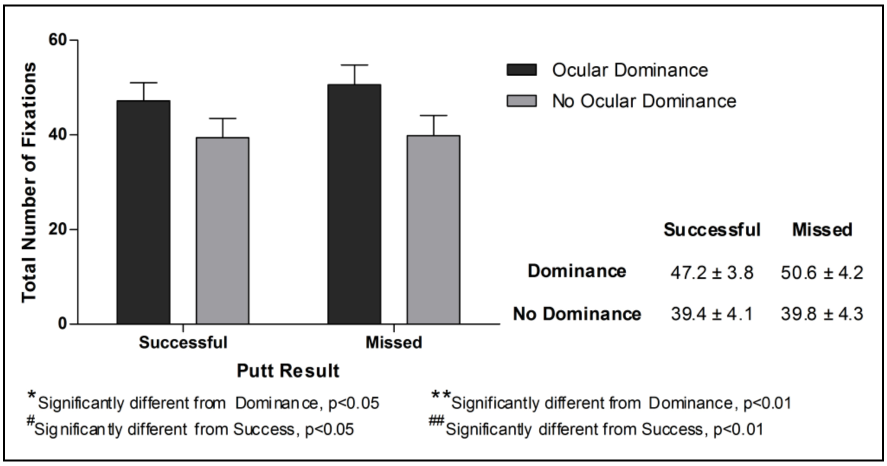
These results further confirm that ocular dominance is associated with longer, more stable fixations in golfers of equal skill level. The increased stability seems to consistent throughout the critical Swing, Contact and Post-contact phases.

6.3.2.2.7 Total Number of Fixations in Address

The presence or absence of ocular dominance was not a significant factor for the Total Number of Fixations made in Address, but there was a trend towards golfers with ocular dominance making more fixations compared to golfers with no ocular dominance (Dominance, 48.9±3.8†; No Dominance, 38.6±4.0†; p=0.104) (Figure 6-19). The trend towards an effect was independent of putt length (Dominance*Putt Length interaction, p=0.877) and the putt outcome (Dominance*Putt Result interaction, p=0.385).

Overall, putt outcome (p=0.601) and putt length (p=0.271) were not significant factors for the Total Number of Fixations in Address and were independent factors (Putt Length*Putt Result, p=0.396).

Figure 6-19: Total Number of Fixations in Address (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.

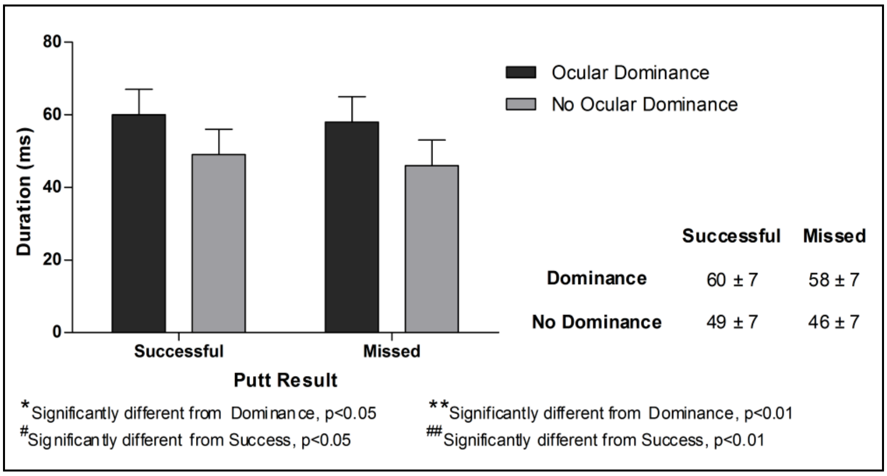


6.3.2.2.8 Mean Fixation Duration in Address

Ocular dominance was not a significant factor for the Mean Fixation Duration (p=0.227), and the effect of ocular dominance was independent of putt length (Dominance*Putt Length interaction, p=0.919) and putt outcome (Dominance*Putt Result interaction, p=0.666) (Figure 6-20).

Putt outcome (p=0.123) and putt length (p=0.961) overall were not significant factors for the Mean Fixation Duration in Address; putt outcome and putt length were also independent factors (Putt Length*Putt Result interaction, p=0.952).

Figure 6-20: Mean Duration of Address Fixations (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.

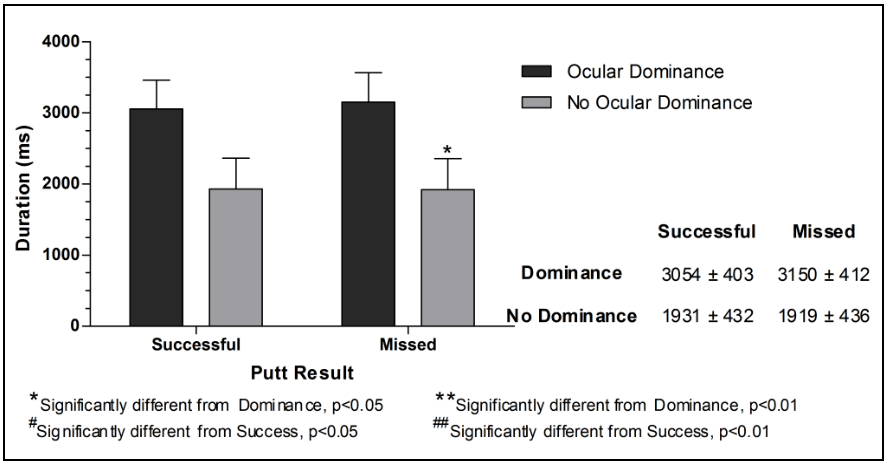


6.3.2.2.9 Total Fixation Duration in Address

There was a trend towards ocular dominance being a significant factor for the Total Fixation Duration in Address (Dominance, 3102±404ms†; No Dominance, 1925±430† p=0.055); this trend was independent of both putt length and putt outcome (Dominance*Putt Length interaction, p=0.915; Dominance*Putt Result interaction, p=0.502) (Figure 6-21).

Overall, putt outcome (p=0.855) and putt length (p=0.599) were not significant factors for the Total Fixation Duration and were independent of each other (Putt Length*Putt Result, p=0.226).

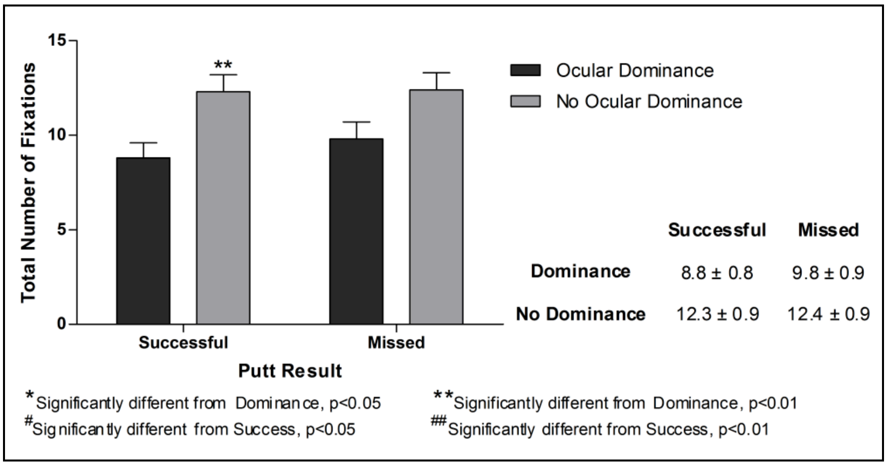
Figure 6-21: Total Fixation Duration in Address (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



6.3.2.2.10 Total Number of Fixations in the Swing

The presence of ocular dominance was a significant factor for the Total Number of Fixations made during the Swing (Dominance, 9.3±0.8†; No Dominance, 12.4±0.8†; p=0.011), but the effect was independent of putt length (Dominance*Putt Length interaction, p=0.823) and putt result (Dominance*Putt Result interaction, p=0.275) (Figure 6-22).

Figure 6-22: Total Number of Fixations in the Swing (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



Overall, putt result was not a significant factor for the Total Number of Fixations (p=0.151) but it was highly dependent on putt length (Putt Length*Putt Result interaction, p=0.030). Post-hoc Bonferroni comparisons showed that for 6 foot putts, significantly fewer fixations were made on successful putts (10.1±0.8†) than on missed putts (11.6±0.9†, p=0.021). For 10 foot putts there was no difference in the number of fixations made on successful (10.9±0.8†) and missed (10.6±0.8, p=0.556†) putts. Putt length (overall) was not a significant factor for the Total Number of Fixations in the Swing (p=0.917).

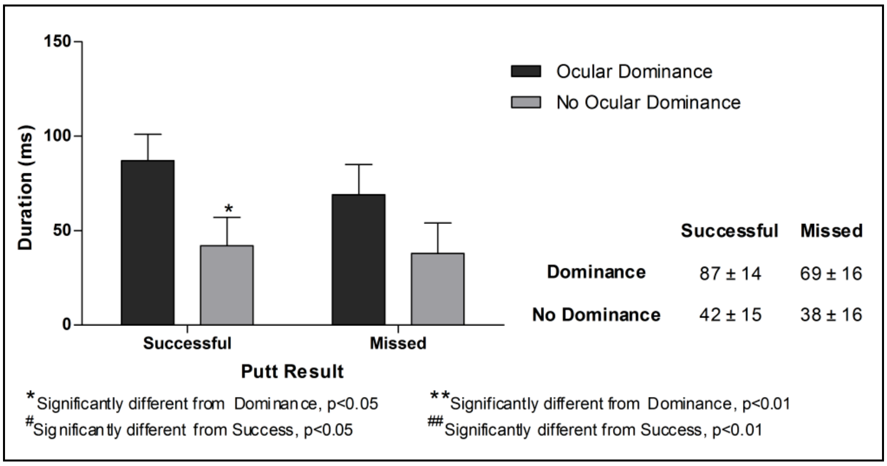
The results presented above indicate that golfers with ocular dominance made fewer fixations in the Swing than golfers with no ocular dominance. Making fewer fixations in the Swing phase is also associated with increased putting success, at least on short putts. Therefore the presence of ocular dominance again appears to be advantageous when putting.

6.3.2.2.11 Mean Fixation Duration in the Swing

Golfers with ocular dominance had a Mean Swing Fixation Duration of 78±14ms†, which was longer than the Mean Swing Fixation Duration of golfers with no ocular dominance (40±14ms†). There was a trend towards ocular dominance being a significant factor for Mean Fixation Duration (p=0.066), which was independent of putt length (Dominance*Putt Length interaction, p=0.936) and putt outcome (Dominance*Putt Result interaction, p=0.282) (Figure 6-23).

There was a trend towards putt outcome being a significant factor for Mean Fixation Duration (p=0.116); this trend was dependent on putt length (Putt Length*Putt Result interaction, p=0.081), although putt length overall was not a significant factor for Mean Fixation Duration (p=0.939). On 6 foot putts, Mean Fixation Duration was significantly longer on successful putts (70±14ms†) compared with missed putts (47±16ms†, p=0.033). On 10 foot putts, Mean Fixation Duration was similar on successful (59±14ms†) and missed (60±15ms†, p=0.890) putts (Figure 6-23).

Figure 6-23: Mean Duration of Swing Fixations (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



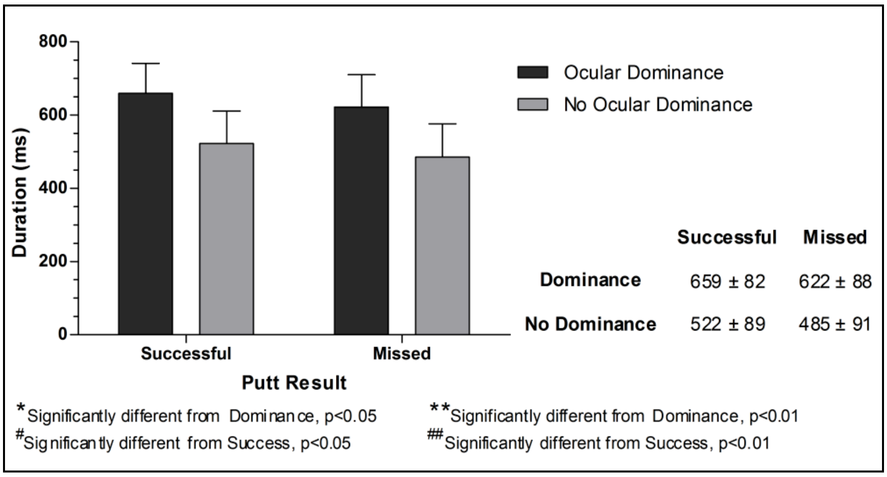
These results demonstrate that there is a trend towards golfers with ocular dominance making longer fixations throughout the Swing phase than golfers with no ocular dominance. There also appears to be a trend towards longer fixations in the Swing phase being associated with putting success.

6.3.2.2.12 Total Fixation Duration in the Swing

Ocular dominance was not a significant factor for the Total Fixation Duration in the Swing (Dominance, 641±82ms†; No Dominance, 503±87ms†; p=0.261) (Figure 6-24). The absence of an effect was independent of both putt length (Dominance*Putt Length interaction, p=0.903) and putt outcome (Dominance*Putt Result interaction, p=0.992). Neither putt length (p=0.223) nor putt length (p=0.903) were significant factors overall for the Total Fixation Duration in the Swing, and they were independent of each other (Putt Length*Putt Result interaction, p=0.837).

Total Fixation Duration in the Swing was not different between golfers with ocular dominance and golfers with no ocular dominance because both ocular dominance and success are associated with making fewer fixations of longer duration whereas no ocular dominance and failure are associated with making more fixations of shorter duration. These two distinctly different strategies result in similar Total Swing Fixation Durations.

Figure 6-24: Total Fixation Duration in the Swing (mean ± standard error) for Professional golfers with and without ocular dominance on successful and missed putts.



6.4 Discussion

The results presented above provide novel perspectives on the vision strategy of golf putting. The training versus competition analysis explores the relationship between a single putt, representative of the scenario golfers face on every putt in a round, and a series of putts, which are representative of golfer's overall performance. The ocular dominance analysis was the first of its kind, and explored the relationship between ocular dominance and putting vision strategy using an eye tracking system.

6.4.1 Training and Competition

The results of the correlation analysis give some indication of the consistency of golfers' behaviours. Overall, the general Address and Swing phase fixation parameters displayed high correlations between the training and competition models in all skill groups, which suggest that golfers' overall gaze behaviours within a particular putting phase are fairly consistent. Interestingly, the duration of the key fixations demonstrated variable, skill dependent correlations between the two putting conditions, suggesting that there is some inconsistency in these parameters.

In Top Professionals the gaze behaviours examined in the training and competition models were very similar, and strong correlations were observed for many of the fixation parameters at both 6 and 10 feet, including the durations of T_{FAQ} and T_{FS1} and the general Address and Swing fixation parameters. Club Professionals and Amateurs on the other hand were found to have poor correlations between the models on the duration of the key fixations, despite strong correlations in the general Address and Swing phase parameters. Of the three groups compared, Top Professionals appear to have the most consistency in their results, as demonstrated by the large number of highly correlated gaze parameters. Club Professionals displayed better consistency in their gaze behaviours on 6 foot putts compared with 10 foot putts, as more individual fixations were correlated at 6 feet. As could be expected, Amateur golfers had the lowest consistency between models at both distances. As consistency is often an important aspect of performance in competitive sports, it is not surprising to see golfers of higher skill levels displaying greater consistency.

In the linear mixed model analysis, condition was found to be a significant factor for the Mean and Total Fixation Durations during the Address, and there was a trend towards condition being a significant factor in the Total Number of Fixations made during the Address and the duration of T_{FS1}. The remainder of the key fixation parameters and the Swing phase fixation parameters were not different between training and competition, which suggests that for the most part, golfers' vision strategies are similar regardless of the condition.

With respect to the Address phase fixation parameters, golfers of all skill levels tended to make more fixations during first putt (Competition) than they did in training. Golfers also tended to have a longer mean fixation duration during the Address of the first putt, and not surprisingly had a longer Total Fixation duration overall in the competition model. These differences were noted in golfers of all skill levels, but were only significant in Top Professionals. These results indicate that golfers, and in particular Top Professionals, attended more to the conditions of the green on their first putt at each distance than they did with repeated putts from the same distance. On the first putt, there is very little information available to golfers about the exact conditions of the green. The direction and speed with which the ball is hit depends entirely on golfers' ability to read and perceive the contours of the green. With this in mind it would make sense that golfers' would spend more time fixating and attending to visual information in the Address on the first putt; as they learn from the results of previous putts they are able to use other information, such as kinaesthetic memory and visual feedback to improve their performance. As there is only so much information that can be attended to at any particular time, this may be why there is a relative decrease in attention to visual information with repetition of the same putts in training.

The Swing phase fixation parameters were not different between training and competition. This would suggest that these aspects of golfers' vision strategy are less associated with information collection during the putt, and serve other purposes, such as assisting with swing biomechanics.

Apart from T_{FA1} all of the key fixations are associated with the movement phase (golfers' putting stroke) of the putt. As such, these fixations may play key roles in stabilizing golfers' body positions during the backswing, forward swing and follow through of their putting stroke, rather than a role in information collection. There was a trend towards T_{FS1} being longer in training than in competition, which may be a direct result of golfers' attempting to modify their swing behaviours to improve upon the results of previous putts.

As mentioned previously in Chapter 5, Vision Strategy in Golf Putting: Skill and Success, T_{FA1} is the first fixation of a series of fixations and gaze behaviours used in aligning the club and the ball. As golfers will have all developed their own unique methods for this process, it was unlikely that a consistent pattern in the behaviour of T_{FA1} fixations would be observed due to the variability amongst golfers.

6.4.2 Ocular Dominance

Poor correlation was found in comparison of fixation parameters between the dominant and non-dominant eyes of golfers with ocular dominance. This is not a surprising result, as the brain is preferentially attending to information from the dominant eye, the dominant and non-dominant eyes do not receive the same amount of control information or feedback. In golfers with no ocular dominance, poor correlations were found between the right and left eye fixation parameters as well. Although theoretically, the brain attends to both eyes equally when there is no ocular dominance, the pattern of this attention is random and unpredictable, which in turn would create random variation in the amount of attention given to either eye and likely accounts for the variability and poor correlation within these results.

The results of the CHAID analysis presented in Chapter 5, Vision Strategy in Golf Putting: Skill and Success, demonstrated that ocular dominance was a significant predictor of putting success in Top Professionals. The results of the dominance analysis presented in this chapter on a sub-group of Professional golfers with and without ocular dominance support this conclusion.

Apart from T_{FA1} all of the key fixations were significantly longer in the professional golfers with ocular dominance than those without. Both T_{FSQ} and T_{FPQ} were significantly longer in golfers with ocular dominance, and there were trends towards T_{FAQ}, T_{FS1} and T_{FCQ} being longer as well.

Longer durations of T_{FAQ} and T_{FS1} have been previously demonstrated to be associated with higher skill and success, and it is interesting to see that longer durations of these two fixations are also associated with ocular dominance. When the durations of these fixations were compared on successful putts T_{FAQ} and T_{FS1} were both significantly longer in golfers with ocular dominance than golfers without. On missed putts, T_{FAQ} and T_{FS1} were still longer in golfers with ocular dominance, but the difference was not significant. Furthermore, in golfers with ocular dominance T_{FAQ} and T_{FS1} were significantly longer on successful putts compared with missed putts. Therefore, it can be seen that longer durations of T_{FAQ} and T_{FS1} are associated with increased putting success, and ocular dominance is a significant factor influencing the length of these fixations.

It was suggested in Chapter 5, Vision Strategy in Golf Putting: Skill and Success, that longer duration of the contact fixations, T_{FSQ}, T_{FCQ} and possibly T_{FPQ} contributed to golfers' success, in addition to being associated with higher skill. All three of these fixations were longer in golfers with ocular dominance compared to golfers without ocular dominance. On successful putts, the duration of these three fixations was significantly longer in golfers with ocular dominance compared to golfers without ocular dominance, but on unsuccessful putts the duration of the fixations in both of these groups was similar. This would suggest that in golfers with ocular dominance at least, longer duration contact fixations are associated with higher success, although statically there was no difference in the length of these fixations on successful and missed puts in either group.

The significance of the results of the contact fixations is important, even though it is less obvious from a statistical perspective. These fixations are relatively short in duration (30 – 60ms on average), and in many golfers non-existent, particularly T_{FCQ}. The variability within golfers, even those of higher skill levels, with respect to the contact fixations makes it difficult to truly understand the significance of these fixations. This variability is likely due, at least in part, to head and body movement during swing and at ball contact. Despite golfer's best efforts to maintain a steady body position throughout the swing, contact is the most dynamic time point of the entire putting stroke and the measurement of small, precise fixations could be dramatically affected by relatively small head and body position movements. Incorporating a head tracking device is recommended for follow-up studies in order to understand the relationship between head and eye movement during putting. This would make it possible to test the hypothesis that the contact fixations lead to a stabilisation of the head during putting.

With T_{FA1} being a fixation during the alignment process of the putt, it would not have been unrealistic to expect to see ocular dominance have an effect on the duration of this fixation. In reality though, the duration of T_{FA1} was not affected by ocular dominance, and this is likely due to the reasons mentioned before: T_{FA1} is only the first fixation in an alignment processes, rather than the fundamental fixation of this process. It is possible that as one gets closer to the swing the adjustments of the putter are smaller, leading to more stable fixation; also concentration on the visual details of the putter and ball may also lead to more stable fixations.

That being said, ocular dominance did have a significant impact on the overall fixation parameters in the Address phase when alignment was taking place. Golfers with ocular dominance made significantly more fixations to the ball during the Address phase and there was a trend towards golfers with ocular dominance having a longer Total Fixation Duration as well. The difference in the Total Fixation Duration between the two groups of golfers was driven by an increased Total Number of Fixations being made, rather than longer fixations being made because the Mean Fixation Duration in both groups was similar. It is possible then, that having ocular dominance, improved golfers' fixation control and enabled them to make more precise fixations, rather than enabling them to maintain the fixations they made for longer. The Address is a dynamic phase from a visual perspective, with golfers aiming to collect adequate information to ensure their club and ball are accurately aligned; making long duration fixations in this phase is likely less advantageous than making more high quality fixations of lesser duration overall.

Ocular dominance had a significant impact on the Swing fixations as well. In the Swing phase, golfers with ocular dominance made significantly fewer fixations to the ball overall, and on successful and missed putts compared with golfers without ocular dominance. There was also a trend towards golfers with ocular dominance having a longer Mean Fixation Duration overall; on successful putts this trend was significant. There was no difference in golfers Total Swing Fixation Duration with and without ocular dominance. The CHAID analysis presented in the previous chapter demonstrated that making fewer fixations during the swing was associated with higher putting success; as having ocular dominance also contributes to making fewer fixations in the swing, it can be seen that ocular dominance can improve putting success.

6.4.3 Conclusions

6.4.3.1 Training and Competition

Perhaps the most important findings of the training and condition analysis, were (i) for the most part golfers' performance is consistent between training and competition, and (ii) the Address fixation strategy was different between the first putt and repeated putts. Consistency between training and competition is important because this implies that if a golfers' putting vision strategy was improved through specific training paradigms, these improvements would be noticeable in competition. The difference in the Address fixation parameters between the competition model and training models is important for the design of future studies, particularly those focused on reading the green and alignment of the ball: if researchers want to truly mimic the environmental conditions of a round of golf, they may need to constantly vary the distance or the line on which putts are taken in order to assess golfers visual performance independently of other information sources.

Like all data modelling techniques, the training and competition models used in this analysis have their limitations. The training model used in this study was consistent with previously published research, but the competition model was different because it does not involve the use of psychological stressors. The author believes that the model is applicable to competition as the design mimicked a true golf game scenario in which only one putt was considered. In Top Professionals particularly, the stress and anxiety of wanting to perform well are inseparable from their competitive performance. Asking golfers were to mimic their on-field performance as much as possible and go through their entire pre-putt routines makes this model applicable to the real-life situation on the golf course.

6.4.3.2 Ocular Dominance

Prior to the studies conducted in this thesis, the impact of ocular dominance on the vision strategy of golfers had not been examined. The results discussed above demonstrate that ocular dominance is very important in fixation control as it aids in the precise control of golfers' gaze behaviours. Precise gaze behaviours contribute to increased success, therefore ocular dominance is also important for putting success.

To a large extent, ocular dominance is believed to be an inherent physiological characteristic of the visual system. Ocular dominance training may be possible, but it would likely resemble other psychophysical training paradigms involving thousands repetitions in order to obtain small gains. Therefore, training ocular dominance in golfers to improve performance is unrealistic. What is realistic though, is manipulation of their visual environment to create an ocular dominance-type situation (pseudo-ocular dominance). There are many ways in which this can be done, including correction of refractive errors, manipulation of the ball position in a golfer's stance, using monocular fixations and/or specific fixation targets. Some of these methods will be discussed in the following chapter which looks at specific case reports where putting vision strategy has been manipulated in individual golfers.

6.5 Summary

Chapter 6, Vision Strategy in Golf Putting: Training, Competition and Ocular Dominance demonstrated that (i) golfers' putting vision strategies are fairly consistent between training and competition and (ii) ocular dominance is an important factor in putting success because it contributes to precise fixation control. The next chapter, Chapter 7, Case Reports: Vision Training in Golf Putting examines specific examples of putting vision strategy training.

Chapter 7

CASE REPORTS: VISION TRAINING IN GOLF PUTTING

7.1 Introduction

Understanding what attributes of the putting vision strategy are associated with higher levels of skill and success, while important, is of little use if it cannot be transferred to and incorporated into the training of golfers who want to improve their performance.

Previous research has demonstrated that training the quiet eye specifically can improve motor performance in various tasks, [42, 54, 56, 63] including golf putting.[30, 51, 52] In golf putting specifically, Vickers advocated using a video-based paradigm where golfers watched footage from the eye tracker with gaze position markers and received specific instructions regarding the quiet eye. Golfers were also shown videos of an elite prototype (a putting vision strategy expert) and given the opportunity to compare the two sets of video footage.[30] Vine, Moore and Wilson used a similar training paradigm in their study on the effects of quiet eye training in elite golfers.[51] The same author, in an earlier study with novice golfers, used a series of verbal instructions regarding the quiet eye for training purposes.[52]

All three of these methods were found to be effective and golfers in the quiet-eye trained groups demonstrated significant improvement in their quiet-eye duration,[30, 51, 52] which was sustained under pressure,[51, 52] and appeared to be transferable to putting performance in real competition, although putting vision strategy was not assessed in real competition to confirm direct transfer.[51]

While the aforementioned studies demonstrate that the putting vision strategy is amenable to training, there are number of inadequacies with the proposed approach. First of all, none of the studies appeared to consider golfers visual status: statistics on uncorrected vision defects in the general population (applicable to amateur golfers) and elite athletes (applicable to elite golfers)[114] demonstrate that it is likely some golfers suffer from vision defects that would negatively affect vision training. Vision defects fall into two categories: refractive errors and binocular vision defects. Although they may not produce any symptoms or skill difficulties in everyday life, they limit the golfers' visual potential in the highly demanding visual environment characteristic of golf putting. Secondly, all of the studies mentioned above focused their vision training on the quiet eye fixation exclusively. Finally, all of these studies were conducted under monocular conditions, which did not account for binocularity or ocular dominance. This thesis has shown that ocular dominance and the optimisation of its use produces improvement in ocular fixation stabilisation that could be as effective as quiet eye training. More importantly the non-optimisation of ocular dominance will limit the potential of any “quiet eye” training.

7.1.1 Refractive Error?

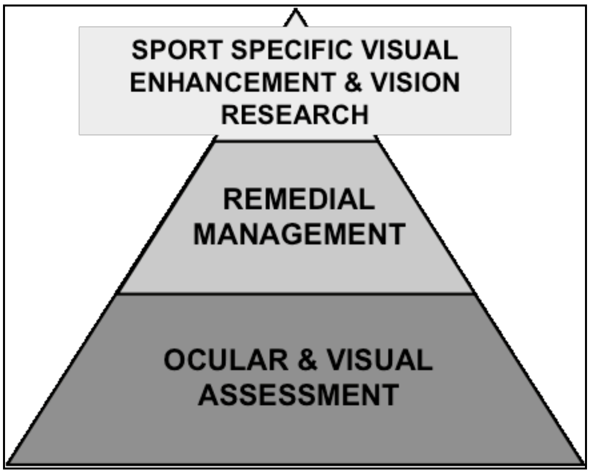
In all sports, golf included, most of the information used to play is visual. Participants in sport rely on information from the environment to adequately respond to the task they are facing. In golf specifically, golfers rely on visual information to be able to accurately read the green, to choose an aim line and a target, to line their ball up with the target, and to line their club up with the ball. Any aspect of this process that is compromised due to a poor vision system has a negative impact on performance.

A 2007 study of American Olympic athletes conducted by the Johnson & Johnson Vision Care Institute found that 87% of athletes believed that vision was important for success in sport.[115] Yet approximately 25% of athletes have never had an eye examination and nearly 30% of them are in need of some sort of visual correction.[114]

With this in mind, Kirschen and Laby (2011) presented a guide to all forms of sports vision work based on a pyramid concept. Items at the bottom of the pyramid were essential to support items further up.[116] A modified version of this pyramid is presented below in Figure 7-1; all of the sports vision training conducted in the Michel Guillon Sports Vision Clinic has been based around this concept.

The base layer of the pyramid is vital to having a vision system which functions optimally and involves a detailed ocular and visual assessment which involves the examination of all aspects of the vision relative to an athlete’s particular sport and identification of any vision problems.

Figure 7-1: Michel Guillon Sports Vision Clinic pyramid; the concepts presented here can be used to guide sports vision interventions in all sport.



The middle layer of the pyramid requires contributions from both optometrists and athletes and involves the management of the issues identified in the base layer. Typically, this layer includes the correction of monocular and binocular refractive errors and addressing binocular vision problems, including issues related to depth perception and fixation disparities. All remedial management is sport and athlete specific.

The top layer of the pyramid includes sport specific vision training and vision strategy enhancement, such as optimising putting vision strategy. Sport specific vision training and vision strategy enhancements are based on the needs of individual athletes and the results of high quality vision research. This level of the pyramid requires a high amount of co-operation between athletes, coaches and vision specialists.

The bottom two layers of the pyramid enable athletes participating in the Michel Guillon Sports Vision Clinic programme to say *“we are not visually inferior to anyone we compete against”* while the top layer of the pyramid enables athletes to say *“while we play, we are visually superior to anyone we compete against”*. The layers of the pyramid are sequential, and sport specific visual enhancement and vision research cannot be undertaken either in isolation or without previous completion of ocular and visual assessment and, if required, remedial management.

This chapter will present some examples of how this pyramid concept has been utilised at the Michel Guillon Sports Vision Clinic to lay the foundations for improved golf performance through the enhancement of putting vision strategy. A large case-controlled study of the effectiveness the putting vision strategy training was not conducted as part of this thesis, but needs to be completed in the future to determine the effectiveness of the training methods employed.

7.2 Methods

7.2.1 Study Participants

The individual cases presented here are of golfers who attended the Michel Guillon Sports Vision Clinic for a full golf-specific optometric examination, a golf-specific optometric screening or a putting vision assessment, and signed an informed consent.

7.2.2 Study Procedures

Visual acuity and ocular dominance were assessed at all visits and golfers were asked to complete a simple questionnaire which asked questions specific to their putting performance (i.e. what grip do you use when you putt, what make of putter do you use, do you put any custom marks on your golf ball, etcetera). If the golfer was at the clinic for a full golf-specific optometric examination than an ocular health assessment (including fundus photography), a binocular vision assessment and a subjective refraction were conducted and a refractive prescription was issued if necessary. When a refractive correction was required to improve a golfer's vision, correction options were discussed with the golfer and appropriate measures were taken to ensure the golfer obtained the appropriate correction. If a golfer attended for an optometric screening, ocular health was assessed with retinal photography, a short binocular vision screening examination using the cover test was carried out and an auto refraction measurement was taken; in the putting-vision assessments, no additional vision testing was completed. If a visual issue (i.e. refractive error or binocular vision defect) was identified on the optometric screening, it was not corrected but golfers were advised to obtain a full optometric examination.

All golfers, regardless of their visit type, wore the Arrington Research ViewPoint binocular eye tracker and completed a series of 20 putts that alternated between 6 and 10 feet in length on a flat, artificial putting green. After the completion of the initial 20 putts, the eye tracking videos were immediately reviewed with the golfers, and instructions were given on techniques that could be used to improve vision strategy. There was no formal structure to the advice given, as all advice was tailored to the specific golfer's needs. For some golfers training focused on improving the pre-shot routine and the alignment of the ball or improving fixation stability during the putting action phase. For other golfers, changes were made to optimise the putting visual environment; one example of improving the putting visual environment was for golfers to use specific ball markings. Golfers were given the opportunity to try the new technique or visual environment in the office, while still wearing the eye tracking equipment. This permitted recording of immediate post-training data.

After the completion of the post-training practice session, videos were again reviewed with the golfers, and further recommendations were made if needed. The cases presented here are examples of some of the more common vision strategy modifications that took place; correction of a refractive error and provision of a visual target on the golf ball which could be used either as an alignment guide or as an instrument for the manipulation of ocular dominance. Habitual (pre-training) and post-training vision strategy parameters have been presented for comparison.

7.2.3 Statistics

Distribution statistics for the habitual and post-training putting vision strategy parameters were calculated, as was the percentage change in each parameter from the habitual to post-training assessment. No other statistical comparisons were made as the habitual and post-test recording sessions differed in both their sample size and methodology.

7.3 Case Reports

7.3.1 Case 1: Refractive Error, Golfer 1

Golfer 1 (G1) was a European Tour golfer who presented to for a full golf-specific ocular visual examination. G1's presenting logMAR visual acuities were 0.02 (6/9 or 20/32) in the right eye and -0.24 (6/4 or 20/12) in the left eye. G1 had a strong right ocular dominance in primary gaze and no ocular dominance and in putting gaze. G1 did not wear spectacles or contact lenses while playing golf. Upon examination, G1 was found to have a significant refractive error in his right eye, which was the reason for the lower visual acuity (Right, +0.50/-1.25x165; Left, +0.25/-0.25x180). No binocular vision defect was detected (Cover test: Distance, orthophoria; Near, 4^{Δ} exophoria). As G1's vision was poorer in the primary gaze dominant eye, it was decided to correct this refractive error in hopes this would improve G1's vision when reading greens and aligning the ball, as well as during the putting action phase. G1 was subsequently fit with a daily disposable toric contact lens in the right eye only.

The results of G1's putting vision assessment, both habitually and after refractive correction and training are displayed below in Table 7-1. What was most noticeable about these results was that many of the putting vision strategy fixation parameters became worse after correction. The durations of T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ} all decreased by approximately 25-30%, as did G1's mean fixation duration in the Swing (25%). The number of fixations made in the Address and Swing phases increased (40-50%), as did the Total Fixation Duration in the Address (28%), but these parameter increases were actually detrimental to G1's vision strategy as they changed the vision strategy from what was deemed optimal (Swing: ≤12 fixations for a Total Fixation Duration 1000-1200ms; Address: Total Fixation duration ≤1300ms).

T_{FPQ} duration, Mean Fixation Duration in the Address and Total Fixation Duration in the Swing remained unchanged with correction (less than 5% change), and the only parameter which demonstrated improvement was T_{FCQ} duration (73%).

Parameter	Habitual (ms)	Post-Training (ms)	Difference from Habitual (%)
T_{FA1} Duration	41.6±77.1	30.7±19.8	-26.3
T_{FAQ} Duration	79.1±86.9	53.7±45.3	-32.1
T_{FS1} Duration	78.7±86.5	53.6±41.3	-31.9
T_{FSQ} Duration	70.4±70.8	52.2±47.1	-25.8
T_{FCQ} Duration	44.6±81.0	77.2±62.0	73.2
T_{FPQ} Duration	35.0±40.4	33.7±32.2	-3.7
Total Number Ball Fixations (A)*	25.6±13.8	38.9±7.8	51.6
Average Ball Fixation Duration (A)	40.6±22.6	42.1±14.2	3.7
Total Ball Fixation Duration (A)	1279.1±1052.4	1641.2±648.8	28.3
Total Number Ball Fixations (S)*	8.5±3.6	12.2±2.0	43.0
Average Ball Fixation Duration (S)	52.5±30.5	39.7±9.7	-24.4
Total Ball Fixation Duration (S)	79.1±86.9	30.7±19.8	-26.3

**Count data, no units*

Table 7-1: Habitual and Post-Training putting vision strategy of G1; putting vision strategy parameters are reported as mean ± standard deviation.

This case is presented, despite having a negative training result, because it raises important issues concerning the correction of refractive error in golfers and athletes in general. Successful golfers, like all athletes, have developed performance routines based on their habitual refractive correction. If one changes this suddenly, then time is needed for adaptation.

In this case, the refractive error changes were made in the off-season, and G1 was asked to gradually build up his contact lens wearing time, introducing the lenses gradually during practice sessions, until they were comfortable to wear for competition. When last seen at the clinic for a post-correction putting vision assessment, G1 reported that the lenses were tolerable, the vision was clearer when he was looking straight ahead, but that it was distorted with eye movements; G1 also reported that wearing contact lenses had made putting more difficult, as indeed it was.

The visual discomfort G1 experienced was likely a result of the toric contact lens rotating on the eye. Therefore the plan at the clinic was to measure the amount of rotation that was occurring while G1 was putting (this can be done with the eye tracker),[117] and re-fit G1 with a more stable contact lens. Unfortunately, G1 left the clinic and has not returned making it impossible to provide further information about how this case was resolved.

This case highlights several key factors that are important for sport specific visual assessments: (i) unless a sudden vision problem emerges, visual assessments should be carried out in the off-season to allow the athlete time to adapt to any vision correction that may be needed during training, (ii) it is necessary to have an unbiased and objective measurement system to quantify the effect of any interactions, and (iii) all management must be individualised because the long term adaptation to less than optimal conditions cannot be manipulated in some athletes and the less than optimal conditions may in some cases produce better results than the ideal theoretical approach.

7.3.2 Case 2: Manipulation of Ocular Dominance, Golfer 2

Golfer 2 (G2) was a Challenge Tour golfer who presented to us for a full golf-specific optometric examination. G2 complained of looking at the putter during the swing and finding it difficult to focus when putting. Presenting logMAR visual acuities were -0.012 (6/4.5 or 20/15) in the right and left eyes. G2 had a strong left ocular dominance in primary gaze and no ocular dominance and in putting gaze. G2 did not wear spectacles or contact lenses while playing golf. Upon examination, G2 had a small refractive error in each eye (Right, 0.00/-0.25x30; Left, -0.25/-0.50x165) that did not significantly affect visual acuity. A binocular vision defect was not observed (Cover test: Distance, orthophoria; Near, 2^{Δ} exophoria). As G2 had good vision in both eyes, the decision was made not to correct the refractive error at the time.

The habitual putting assessment demonstrated that some aspects of G2's putting vision strategy could be improved (Table 7-2), particularly T_{FAQ}, T_{FS1} and T_{FCQ} durations, the Mean Fixation Duration in Address and the Total Fixation Duration in the Swing. When discussing the results with G2, it was originally suggested to try putting a thin line on the ball to provide a fixation target that would also double as a fixation guide. The purpose of the fixation target was to give G2 something to focus on in order to force his brain to pay attention to one eye over the other and create a pseudo-ocular dominance[**] environment and to create active attention to the vision. G2 reported having tried using a thin line before and finding it very distracting therefore it was decided to mark the ball simply with a small black dot. G2 was instructed to follow his normal putting routine and asked to focus on the dot from the initiation of the swing until ball contact. At contact G2 was asked to focus on the afterimage left by the ball on the green until the swing follow-through was complete.

Parameter	Habitual (ms)	Post-Training (ms)	Difference from Habitual (%)
T_{FA1} Duration	72.5±81.6	43.7±36.7	-39.8
T_{FAQ} Duration	133.7±113.2	185.3±84.6	38.6
T_{FS1} Duration	130.4±114.6	180.8±87.6	38.7
T_{FSQ} Duration	43.7±38.5	41.6±21.9	-4.9
T_{FCQ} Duration	25.9±44.9	40.0±27.9	54.6
T_{FPQ} Duration	31.0±24.6	35.1±10.6	13.4
Total Number Ball Fixations (A)*	32.4±10.1	53.9±11.4	66.1
Average Ball Fixation Duration (A)	53.1±17.7	67.9±15.9	27.8
Total Ball Fixation Duration (A)	1618.2±482.3	3547.1±689.2	119.2
Total Number Ball Fixations (S)*	14.4±2.3	14.8±1.8	2.6
Average Ball Fixation Duration (S)	61.1±20.7	66.4±14.8	8.7
Total Ball Fixation Duration (S)	848.4±208.5	963.1±165.1	13.5

**Count data, no units*

Table 7-2: Habitual and Post-Training putting vision strategy of G2; putting vision strategy parameters are reported as mean ± standard deviation.

The striking characteristics of G2's training session results were that apart from T_{FA1} duration which decreased (40%), and T_{FSQ} duration and the Total Number of Fixations in the Swing

[**] Pseudo-ocular dominance occurs when the binocular visual environment is manipulated so that the brain selectively attends to one eye more than the other in an artificial ocular dominance-type situation.

which were unchanged (3-5% change), all of the other gaze parameters improved. T_{FAQ}, T_{FS1} and T_{FCQ} durations improved markedly (40-50%) as did the Mean Fixation Duration in the Address (28%) and the Total Fixation Duration in the Swing (14%). The Total Number of Fixations made in the Address and the Total Fixation Duration in the Address increased as well (65-120%), although these increased beyond what was considered ideal.

Videos of G2's habitual and post-training performance can be found in Appendix F. In the habitual putting video, the right and left gaze markers can be seen to oscillate significantly, as neither eye is particularly dominant and the brain was randomly attending to only one eye at a time. In the post-training video, the blue dot, which represents the left eye's relative position, is very stable, which suggests that the brain is attending to this eye almost exclusively. The right eye (represented by the green dot) oscillated significantly more compared with the left eye as its position was attended by the brain only as much as was necessary to maintain fixation within Panum's fusional area and to avoid visual symptoms such as diplopia.

G2 found using a dot on the back of the ball very comfortable, and in the immediate post-training session as G2 was no longer aware of the club during the swing and was finding more consistency in putting and an improvement in success. The addition of the dot as a fixation target allowed G2 to selectively attend to the central vision, while the movement of the putter was followed with the peripheral vision. Contrary to G2's belief, G2 was not following the putter with the eyes but saw it with the peripheral vision. The use of the dot forced G2 to concentrate on the central vision aspects (i.e. ball fixations) of the putting vision strategy; in turn this made it easier for G2 to ignore distracting visual information from the peripheral retina. G2 has not returned to the clinic for a second assessment, therefore there has been no opportunity to re-evaluate G2's performance. The results of the immediate post-training assessment suggest that the addition of a dot on the back of G2's ball improved performance.

The key factors for training vision strategy that this case highlights include: (i) modifying the visual environment can produce a modification of the vision strategy, (ii) training is effective from a positive perspective (i.e. encouraging central attention) not from a negative perspective (i.e. avoidance of peripheral attention), and (iii) the incorporation of fine details helps prolong fixation and improve stabilisation of the ocular system.

7.3.3 Case 3: Alignment and Fixation Control, Golfer 3

Golfer 3 (G3) was an amateur golfer with very little experience who presented to the clinic for a putting vision assessment. G3's logMAR visual acuities were 0.00 (6/6 or 20/20) in the right and left eyes, and G3 did not wear spectacles or contact lenses. G3 had a strong left ocular dominance in both primary and putting gazes.

The results of G3's habitual putting and post-training assessments can be found in Table 7-3. G3 was a very inexperienced golfer and had very poor fixation control. In the habitual putting assessment, G3's average fixation duration was just over one movie frame (16.67ms) in length. G3 was advised to use a line on the ball which matched a line on the putter to help improve alignment of the club and the ball, to use a consistent routine on every putt, and to concentrate on maintaining a stable gaze throughout the putt, especially during the swing and at contact by looking at the line.

Parameter	Habitual (ms)	Post-Training (ms)	Difference from Habitual (%)
T_{FA1} Duration	22.9±13. 5	24.3±16.1	6.2
T_{FAQ} Duration	20.4±7.0	22.2±8.6	8.8
T_{FS1} Duration	19.2±13.4	19.5±6.8	1.6
T_{FSQ} Duration	20.8±15.9	25.0±20.4	19.9
T_{FCQ} Duration	2.9±10.6	6.7±0.0	128.9
T_{FPQ} Duration	20.0±9.4	19.4±6.8	-3.0
Total Number Ball Fixations (A)*	8.9±18.3	47.3±55.4	429.1
Average Ball Fixation Duration (A)	10.7±11.3	12.0±12.8	12.0
Total Ball Fixation Duration (A)	202.4±421.7	1129.1±1317.9	457.8
Total Number Ball Fixations (S)*	1.2±2.8	5.5±6.2	366.1
Average Ball Fixation Duration (S)	4.2±9.5	16.8±18.87	297.2
Total Ball Fixation Duration (S)	27.5±64.5	175.0±187.2	536.6

**Count data, no units*

Table 7-3: Habitual and Post-Training putting vision strategy of G3; putting vision strategy parameters are reported as mean ± standard deviation.

The results of the post-training session demonstrated marked improvement in all of the parameters (6-535%) except for T_{FS1} (2%) and T_{FPQ} (-3%), which remained unchanged. Although the percentage differences were large, on some parameters at least, the actual physical improvement was still relatively small. For example, the mean T_{FCQ} duration improved from 2.91ms to 6.66ms, but was still less than a single movie frame in length. Yet on other parameters, such as the Total Fixation Duration in the Address and Swing phases, significant improvements in percentage and actual time values were observed. G3's putting vision strategy demonstrated improvement after one discussion, and this improvement would likely be more marked with practice. Unfortunately G3 has not returned to the clinic for a second session, and no additional information could be gleaned regarding G3's performance. This case highlights that: (i) improving vision strategy is not limited to elite athletes, and vision strategy improvements can be made in amateurs with relatively low skill, (ii) the implementation of a specific visual routine, which includes specific visual details as fixation targets, helps to stabilise the ocular system, and (iii) simple interventions need to be successfully incorporated into athlete's routines prior to using more specialised training paradigms.

7.4 Discussion

The three cases presented above provide examples of how a systematic approach to sports vision interventions can be applied in golf specifically. All three of the examples demonstrate that through the manipulation of the visual environment, either through the correction of a refractive error or the provision of a fixation target, can significantly impact golfers' putting vision strategy.

Using a systematic approach to sports vision interventions, specifically for golf putting in this case, requires that refractive issues and binocular vision issues be addressed prior to visual mechanics and vision strategy issues; when all levels of the pyramid are optimised performance should improve.

Vision strategy interventions have previously been demonstrated to improve quiet eye performance in golfers under pressure and in the real world,[30, 51, 52] and there is no reason to think that any other aspect of the vision strategy would demonstrate a different result if trained.

As clinicians and sports vision specialists, it is important to remember that interventions must be specifically tailored to specific individuals, and if refractive corrections are implemented, they must be introduced gradually. In addition to the methods described above, ocular dominance in primary gaze can be manipulated to improve accuracy in aligning the ball with the target. In primary gaze, golfers will find better alignment success if they use the hand that corresponds with their dominant eye when positioning the ball as this will make the alignment process more linear. Improved alignment will ultimately lead to improved performance if all other factors remain equal.

Understandably, these case reports only provide a glimpse of the impact vision strategy training can have in golf, and demonstrate that more information is needed. A full investigational case-controlled study is needed to investigate the impact of vision strategy training on all of the key aspects of the putting vision strategy. The impact this training has on real-world performance needs to be investigated as well.

7.5 Summary

Chapter 7, Case Reports: Vision Training in Golf Putting examined specific examples of putting vision strategy training and demonstrated that it was possible for training to modify the strategy.

Chapter 8
DISCUSSION

8.1 Introduction

Golf, much like many sports relies heavily on visual information. Golf putting is no exception to this, as success in putting is based almost exclusively on interpreting the environment based on visual clues. Green reading requires golfers accurately judge the distance between the ball and the hole and correctly deduce the contours of the green through the use of depth perception and the interpretation of colour contrast. Alignment of the ball with the target and the club with the ball both require golfers to make highly accurate Vernier acuity judgements, and the action phase of the putt demands that golfers exhibit exceptional gaze control.

Golfers, coaches and researchers alike, have all keyed in on golf putting as an important aspect of overall golf performance, and putting is often thought to be one of the most important parts of the game, as well as one of the most difficult.[1]

Of the three principle putting tasks (green reading, alignment and the putting action phase), it is the putting action phase that has attracted the most attention from coaches, players and researchers alike. The putting action phase includes the alignment of the club with the ball, the swing and ball contact. It is the biomechanical aspects of this phase that have lead many to believe it has a significant potential to influence performance. It is also the phase that is the most susceptible to external and internal distracters, because it demands such precision and accuracy from a motor task.

Previous research on the putting action phase has looked at the putting stance,[16] the swing,[18] whether to look at the ball or the hole during the swing,[17] the role ocular dominance plays,[102-105] and the putting vision strategy[28, 30, 32, 34-36, 38, 51, 52] to try and improve performance. Apart from the two publications on golfers' stance and swing, the visual aspects of the putting strategy have attracted the most research attention, which further suggests that the putting vision strategy is believed to impact success.

The quiet eye, a concept introduced by Dr. Joan Vickers,[29, 31] has been defined in golf specifically as the final fixation or tracking gaze prior to the onset of the swing, that is located on the ball within 3° of visual angle (or less) for a minimum of 100ms,[29-31] and has been found to be associated with both higher skill and success in putting.[28]

Unfortunately, all of the putting vision strategy and quiet eye research conducted to date suffers from a number of flaws including: (i) all of the golf research to date has been based on fixations with a minimum duration of 100-120ms, which was assumed to represent cognitive attention in all golfers irrespective of their skill or experience,[28] (ii) fixations within 1° to 3° visual angle,[27, 28, 30, 31, 38] are not truly fixations; the criterion used to define them is excessively large, compared with vision research in reading studies that measure fixations within 0.29° visual angle,[67] and (iii) all of the golf research has been conducted under monocular conditions, which means factors such as ocular dominance cannot be accounted for.

Therefore, the purpose of this thesis was to address these limitations through the development of an accurate analysis method for binocular eye tracking data, to determine optimal criteria for putting vision strategy assessment, to assess the putting vision strategies of golfers of various skill levels (including an assessment of the impact of ocular dominance on the putting vision strategy), and finally, to develop and examine methods for training the binocular vision strategy of golfers which are based on sound vision science principles.

8.2 Binocular Eye Tracking

The Arrington Research Binocular ViewPoint Eye Tracker was used for all of the data collected in this thesis. The examination of this data required the development of the GazeDetection software package, which was based on the principles of vector mathematics and enabled the objective quantification of fixations made by both the right and left eyes simultaneously.

Previous software designed for the analysis of eye tracking data in sports relied heavily on subjective manual coding of gaze behaviours in the putt, and required that all videos be examined on a frame-by-frame basis. This method was very time consuming when used with monocular data, and would have been twice as time consuming had it been used with binocular data.

GazeDetection was designed at Aston University in conjunction with the Optometric Technology Group specifically for the investigation of golf data; users needed to code only 6 time points within the putt (Stationary Ball, Address, Backswing, Pre-Contact, Post-Contact and Gaze Break) to obtain an accurate analysis of every fixation made within the putt. This saved a significant amount of time, and also made the analysis of fixations very objective. In addition to being objective, GazeDetection was designed to analyse the same data under various conditions. For example, a single putt could be examined using 0.5°, 1.0°, 1.5°, 2.0°, 2.5° and 3.0° fixation criteria at the same time. Using traditional methods to do this type of analysis would have required that the video be manually recoded for each of the criterion used. GazeDetection also permitted users to set their minimum gaze time to any value; in these studies it was set to the length of a single movie frame (16.67ms).

As GazeDetection was an entirely new software package, it needed to be validated before its use, and the validation consisted of two stages. Initially the fixation calculations made with the software were compared with manual calculations made on the same data. The second stage of the validation required examination of the repeatability of the 6 video coding parameters.

With respect to the fixation calculations, the preliminary version of the software was found to demonstrate only small differences from the manually calculated results for the Start-Y and End-Y positions of the gaze and the fixation duration. The Start- and End-Y position calculation differences were considered to be acceptable, because they were related to the precision with which the normalised Y-coordinate was calculated. In the manual analysis, the normalised Y-coordinate was calculated with a precision of four decimal places; in GazeDetection this coordinate using ‘double precision’ which is accurate to 15 or 16 decimal places. As the original data was only measured with a four decimal place precision the differences in the Y-coordinate positions were not deemed to be significant.

The fixation duration differences, although small, were of concern because this was the primary outcome of the analysis. Examination of the raw data demonstrated that there were occasional errors in the data recording system that needed to be accounted for in the analysis. GazeDetection was re-written to enable it to identify and ignore the erroneously recorded data. When the second version of the software was compared with the manual analysis, there were no differences in any of the parameters except for the Start- and End-Y coordinates.

The video coding repeatability study demonstrated that Address, using the Tangent Address criteria, Swing, Pre-Contact and Post-Contact points could be coded with exceptional consistency. Each of these time points demonstrated less than a single frame (16.67ms) error over a series of three repeated evaluations. The single frame error in the measurements was equivalent to a 1.1% error or less in the duration of the associated putt phase. Stationary Ball and Gaze Break were found to have significantly higher coding errors (Gaze Break coding: 15% of the Post-Contact phase duration; Stationary Ball coding: 22% of the Preparation phase duration), but they were still considered to be acceptable as Gaze Break and Stationary Ball did not define critical phases of the putt.

Despite being designed for golf specifically, the development of GazeDetection has been a large step forward in the analysis of binocular eye tracking data collected in all sports. The basic mathematic principles underling GazeDetection and its simple interface can be applied to fixations made in any sport; all that would need to chance would be the video time coding parameters and their relationship to the data in question. Expanding the GazeDetection program to deal with multiple sporting applications needs to be addressed in the near future, as this would permit the study of other sports, as well as the study of the vision strategies associated with other aspects of golf such as reading the green.

8.3 What is a Fixation?

Conceptually, a fixation occurs when the eyes are not moving and their velocity is nearly equal to zero. The velocity of the eyes cannot be exactly equal to zero because small eye movements, known as microsaccades occur with stationary gazes.[76] In eye tracking research, where both the individual and the target of interest are in fixed positions (i.e. reading or computer use studies) it is relatively simple to determine when the eyes are stationary. In golf and other sport eye tracking research it is much more difficult to measure gaze behaviour because people are moving. The eye and scene cameras are typically head mounted, which means there is no fixed reference frame to compare too. Using a head tracker is one option to solve this problem, but it increases the amount of equipment that needs to be worn. Therefore other techniques needed to be developed to ensure that the gaze behaviours being examined in golf and other sports vision research were the same as the gaze behaviours being examined in other, fixed scenario eye tracking studies.

Research has demonstrated that smooth pursuit movements occur when the eyes were tracking a target that was moving with some velocity. Although it has been demonstrated that individuals can track targets with velocities up to 100°/s,[69] other research has suggested that the maximum target velocity that can be tracked with smooth pursuit movements is somewhere in the area of 40-50°/s.[66] Saccades then, are thought to be fast eye movements with velocities greater than 50°/s.[70] Previous research on the quiet eye and the golf putting vision strategy have used 1° or 3° visual angle as fixation criterion. [28,32,34,35,36,37,38] At a distance of 1.5m, the 3° fixation criterion permitted pursuits and small saccades with velocities up to 90°/second to be incorrectly classified as fixations. The 1° fixation criterion is better, but not yet ideal, as a 1° fixation still permits some small pursuit movements to be classified as fixations.

In order for the results of golf putting vision strategy research to be comparable to other fixed location gaze behaviour research, a 0.5° fixation criterion must be used. If the resolution of the recording system used does not permit the use of a 0.5° fixation criterion, than a 1° fixation criterion would be acceptable. Fixation criteria larger than 1° visual angle do not represent true fixations; rather they record a mixture of eye movements which include pursuits and saccades. Fixations measured with fixation criteria larger than 1° visual angle are only representative of regions of interest rather than specific fixations.

8.4 Ocular Dominance

In golf, ocular dominance is an essential visual component of putting. It is important in the alignment phase of the putt, where golfers' make critical Vernier acuity judgements to align the ball with the target and the club with the ball, and it is important in the putting action phase where it can influence fixation control during the swing. The research presented in this thesis demonstrated that primary gaze and putting gaze ocular dominance are not equal and one cannot be predicted from the other. The magnitude of ocular dominance in the putting gaze was equal or less than the magnitude of ocular dominance in primary gaze in all golfers. The distribution of ocular dominance was not affected by golfers' skill level in either gaze, nor was it related to golfers' handedness as might have been expected.[80, 94]

The results of this study demonstrated that it is vital to measure golfers' ocular dominance in both primary and putting gazes. Ocular dominance in primary gaze can be manipulated to improve accuracy in aligning the ball with the target and ocular dominance in putting gaze can be used to improve the alignment of the club with the ball and fixation control. In primary gaze, golfers will find greater alignment success using the hand that corresponds with their dominant eye when positioning the ball because this makes the alignment process more linear. If there is no dominant eye, particularly in putting gaze, the ball position can be adjusted or fixation targets can be used to create a pseudo-ocular dominance situation.

Prior to the studies conducted in this thesis, the impact of ocular dominance on the vision strategy of golfers had never been examined. These studies demonstrated that ocular dominance is very important in fixation control as it allows golfers' to control specific gaze behaviours more accurately, which in turn contributes to higher putting success.

To a large extent, ocular dominance is believed to be an inherent physiological characteristic of individuals. While training may be possible, it would likely resemble other psychophysical training paradigms involving thousands repetitions in order to obtain small gains.[118] Therefore, training ocular dominance in golfers to improve performance is unrealistic. What is realistic is manipulation of their visual environment to create an ocular dominance-type situation. There are many ways in which this can be done, including correcting refractive errors and providing golfers with specific fixation targets. Both of these methods were demonstrated in the case reports that were presented in Chapter 7, Case Reports: Vision Training in Golf Putting, and significantly improved the fixation behaviours of the Club Professional and Amateur golfer studied.

Correcting the refractive error of the Top Professional golfer, unfortunately did not initially improve the golfers' fixation behaviours because it so radically changed G1's visual environment. In primary gaze, G1's right eye was dominant, but without refractive correction it had the poorest vision. As the brain has a preference for clear visual information, there was a conflict between which information to attend to: information from the dominant right eye or the clear left eye. The correction of the refractive error in the right eye allowed for the brain to attend to clear information from the dominant eye, but this dramatically changed G1's putting visual environment, and ultimately lead to a poorer performance that could not be remedied before G1 was lost to follow up.

This particular case highlights the importance of making gradual changes in the visual environment of golfers, as dramatic changes can cause serious upset. Refractive corrections in particular, need to be gradually incorporated into training first, and the golfer must be comfortable with the correction before it is introduced into competition. This principle does not apply solely to golf; manipulation of the visual environment of any individual who plays sports can have dramatic impact on performance, and patience and persistence are needed to ensure they change has a significant benefit.

8.5 Putting Vision Strategy

The putting vision strategy associated with both higher skill and success cannot be defined simply by one fixation. An optimal putting vision strategy should include the following parameters: $T_{FAQ}=T_{FS1}$ with a duration of 200-300ms, $T_{FSQ}=T_{FCQ}$ with a minimum duration similar to other fixations in the Swing phase (70ms), no more than 12 fixations during the swing phase for a total Swing phase fixation duration of 1000-1200ms. In the Address, fixations should have a mean duration of 70ms, and the total amount of time spent fixating the ball during the Address should be less than 1300ms.

Of the 6 key fixations examined, $T_{FAQ}=T_{FS1}$ and $T_{FSQ}=T_{FCQ}$ were both important fixations in the putting vision strategies of highly skilled and successful golfers. Previous research has suggested that both of these fixations (essentially the quiet eye and the quiet eye dwell time) are important to golfers putting vision strategy as they are associated with cognitive pre-programming of the backswing movement and minimising distraction from internal and external cues.[29, 31] From a biomechanical perspective, both of these fixations occur at critical time points in the swing: $T_{FAQ}=T_{FS1}$ occurs at the initiation of the swing and $T_{FSQ}=T_{FCQ}$ occurs at the point of contact and is maintained through the start of the follow through. Precise, concentrated fixations at critical movement phases in the swing can help control head and body position, making the swing mechanics more consistent and repeatable.

The Address and Swing fixation parameters were also significant factors in the putting vision strategy, with higher performance on these parameters being associated with better fixation behaviours overall. All of the Address and Swing fixation parameters found to be significantly associated with putting success were included in the optimal putting vision strategy except for the Total Number of Fixations in Address. The Total Number of Fixations in the Address is less important to the vision strategy of golfers because it is associated with both the Mean and Total Fixation Durations of this phase; as Mean Address Fixation Duration improves, the Total Number of Address Fixations will inherently decrease in order to attain an optimal Total Address Fixation Duration.

T_{FPQ} is an interesting fixation, in that it was either the first fixation after contact (if there was no fixation at contact) or it was the first fixation that started after the contact fixation. Depending on the length of the contact fixation, T_{FPQ} could have started at very different time points after contact. With this in mind, it makes conclusions about T_{FPQ} difficult to draw. Overall, it does not appear to be significantly associated with putting success, but it was associated with success in golfers with ocular dominance and it was associated with higher skill. In golfers who did not have a T_{FCQ} fixation, T_{FPQ} may play a different role than it does in golfers with a T_{FCQ} fixation, as T_{FPQ} in golfers without a contact fixation may represent a golfers' attempt to keep his eyes steady on the ball after contact.

T_{FPQ} and the other contact fixations (T_{FSQ}, T_{FCQ}) demonstrated a high amount of variability in their durations, even in golfers of higher skill levels, which makes it harder to truly understand the significance of these fixations. This variability is likely due, at least in part, to head and body movement during swing and at ball contact. Despite golfer's best efforts to maintain a steady body position throughout the swing, ball contact is the most dynamic time point of the entire putting stroke and relatively small head and body position movements could have affected the measurement of small, precise fixations. Incorporating a head tracking device into this type of study would likely significantly increase the duration of fixations measured at and around ball contact and make it easier to understand the role the contact fixations play in the putting vision strategy of golfers.

T_{FA1} was not included in the optimal vision strategy, because it was not found to be significantly associated with increased putting success, despite its significant association with skill. T_{FA1} was the first fixation in the visually dynamic process of aligning the club with the ball, relative to a chosen target. While one might expect golfers to make a long concentrated fixation on this aiming task, and indeed some golfers did, this was not the case for all golfers. Aligning the club and the ball involves various gaze behaviours including fixations on the ball, fixations on the club, fixations on the hole or target, and pursuits and saccades between targets. The method through which golfers align the club and the ball are highly individual and strongly associated with the particular aspects of each putt. It is likely the quality of the alignment of the ball and the club and the aim line that plays a greater role in putting success than the duration of a single fixation measured in this stage, which is only one of a number of fixations made during the process.

The putting vision strategies of all golfers appear to be fairly consistent in practice and competition, at least in models where additional cognitive stress was not induced. The competition model used in this thesis represented golfers first attempt at a putt and mimicked the environment of the golf course were golfers have only one opportunity to make each putt. The training model used in this thesis represented golfers' overall performance. The only significant differences between these models were found in the Address fixation parameters, where it was apparent that all golfers and Top Professional golfers especially, spent more time aligning their club with the ball in the competition model. This result suggests that golfers are able to learn from previous performances; when a single putt is repeated many times golfers' appear to become more comfortable in their alignment judgments and spend less time making them. This is an important consideration in designing future studies of the putting vision strategy, as most study paradigms are based upon repetition of a single putt many times. Using fewer repetitions or using a greater variety of putting conditions may improve study designs, making them more representative of performance in a natural environment.

The optimal vision strategy presented here contains significantly more visual aspects than vision strategies presented before. This is due to the stricter fixation criterion of 0.5° visual angle used in this study, which allowed for the observation of greater differences between golfers of different skill levels. Using this fixation criterion also meant that the fixations made by golfers of all skill levels were significantly shorter than those previously measured. The 0.5° fixation criterion is intolerant of pursuit and saccadic gaze behaviours and large head and body movements. As the arms, and to some extent the shoulders and torsos of golfers are rotating throughout the backswing and contact of the ball, the body movement may have been enough to limit the length of fixations measured, making it essential to re-visit the analysis of the putting using a binocular eye tracker and a head tracker in future studies. The relationship between golfers' fixation behaviours and their swing biomechanics would be interesting to explore, as it appears that these two aspects of performance are much more associated with each other than would have been previously thought.

8.6 Training the Putting Vision Strategy

Vision strategy interventions have previously been demonstrated to improve quiet eye performance in golfers under pressure and in the real world,[30, 51, 52] and there is no reason to think that any other aspect of the vision strategy would demonstrate a different result if trained. What is important to remember when implementing training programs to improve the putting vision strategy is that the training programs will be more effective if the ocular system is functioning properly. The presence of refractive errors, poor visual acuity or binocular vision defects can significantly impair the ability of a golfer to perform challenging visual tasks, such as making accurate Vernier acuity judgments or perceiving depth.

Using a systematic approach to sports vision interventions, specifically for golf putting in this instance, requires that refractive issues and binocular vision issues are addressed prior to vision strategy issues. That is to say, the base levels of the pyramid[116] introduced in Chapter 7, Case Reports: Vision Training in Golf Putting, must be optimised before undertaking vision strategy enhancement. The base levels of the pyramid must also be optimised before undertaking any form of vision research in sport.

The three cases presented in Chapter 7, Case Reports: Vision Training in Golf Putting, were examples of how a systematic approach to sports vision interventions can be applied in golf specifically. All three cases demonstrated that manipulation of the visual environment, through the correction of a refractive error or the provision of a fixation target, significantly impacted golfers' putting vision strategy.

Case 1, G1, was a Top Professional golfer who was in need of a refractive correction. Addressing this issue was initiated through the use of daily disposable contact lenses. Unfortunately G1 struggled with adaptation to the refractive correction and it significantly impacted G1's putting performance; the issue was never fully resolved as G1 was lost to follow up. This case demonstrates the importance of carrying out visual assessments in the off-season unless a sudden vision problem emerges and that time is needed to adapt to vision corrections as they can dramatically alter the visual environment.

Case 2, G2, was a Club Professional golfer who had did not have ocular dominance and had trouble maintaining a steady gaze through the swing and at ball contact. Introducing a small black dot on the back of the ball, which was used as a simple fixation target created a pseudo-ocular dominance situation where G2 was attending to one eye almost exclusively during the swing, and this lead to significant improvements in the stability of the gaze behaviours overall, and in the swing specifically. This case demonstrates that modification of the visual environment, through the use of fine details such as a dot on the back of the ball, can lead to modification of the visual strategy through improved stability in the individual fixation parameters.

Case 3, G3 was an Amateur golfer with very little experience and a poor vision strategy in all aspects. The introduction of a straight black line on the back of the ball created an instrument which could be used to guide and improve ball alignment with the target, improve club alignment with the ball and improve fixation quality by acting as a fixation target. With relatively little practice (a few putts), significant improvement in G3's vision strategy was observed. This case demonstrates that improvements in the putting vision strategies of golfers of any skill level can achieved, as long as the interventions are specific to the individual and adequate time is given for adaptation and practice.

Understandably, these case reports only provide a glimpse of the impact vision strategy training can have in golf, and demonstrate that more information is needed. Previous research has shown that video-feedback and the provision of coaching tips are successful methods to alter golfers' vision strategies.[30, 51, 52] The cases presented here demonstrate that correcting refractive errors and provision of fixation targets, can improve golfers' vision strategies, particularly when used in conjunction with video feedback and coaching advice. As clinicians and sports vision specialists, it is important to establish the base layers of the pyramid first, through the investigation and remedial management of any ocular-visual problems, before making changes to the top, vision strategy, layer of the pyramid.

A full scale, long-term investigational case-controlled study of vision strategy training was not conducted as part of this thesis, but is still needed to investigate the impact of vision strategy training on performance. This study needs to investigate the effects of training paradigms on all of the key aspects of the putting vision strategy, not just the quiet eye, and it needs to assess the impact that training has on real-world performance. This will be a challenging study to design and conduct, as it must take into account golfers' individual needs for refractive error and/or binocular vision correction, and ocular dominance.

8.7 Summary

In golf, vision serves two purposes: information collection and biomechanical stabilisation. Reading the green and aligning the ball and the club require accurate collection and interpretation of the visual environment, while maintaining a stable body position during the swing depends to some extent on the golfer's ability to maintain steady, concentrated fixations. These steady concentrated fixations would not be maintainable if the head and body were moving dramatically, and this highlights the importance of the relationship between vision and biomechanics.

The research completed in this thesis was undertaken in order to gain a better understanding of the human visual system and how it relates to the performance of golfers specifically. Ultimately, the analysis techniques and methods developed are applicable to the assessment of individuals' vision strategies in all sports. Examination of the relationship between vision and sports performance is a vital aspect of sports vision research, which needs to be conducted in a methodical manner and adhere to strict principles of vision science. The physiology of the ocular system must be accounted for first, including the correction of refractive errors and/or binocular vision defects if needed. Only then, can vision strategy research proceed. Vision strategy research must then consider the mechanics of the eye movements, use a fixation criterion which is appropriate for the precise measurement of gaze behaviours in the specific environment of the sport and be conducted in as natural an environment as possible.

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Appendix A

Selection of Key Parameters for Examination of the Putting Vision Strategy

Prior to the work conducted in this thesis, the vision strategy of the entire putt had only been examined on one previous occasion.[1] Due to the limitations of this work (discussed in Chapter 1, Introduction), the entire putt (including gaze behaviours and other parameters) was re-examined objectively to determine which parameters were of importance for inclusion in the final putting vision strategy analysis conducted.

The initial parameters considered for inclusion in the putting vision strategy analysis were the duration of the first (T_{FA1}) and last (T_{FAQ}) fixations of the Address phase, the first (T_{FS1}) and last (T_{FSQ}) fixations of the Swing phase, the fixation at contact (T_{FCQ}) and the first fixation immediately after contact (T_{FPQ}), as well as when these fixations started and ended relative to ball contact (T_0). These six fixations were thought to be the key fixations in the assessment of putting vision strategy. The Total Number of Fixations made on the ball and the hole, the Mean Duration of ball and hole fixations, and the Total Duration of ball and the hole fixations in each of the Address and Swing phases were included, as were the durations of the entire putt and the Preparation, Address, Swing and Post Contact phases. The six key fixations are described in more detail below

A.1 Statistical Methods

Correlation analyses were conducted on the overall population and each skill group with the right and left eye data pooled initially to identify which parameters were of interest, and which were correlated and therefore could be considered equivalent performance predictors. The vast majority of the parameters measured did not have normal Gaussian distributions, therefore non-parametric Spearman correlations were used. A secondary correlation analysis was conducted to compare the right and left eye data. The strength of the correlations was defined as follows: 0.0 to 0.199 very weak (negligible), 0.2 to 0.399 weak, low correlation (not significant), 0.4 to 0.699 moderate correlation, 0.7 to 0.899 strong, high correlation, and 0.9 to 1.000 very strong correlation.[2-4] The significance value for all analyses was $\alpha=0.05$ unless otherwise stated.

A.2 Results

The results of the Spearman correlation analyses for the overall population were instrumental in the determination of which parameters were included in the analysis of the putting vision strategy (Tables A.1 to A.5), and are discussed below. The Spearman correlation analyses conducted on the individual skill groups were similar to the overall population, and as such they have not been included in this discussion.

A.2.1.Putt Duration Parameters

With respect to the putt phase duration parameters, putt duration was very strongly correlated with Preparation phase duration ($r=0.919$, $p<0.01$), which supports the earlier observation and demonstrates that the vast majority of golfers' time is spent in Preparation when putting (Tables A.1 and A.2). None of the other putt phase durations were strongly correlated with the total putt duration ($r=-0.131$ to 0.433, $p<0.01$ to $p>0.05$).

The total putt duration did not correlate strongly with any of the key fixation parameters in either the Address (T_{FA1}: $r=-0.064$, $p<0.05$; T_{FAQ}: $r=-0.060$, $p<0.05$) or Swing (T_{FS1}: $r=-0.096$, $p<0.01$; T_{FSQ}: $r=0.039$, $p>0.05$) phases. Total putt duration also did not strongly correlate with the Total Number of Fixations (Ball: Address, $r=-0.108$, $p<0.01$; Swing, $r=-0.199$, $p<0.01$; Hole: Address, $r=0.001$, $p>0.05$; Swing, $r=-0.016$, $p>0.05$), Mean Fixation Duration (Ball: Address, $r=-0.131$, $p<0.01$; Swing, $r=-0.049$, $p>0.05$; Hole: Address, $r=-0.033$, $p>0.05$; Swing, $r=-0.017$, $p>0.05$) or the Total Fixation Duration (Ball: Address, $r=-0.106$, $p<0.01$; Swing, $r=0.096$, $p<0.01$; Hole: Address, $r=-0.001$, $p>0.05$; Swing, $r=-0.017$, $p>0.05$).

The lack of correlation between these parameters indicated that putting vision strategy was independent of the length of time spent putting and that the simple measurements of putt and phase durations are not indicative of putting vision strategy. For this reason the putt duration parameters were not included in any further analyses.

A.2.2 Address Phase Fixation Parameters

Within the Address phase, T_{FAQ} duration was strongly correlated with the Mean Ball Fixation Duration ($r=0.735$, $p<0.01$) (Table A.1). As there were a large number of fixations made during the Address (Median=42), this strong correlation suggests that the duration of T_{FAQ} not only represents a unique fixation, but also represents the overall fixation strategy during the Address phase. With respect to training golfers' putting vision strategies, these results would suggest that the duration of T_{FAQ} could be trained by training all of the fixations in the Address Phase.

The Total Ball Fixation Duration was strongly correlated with both the Total Number of Ball Fixations ($r=0.874$, $p<0.01$) and the Mean Ball Fixation Duration ($r=0.871$, $p<0.01$), which was not an unexpected result. Making more fixations or making longer fixations both would have the effect of increasing the total amount of time spent on fixating the ball during the Address.

The Total Number of Hole Fixations ($r=0.972$, $p<0.01$) and the Mean Hole Fixation Duration ($r=0.803$, $p<0.01$) were both highly correlated with the Total Hole Fixation Duration during Address and moderately correlated with each other ($r=0.667$, $p<0.01$). In contrast, hole fixation parameters were not correlated with ball fixation parameters ($r=-0.090$ to 0.130, $p>0.05$).

	T_{FA1}	T_{FAQ}	Address Total Fix. (B)	Address Mean Fix. Dur. (B)	Address Total Fix. Dur. (B)	Address Total Fix. (H)	Address Mean Fix. Dur. (H)	Address Total Fix. Dur. (H)	Total Putt Duration	Preparation Duration	Address Duration	Swing Duration	Post Contact Duration
T_{FA1}													
T_{FAQ}	0.273** (n=1072)												
Address Total Fix. (B)	0.240** (n=1072)	0.405** (n=1072)											
Address Mean Fix. Dur. (B)	0.408** (n=1072)	0.735** (n=1072)	0.560** (n=1072)										
Address Total Fix. Dur. (B)	0.355** (n=1072)	0.647** (n=1072)	0.874** (n=1072)	0.871** (n=1072)									
Address Total Fix. (H)	0.015 (n=1072)	0.061* (n=1072)	-0.090* (n=1072)	-0.020 (n=1072)	-0.071* (n=1072)								
Address Mean Fix. Dur. (H)	0.084** (n=1072)	0.175** (n=1072)	0.026 (n=1072)	0.130** (n=1072)	0.081* (n=1072)	0.667** (n=1072)							
Address Total Fix. Dur. (H)	0.042 (n=1072)	0.111** (n=1072)	-0.048 (n=1072)	0.041 (n=1072)	-0.011 (n=1072)	0.972** (n=1072)	0.803** (n=1072)						
Total Putt Duration	-0.064* (n=1072)	-0.086** (n=1072)	-0.108** (n=1072)	-0.131** (n=1072)	-0.106** (n=1072)	0.001 (n=1072)	-0.033 (n=1072)	-0.001 (n=1072)					
Preparation Duration	-0.15 (n=1072)	-0.060* (n=1072)	-0.120** (n=1072)	-0.058 (n=1072)	-0.086** (n=1072)	-0.105** (n=1072)	-0.067* (n=1072)	-0.100** (n=1072)	0.919** (n=1072)				
Address Duration	-0.67* (n=1072)	0.041 (n=1072)	0.226** (n=1072)	-0.076* (n=1072)	0.129** (n=1072)	0.276** (n=1072)	0.134** (n=1072)	0.272** (n=1072)	0.191** (n=1072)	-0.131** (n=1072)			
Swing Duration	-0.118** (n=1072)	-0.133** (n=1072)	-0.188** (n=1072)	-0.226** (n=1072)	-0.216** (n=1072)	0.272** (n=1072)	0.087** (n=1072)	0.238** (n=1072)	0.211** (n=1072)	0.043 (n=1072)	0.433** (n=1072)		
Post Contact Duration	-0.020 (n=1072)	0.042 (n=1072)	-0.030 (n=1072)	0.024 (n=1072)	0.001 (n=1072)	-0.002 (n=1072)	-0.013 (n=1072)	-0.001 (n=1072)	0.306** (n=1072)	0.201** (n=1072)	0.065* (n=1072)	0.086** (n=1072)	

**Correlation significant at the 0.05 level; **Correlation significant at the 0.01 level*

Table A.1: Overall Spearman correlations between Address fixation parameters (T_{FA1} duration, T_{FAQ} duration, Address Total Fixations, Address Mean Fixation Duration, Address Total Fixation Duration at the ball and the hole) and putt duration parameters; strong (r=0.7 to 0.9) and very strong (r >0.9) correlations are highlighted [Fix=Fixation, Dur=Duration, B=Ball, H=Hole].

A.2.3 Swing Phase Fixation Parameters

T_{FS1} duration strongly correlated with the Mean Ball Fixation Duration ($r=0.800$, $p<0.01$) and the Total Ball Fixation Duration ($r=0.764$, $p<0.01$) indicating, that T_{FS1}, much like T_{FAQ}, is not simply a unique fixation and is representative of the overall fixation strategy in the Swing phase. Much like the training of T_{FAQ}, training of T_{FS1} can be again accomplished by training fixations throughout the entire Swing phase (Table A.2).

Similarly to the Address phase, the Total Ball Fixation Duration in the Swing phase was strongly correlated with both the Total Number of Ball Fixations ($r=0.700$, $p<0.01$) and the Mean Ball Fixation Duration ($r=0.894$, $p<0.01$), which was again not unexpected. Making more fixations or making longer fixations both would have the effect of increasing the total amount of time spent on fixating the ball during the Swing.

The correlations between the Swing hole fixation parameters were essentially perfect ($r=1.000$, $p<0.01$); this is likely due to fact that there were very few fixations made to the hole during the Swing (Median=0). Hole fixation parameters were not correlated with ball fixation parameters ($r=-0.303$ to -0.233, $p<0.01$).

	T_{FS1}	T_{FSQ}	Swing Total Fix. (B)	Swing Mean Fix. Dur. (B)	Swing Total Fix. Dur. (B)	Swing Total Fix. (H)	Swing Mean Fix. Dur. (H)	Swing Total Fix. Dur. (H)	Total Putt Duration	Preparation Duration	Address Duration	Swing Duration	Post Contact Duration
T_{FS1}													
T_{FSQ}	0.323** (n=1072)												
Swing Total Fix.(B)	0.384** (n=1072)	0.097** (n=1072)											
Swing Mean Fix. Dur. (B)	0.800** (n=1072)	0.404** (n=1072)	0.433** (n=1072)										
Swing Total Fix. Dur. (B)	0.764** (n=1072)	0.348** (n=1072)	0.700** (n=1072)	0.894** (n=1072)									
Swing Total Fix.(H)	-0.085** (n=1072)	0.048 (n=1072)	-0.303** (n=1072)	-0.233** (n=1072)	-0.282** (n=1072)								
Swing Mean Fix. Dur. (H)	-0.084** (n=1072)	0.050 (n=1072)	-0.303** (n=1072)	-0.233** (n=1072)	-0.282** (n=1072)	1.000** (n=1072)							
Swing Total Fix. Dur. (H)	-0.084** (n=1072)	0.049 (n=1072)	-0.303** (n=1072)	-0.233** (n=1072)	-0.282** (n=1072)	1.000** (n=1072)	1.000** (n=1072)						
Total Putt Duration	-0.096** (n=1072)	0.039 (n=1072)	-0.199** (n=1072)	-0.049 (n=1072)	-0.096** (n=1072)	-0.016 (n=1072)	-0.017 (n=1072)	-0.017 (n=1072)					
Preparation Duration	0.065* (n=1072)	0.038 (n=1072)	-0.070* (n=1072)	0.002 (n=1072)	-0.026 (n=1072)	-0.115** (n=1072)	-0.115** (n=1072)	-0.115** (n=1072)	0.919** (n=1072)				
Address Duration	0.028 (n=1072)	0.005 (n=1072)	-0.220** (n=1072)	-0.026 (n=1072)	-0.047 (n=1072)	0.227** (n=1072)	0.226** (n=1072)	0.226** (n=1072)	0.191** (n=1072)	-0.131** (n=1072)			
Swing Duration	-0.148** (n=1072)	-0.048 (n=1072)	-0.144** (n=1072)	-0.214** (n=1072)	-0.171** (n=1072)	0.266** (n=1072)	0.266** (n=1072)	0.266** (n=1072)	0.211** (n=1072)	0.043 (n=1072)	0.433** (n=1072)		
Post Contact Duration	0.028 (n=1072)	0.019 (n=1072)	-0.022 (n=1072)	0.053 (n=1072)	0.047 (n=1072)	-0.107** (n=1072)	-0.107** (n=1072)	-0.107** (n=1072)	0.306** (n=1072)	0.201** (n=1072)	0.065* (n=1072)	0.086** (n=1072)	

**Correlation significant at the 0.05 level; **Correlation significant at the 0.01 level*

Table A.2: Overall Spearman correlations between Swing fixation parameters (T_{FS1} duration, T_{FSQ} duration, Swing Total Fixations, Swing Mean Fixation Duration, Swing Total Fixation Duration at the ball and the hole) and putt duration parameters; strong (r=0.7 to 0.9) and very strong (r >0.9) correlations are highlighted [Fix=Fixation, Dur=Duration, B=Ball, H=Hole].

A.2.4 Address, Swing, Contact and Post-Contact Ball Fixations

Based on the correlation analysis of the key fixation durations and the Address and Swing phase ball fixation parameters important conclusions could be drawn (Table A.3). First of all, the duration of T_{FAQ} was strongly correlated ($r=0.802$, $p<0.001$) with the duration of T_{FS1}. This was not an unexpected result, as T_{FAQ} (the last fixation of the Address phase) and T_{FS1} (the first fixation of the Swing phase) are very similar fixations as discussed earlier. Additionally, the duration of T_{FAQ} was highly correlated with the Mean Fixation Duration in the Swing ($r=0.730$, $p<0.001$) and the Total Duration of Fixations in the Swing ($r=0.717$, $p<0.001$).

The duration of T_{FS1} was strongly correlated with the Mean Fixation Duration in Address ($r=0.726$, $p<0.001$), the Mean Fixation Duration in the Swing ($r=0.800$, $p<0.001$) and the Total Duration of Fixations in the Swing ($r=0.764$, $p<0.001$). The correlations between T_{FAQ} and T_{FS1} and the Address and Swing fixation parameters suggest that T_{FAQ} and T_{FS1} are both significant fixations and representative of their respective phases. These results are of particular importance with respect to training golfers' putting vision strategies; the high correlations between T_{FAQ}, T_{FS1} and various parameters of the Address and Swing phases would suggest that Swing fixation strategy could be improved through training Address fixation strategy and vice versa.

The other key fixations (T_{FA1}, T_{FSQ}, T_{FCQ} or T_{FPQ}) were not correlated with each other, or with the Address and Swing fixation parameters ($r=-0.009$ to 0.420, $p<0.001$ to $p>0.05$). Although they were not highly correlated with other fixation parameters, these fixations were not excluded from the putting vision strategy analysis, as more investigation was needed to determine their relevance and importance.

Perhaps the most significant finding in this particular correlation analysis was that both the Address Mean and Total Fixation Durations were strongly correlated with the Swing Mean and Total Fixation Durations ($r=0.711$ to 0.839, $p<0.001$). This is an important result as it has significant implications for training golfers' putting vision strategy, as demonstrated in the discussion.

	T_{FA1}	T_{FAQ}	T_{FS1}	T_{FSQ}	T_{FCQ}	T_{FPQ}	Address Total Fixations	Address Mean Fixation Duration	Address Total Fixation Duration	Swing Total Fixations	Swing Mean Fixation Duration	Swing Total Fixation Duration
T_{FA1}												
T_{FAQ}	0.273** (n=1072)											
T_{FS1}	0.302** (n=1072)	0.802** (n=1072)										
T_{FSQ}	0.148** (n=1072)	0.261** (n=1072)	0.323** (n=1072)									
T_{FCQ}	0.155** (n=1072)	0.314** (n=1072)	0.337** (n=1072)	0.420** (n=1072)								
T_{FPQ}	0.110** (n=1072)	0.154** (n=1072)	0.132** (n=1072)	0.110** (n=1072)	0.102** (n=1072)							
Address Total Fixations	0.240** (n=1072)	0.405** (n=1072)	0.434** (n=1072)	0.147** (n=1072)	0.282** (n=1072)	0.068* (n=1072)						
Address Mean Fixation Duration	0.408** (n=1072)	0.735** (n=1072)	0.726** (n=1072)	0.301** (n=1072)	0.363** (n=1072)	0.150** (n=1072)	0.560** (n=1072)					
Address Total Fixation Duration	0.355** (n=1072)	0.647** (n=1072)	0.663** (n=1072)	0.255** (n=1072)	0.368** (n=1072)	0.128** (n=1072)	0.874** (n=1072)	0.871** (n=1072)				
Swing Total Fixations	0.244** (n=1072)	0.342** (n=1072)	0.384** (n=1072)	0.097** (n=1072)	0.182** (n=1072)	-0.009 (n=1072)	0.598** (n=1072)	0.568** (n=1072)	0.638** (n=1072)			
Swing Mean Fixation Duration	0.337** (n=1072)	0.730** (n=1072)	0.800** (n=1072)	0.404** (n=1072)	0.381** (n=1072)	0.130** (n=1072)	0.476** (n=1072)	0.783** (n=1072)	0.711** (n=1072)	0.433** (n=1072)		
Swing Total Fixation Duration	0.359** (n=1072)	0.717** (n=1072)	0.764** (n=1072)	0.348** (n=1072)	0.407** (n=1072)	0.123** (n=1072)	0.602** (n=1072)	0.839** (n=1072)	0.816** (n=1072)	0.700** (n=1072)	0.894** (n=1072)	

**Correlation significant at the 0.05 level; **Correlation significant at the 0.01 level*

Table A.3: Overall Spearman correlations between Address and Swing ball fixation parameters; strong (r=0.7 to 0.9) and very strong (r>0.9) correlations are highlighted.

A.2.5 Start and End Times of Key Fixations

The start and end times of each of the key fixations from T_0 are not related, except for the start and end times of T_{FSQ} and T_{FCQ} (Table A.4). The start of T_{FA1} was only correlated with the end of T_{FA1} ($r=1.000$, $p<0.001$), just as the start of T_{FAQ} was only correlated with the end of T_{FAQ} ($r=0.786$, $p<0.001$), the start of T_{FS1} was only correlated with the end of T_{FS1} ($r=0.770$, $p<0.001$) and the start of T_{FPQ} was only correlated with the end of T_{FPQ} ($r=0.972$, $p<0.001$).

T_{FSQ} and T_{FCQ} were exceptions, because the start of T_{FSQ} was strongly correlated with the start of T_{FCQ} ($r=0.992$, $p<0.001$) as well as the end of T_{FSQ} ($r=0.864$, $p<0.001$), and the end of T_{FSQ} correlated with the end of T_{FCQ} ($r=0.999$, $p<0.001$). The strong correlations between T_{FSQ} and T_{FCQ} were a direct result of the definition of these fixations, rather than a significant finding. If a fixation with a duration greater than 0.00ms occurred at contact it had to have started in the Swing phase, thus $T_{FCQ}=T_{FSQ}$; hence their similarity.

Despite the strong correlations between the start and end times of the individual key fixations, these parameters did not provide much information about the overall putting vision strategy; rather they simply indicated that the start and end times of each fixation were correlated with each other. For this reason, they were excluded from any further analyses of the putting vision strategy. Had the start and end times of the key fixations correlated with each other they may have been able to provide more information about the overall putting strategy.

A.2.6 Right and Left Eye Fixations

Table A.5 displays the mean ± standard deviations and the Spearman correlation r-values for the right and left eye fixation parameters. Apart from the Total Number of Fixations ($r=0.776$) and the Total Fixation Duration (Spearman $r=0.778$) in Address, no other parameters demonstrated strong correlations between the right and left eyes. The lack of correlation between right and left eye data indicated that eye needed to be considered as a factor in all further analyses. It also demonstrated that analysis of one eye only, as has been done previously in monocular studies, was based on an incorrect assumption that both eyes are acting in a similar manner.

	T_{FA1} Start from T0	T_{FA1} End from T0	T_{FAQ} Start from T0	T_{FAQ} End from T0	T_{FS1} Start from T0	T_{FS1} End from T0	T_{FSQ} Start from T0	T_{FSQ} End from T0	T_{FCQ} Start from T0	T_{FCQ} End from T0	T_{FPQ} Start from T0	T_{FPQ} End from T0
T_{FA1} Start from T0												
T_{FA1} End from T0	1.000** (n=1072)											
T_{FAQ} Start from T0	0.447** (n=1072)	0.447** (n=1072)										
T_{FAQ} End from T0	0.294** (n=1072)	0.297** (n=1072)	0.786** (n=1072)									
T_{FS1} Start from T0	0.378** (n=1043)	0.375** (n=1043)	0.472** (n=1043)	0.157** (n=1043)								
T_{FS1} End from T0	0.286** (n=1043)	0.286** (n=1043)	0.388** (n=1043)	0.494** (n=1043)	0.770** (n=1043)							
T_{FSQ} Start from T0	0.102** (n=1042)	0.104** (n=1042)	0.265** (n=1042)	0.378** (n=1042)	-0.102** (n=1042)	0.041 (n=1042)						
T_{FSQ} End from T0	0.050 (n=1042)	0.054 (n=1042)	0.234** (n=1042)	0.446** (n=1042)	-0.198** (n=1042)	0.045 (n=1042)	0.864** (n=1042)					
T_{FCQ} Start from T0	0.123* (n=295)	0.118* (n=295)	0.139* (n=295)	-0.055 (n=295)	0.232** (n=295)	0.058 (n=295)	0.992** (n=295)	-0.046 (n=295)				
T_{FCQ} End from T0	-0.110 (n=295)	-0.108 (n=295)	-0.083 (n=295)	0.128* (n=295)	-0.184** (n=295)	0.017 (n=295)	-0.038 (n=295)	0.999** (n=295)	-0.044 (n=295)			
T_{FPQ} Start from T0	0.078* (n=1071)	0.075* (n=1071)	-0.154** (n=1071)	-0.270** (n=1071)	0.204** (n=1042)	0.083* (n=1042)	-0.178** (n=1042)	-0.161** (n=1042)	0.070 (n=295)	0.168** (n=295)		
T_{FPQ} End from T0	0.070* (n=1071)	0.068* (n=1071)	-0.153** (n=1071)	-0.242** (n=1071)	0.186** (n=1042)	0.098* (n=1042)	-0.172** (n=1042)	-0.148** (n=1042)	0.005 (n=295)	0.138* (n=295)	0.972** (n=1071)	

**Correlation significant at the 0.05 level; **Correlation significant at the 0.01 level*

Table A.4: Overall Spearman correlations between the Start and End from T_0 of the key fixations (T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}); strong (r=0.7 to 0.9) and very strong (r>0.9) correlations are highlighted.

Parameter	Right Eye	Left Eye	Spearman r-value
T_{FA1} Duration	37.7 ± 39.9	40.9 ± 47.8	0.262**
T_{FAQ} Duration	89.0 ± 120.1	123.2 ± 174.5	0.391**
T_{FS1} Duration	85.6 ± 119.7	115.1 ± 175.2	0.452**
T_{FSQ} Duration	31.8 ± 36.7	35.1 ± 55.5	0.146**
T_{FCQ} Duration	14.5 ± 39.5	16.2 ± 51.8	0.209**
T_{FPQ} Duration	25.4 ± 25.2	23.7 ± 17.5	0.036
Total Number of Fixations (A)*	44.9 ± 22.7	40.1 ± 23.1	0.776**
Mean Fixation Duration (A)	40.9 ± 22.5	44.7 ± 26.3	0.609**
Total Fixation Duration (A)	2020.7 ± 1607.0	2059.2 ± 1726.5	0.778**
Total Number Fixations (S)*	10.0 ± 5.0	9.1 ± 5.4	0.587**
Mean Fixation Duration (S)	41.6 ± 32.5	48.0 ± 56.9	0.551**
Total Fixation Duration (S)	435.0 ± 317.9	452.3 ± 374.1	0.668**

**Count data without units; **Correlation is significant at p < 0.01*

Table A.5: Mean ± standard deviations and Spearman correlation values for the comparison of right and left eye gaze data in the overall population (skill groups pooled). Mean ± standard deviations are reported in milliseconds (ms) except for the Total Number of Ball Fixations in the Address (A) and Swing (S) which are count data and do not have units.

A.3 Conclusions

Based on the preliminary analyses, the decision was made to include only the following 12 parameters in the analysis of putting vision strategy: T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}, the Total Number of Fixations to the ball in the Address and Swing, the Mean Fixation Duration of fixations to the ball in the Address and Swing and the Total Fixation Duration of fixations to the ball in the Address and Swing.

The poor correlations between the hole and ball fixation parameters and the small number of hole fixations made during both the Address (Median=4) and Swing (Median =0) phases, suggests that fixations to the hole, as defined in this study, do not significantly impact putting vision strategy. This may be due, in part to the inherent lack of precision in the measurement of hole fixations in this study. The eye tracking system used in this study was set up and calibrated to accurately measure ball fixations in putting gaze, rather than hole fixations which occurred in a side gaze position. Consequently, hole fixations were excluded from all further analyses of putting vision strategy.

Appendix B
Examination of a Learning Effect in Golf Putting with an Eye Tracking Device

As none of the golfers had previously worn eye tracking equipment, it was deemed prudent to determine if there was any sort of adaptation or learning effect due to wearing the equipment that would have affected the analysis of the putting vision strategy. A repeated measures multivariate ANOVA as completed on each of the following parameters: T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ}, Total Number of Fixations, Mean Fixation Duration, and Total Fixation Duration in both the Address and Swing phases. One Club Professional golfer was excluded from this analysis because only 8 putts had been recorded at each distance; data from the remaining nine Top Professionals, five Club Professionals and twelve Amateurs was included. It was hypothesised that golfers would not experience significant adaptation to the eye tracking equipment, and that the effect of Putt Trial*Eye would not be significant.

B.1 Statistical Methods

To examine for a learning effect, a repeated measures multivariate ANOVA model was used, whereby Skill (Top Professional, Club Professional or Amateur), Putt Length (6 or 10 foot) and Putt Result (Success or Failure) were used as between subjects factors and Putt Trial was used as a within subjects factor. Eye (right or left) was used a within subjects factor, nested within the Putt Trial term as a sample size control variable. Eye could not be assessed as an independent factor without first considering the influence of ocular dominance, therefore the effect of Eye was not considered to be significant in the results.

Pillai's trace was used to determine the significance of the multivariate effects. The F-statistic (F) and the significance value of the test (p) are both reported. Post-hoc Bonferroni comparisons were used to compare the estimated marginal means of the between subjects factors. When estimated marginal means are reported, they are reported as mean ± standard error and denoted with " † "; all other mean values are reported as mean ± standard deviation.

B.2 Results

Putt Trial*Eye did not have a significant effect on T_{FA1} ($F_{(9,38)}$=1.378, p=0.232), T_{FAQ} ($F_{(9,38)}$=1.066, p=0.409), T_{FS1} ($F_{(9,38)}$=0.993, p=0.462), T_{FSQ} ($F_{(9,38)}$=0.9558, p=0.491), T_{FCQ} ($F_{(9,38)}$=0.514, p=0.855), T_{FPQ} ($F_{(9,38)}$=0.759, p=0.654), the Total Number of Fixations in the Address ($F_{(9,38)}$=1.015, p=0.445) and Swing ($F_{(9,38)}$=0.409, p=0.922) phases, the Mean Fixation Duration in the Address ($F_{(9,38)}$=1.520, p=0.176) and Swing ($F_{(9,38)}$=1.164, p=0.345) phases, and the Total Fixation Duration in the Swing ($F_{(9,38)}$=0.820, p=0.602) phase.

Putt Trial*Eye did have a significant effect on the Total Fixation Duration in the Address ($F_{(9,38)}$=2.220, p=0.042). Pairwise comparisons revealed non-significant differences between all putts (p=0.203 – 1.000), except for Putt 1 versus Putt 10 (p=0.030). The estimated mean values for each putt ranged from a low of 1.839±0.178[†] on Putt 10 to a high of 2.117±0.199[†] on Putt 1; the Total Fixation Duration in the Address varied randomly between its minimum and maximum values for Putts 2 – 9. Therefore, it was concluded that there was no specific adaptation or learning effect influencing the Total Fixation Duration in Address measurement, and that the significance of the multivariate test was a random occurrence.

As no significant effects of Putt Trial*Eye were found for any of the other variables, there did not appear to be an adaptation effect associated with the eye trackers. Golfers seemed reasonably comfortable wearing the equipment and were capable of putting consistently during the sessions, therefore performance during testing was thought to be representative of their performance on a golf course. To make the testing conditions more representative of normal golf putting, golfers were asked to go through their normal full putting routine starting with initially reading the green, and ending after ball contact, during the tests.

Appendix C

Data Collection Efficiency

As an analysis of this type had never been done before, it was decided that ten putts would be assessed at each distance as it was thought this would give a good indication of golfers' performance. As no learning effect was detected, it may have been possible to measure a golfer's performance with fewer putts, which would save time and increase efficiency when recording and processing data in future studdies.

C.1 Methods

To determine how many putts were needed for the analysis of the putting vision strategy, Spearman correlations were used to compare the results of the session mean (ten putts) with the means of the first three and the first five putts taken in each session. As golfers usually took ten putts at each distance per session, the session means were calculated each distance using all ten putts. In one golfer (a Club Professional) only eight putts were included in the calculation of the session mean at each distance, as two putts at each distance could not be analysed due to problems with the recording system.

Correlations of 0.0 to 0.199 were defined as very weak (negligible), 0.2 to 0.399 weak, low correlation (not significant), 0.4 to 0.699 moderate correlation, 0.7 to 0.899 strong, high correlation, and 0.9 to 1.000 very strong correlation.[2-4] Non-parametric Spearman correlations were used because the majority of the parameters measured did not have a normal Gaussian distributions. Strong correlations between parameters were considered to be indicative of similar samples. The significance value for all analyses was α=0.05 unless otherwise stated.

C.2 Results

The three putt mean results were strongly correlated with the session means for the population and Top Professionals overall and at both at 6 and 10 feet. In these particular groups at least 11 of the 12 parameters were strongly correlated ($r \geq 0.700$). In the Club Professional group overall and at 6 feet, and in the Amateur group overall and at 6 and 10 feet, at least 9 of the parameters were strongly correlated with each other. The Club Professional group at 10 feet had the lowest number of strong correlations between the three putt and the Session results, with only 6 parameters demonstrating strong correlations (Table C.1).

Comparing the five putt mean results with the session mean demonstrated even better results; the entire population and each of the individual skill groups demonstrated strong correlations on all 12 parameters overall and at both 6 and 10 feet. The only exception to was the Club Professional group at 10 feet, which only demonstrated strong correlations between 9 parameters. Notably in the population and the Top Professional group, most of the parameters were actually very strongly correlated ($r \geq 0.900$) which highlights the similarity between the five putt and session (ten putt) results (Table C.2).

C.3 Conclusions

Although many of the three putt results correlated well with the session means, there were not enough strong correlations to consider the three putt results representative of the overall performance. The five putts results give a good representation of golfers' putting performance as the five putt means correlate strongly with the session means (ten putt) on almost every parameter. Despite the excellent correlation between the five putt and session mean results, the analyses presented in this thesis were still based on the session mean values as it was felt that the session means still gave a superior indication of a golfers' performance. Had it not been possible to measure ten putts, five putts could have been used and this will be borne in mind for future studies.

Condition	Overall	Top Pro	Club Pro	Amateurs	6 foot	10 foot	Top Pro, 6 foot	Top Pro, 10 foot	Club Pro, 6 foot	Club Pro, 10 foot	Amateurs, 6 foot	Amateurs, 10 foot
3 Putt Mean	**Session Mean**											
TFA1 Duration	0.784** (n=108)	0.802** (n=36)	0.651** (n=24)	0.724** (n=48)	0.730** (n=54)	0.815** (n=54)	0.577* (n=18)	0.878** (n=18)	0.704* (n=12)	0.648* (n=12)	0.710** (n=24)	0.752** (n=24)
TFAQ Duration	0.900** (n=108)	0.895** (n=36)	0.678** (n=24)	0.794** (n=48)	0.909** (n=54)	0.876** (n=54)	0.891** (n=18)	0.922** (n=18)	0.853** (n=12)	0.406 (n=12)	0.714** (n=24)	0.833** (n=24)
TFS1 Duration	0.902** (n=108)	0.920** (n=36)	0.715** (n=24)	0.851** (n=48)	0.918** (n=54)	0.878** (n=54)	0.905** (n=18)	0.961** (n=18)	0.681** (n=12)	0.587* (n=12)	0.850** (n=24)	0.843** (n=24)
TFSQ Duration	0.758** (n=108)	0.850** (n=36)	0.824** (n=24)	0.607** (n=48)	0.731** (n=54)	0.750** (n=54)	0.747** (n=18)	0.920** (n=18)	0.878** (n=12)	0.773** (n=12)	0.642** (n=24)	0.553** (n=24)
TFCQ Duration	0.811** (n=108)	0.926** (n=36)	0.771** (n=24)	0.636** (n=48)	0.829** (n=54)	0.789** (n=54)	0.932** (n=18)	0.931** (n=18)	0.891** (n=12)	0.511 (n=12)	0.668** (n=24)	0.651** (n=24)
TFPQ Duration	0.728** (n=108)	0.873** (n=36)	0.671** (n=24)	0.615** (n=48)	0.699** (n=54)	0.758** (n=54)	0.886** (n=18)	0.831** (n=18)	0.747** (n=12)	0.627* (n=12)	0.479* (n=24)	0.745** (n=24)
Address Total Fixations	0.938** (n=108)	0.819** (n=36)	0.861** (n=24)	0.900** (n=48)	0.928** (n=54)	0.939** (n=54)	0.763** (n=18)	0.801** (n=18)	0.479 (n=12)	0.688* (n=12)	0.921** (n=24)	0.873** (n=24)
Address Mean Fixation Duration	0.974** (n=108)	0.964** (n=36)	0.899** (n=24)	0.920** (n=48)	0.979** (n=54)	0.968** (n=54)	0.946** (n=18)	0.975** (n=18)	0.944** (n=12)	0.846** (n=12)	0.902** (n=24)	0.922** (n=24)
Address Total Fixation Duration	0.980** (n=108)	0.983** (n=36)	0.921** (n=24)	0.926** (n=48)	0.980** (n=54)	0.977** (n=54)	0.973** (n=18)	0.979** (n=18)	0.902** (n=12)	0.895** (n=12)	0.922** (n=24)	0.913** (n=24)
Swing Total Fixations	0.960** (n=108)	0.894** (n=36)	0.932** (n=24)	0.970** (n=48)	0.946** (n=54)	0.962** (n=54)	0.829** (n=18)	0.923** (n=18)	0.926** (n=12)	0.900** (n=12)	0.953** (n=24)	0.982** (n=24)
Swing Mean Fixation Duration	0.951** (n=108)	0.969** (n=36)	0.891** (n=24)	0.909** (n=48)	0.953** (n=54)	0.948** (n=54)	0.965** (n=18)	0.969** (n=18)	0.951** (n=12)	0.797** (n=12)	0.870** (n=24)	0.930** (n=24)
Swing Total Fixation Duration	0.977** (n=108)	0.900** (n=36)	0.956** (n=24)	0.973** (n=48)	0.979** (n=54)	0.972** (n=54)	0.897** (n=18)	0.899** (n=18)	0.979** (n=12)	0.930** (n=12)	0.976** (n=24)	0.983** (n=24)

**Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level*

Table C.1: Spearman correlations comparing the Session Mean to the Mean of the First 3 Putts for T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ} and the Address and Swing phase parameters; Session means are in the vertical columns, Means of the First 3 Putts are in the horizontal rows; the parameters compared are listed horizontally and the groups compared are listed vertically; strong (r=0.7 to 0.9) and very strong (r >0.9) correlations are highlighted.

Condition	Overall	Top Pro	Club Pro	Amateurs	6 foot	10 foot	Top Pro, 6 foot	Top Pro, 10 foot	Club Pro, 6 foot	Club Pro, 10 foot	Amateurs, 6 foot	Amateurs, 10 foot
Mean of 5 Putts	**Session Mean**											
TFA1 Duration	0.898** (n=108)	0.904** (n=36)	0.838** (n=24)	0.862** (n=48)	0.886** (n=54)	0.899** (n=54)	0.812** (n=18)	0.936** (n=18)	0.830** (n=12)	0.846** (n=12)	0.865** (n=24)	0.858** (n=24)
TFAQ Duration	0.955** (n=108)	0.948** (n=36)	0.796** (n=24)	0.884** (n=48)	0.971** (n=54)	0.927** (n=54)	0.967** (n=18)	0.946** (n=18)	0.900** (n=12)	0.757** (n=12)	0.907** (n=24)	0.852** (n=24)
TFS1 Duration	0.945** (n=108)	0.949** (n=36)	0.846** (n=24)	0.873** (n=48)	0.956** (n=54)	0.921** (n=54)	0.953** (n=18)	0.963** (n=18)	0.958** (n=12)	0.673* (n=12)	0.906** (n=24)	0.819** (n=24)
TFSQ Duration	0.878** (n=108)	0.887** (n=36)	0.856** (n=24)	0.816** (n=48)	0.820** (n=54)	0.905** (n=54)	0.853** (n=18)	0.951** (n=18)	0.802** (n=12)	0.821** (n=12)	0.789** (n=24)	0.798** (n=24)
TFCQ Duration	0.904** (n=108)	0.941** (n=36)	0.829** (n=24)	0.855** (n=48)	0.898** (n=54)	0.902** (n=54)	0.942** (n=18)	0.961** (n=18)	0.878** (n=12)	0.660* (n=12)	0.869** (n=24)	0.861** (n=24)
TFPQ Duration	0.873** (n=108)	0.920** (n=36)	0.837** (n=24)	0.793** (n=48)	0.869** (n=54)	0.857** (n=54)	0.938** (n=18)	0.876** (n=18)	0.861** (n=12)	0.755** (n=12)	0.783** (n=24)	0.796** (n=24)
Address Total Fixations	0.971** (n=108)	0.903** (n=36)	0.804** (n=36)	0.959** (n=48)	0.969** (n=54)	0.965** (n=54)	0.833** (n=18)	0.870** (n=18)	0.809** (n=12)	0.682* (n=12)	0.977** (n=24)	0.946** (n=24)
Address Mean Fixation Duration	0.986** (n=108)	0.977** (n=36)	0.935** (n=36)	0.954** (n=48)	0.989** (n=54)	0.963** (n=54)	0.971** (n=18)	0.988** (n=18)	0.965** (n=12)	0.895** (n=12)	0.950** (n=24)	0.953** (n=24)
Address Total Fixation Duration	0.991** (n=108)	0.994** (n=36)	0.923** (n=36)	0.971** (n=48)	0.993** (n=54)	0.986** (n=54)	0.981** (n=18)	0.996** (n=18)	0.944** (n=12)	0.846** (n=12)	0.970** (n=24)	0.969** (n=24)
Swing Total Fixations	0.977** (n=108)	0.946** (n=36)	0.975** (n=36)	0.981** (n=48)	0.968** (n=54)	0.979** (n=54)	0.919** (n=18)	0.931** (n=18)	0.977** (n=12)	0.984** (n=12)	0.972** (n=24)	0.988** (n=24)
Swing Mean Fixation Duration	0.967** (n=108)	0.977** (n=36)	0.861** (n=36)	0.947** (n=48)	0.972** (n=54)	0.956** (n=54)	0.953** (n=18)	0.981** (n=18)	0.951** (n=12)	0.706** (n=12)	0.933** (n=24)	0.953** (n=24)
Swing Total Fixation Duration	0.986** (n=108)	0.917** (n=36)	0.980** (n=36)	0.983** (n=48)	0.987** (n=54)	0.988** (n=54)	0.889** (n=18)	0.953** (n=18)	0.986** (n=12)	0.965** (n=12)	0.990** (n=24)	0.988** (n=24)

**Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level*

Table C.2: Spearman correlations comparing the Session Mean to the Mean of the First 5 Putts for T_{FA1}, T_{FAQ}, T_{FS1}, T_{FSQ}, T_{FCQ}, T_{FPQ} and the Address and Swing phase parameters; Session means are in the vertical columns, Means of the First 5 Putts are in the horizontal rows; the parameters compared are listed horizontally and the groups compared are listed vertically; strong (r=0.7 to 0.9) and very strong (r >0.9) correlations are highlighted.

Appendix D
Linear Mixed Model Development

The purpose of the analyses conducted in Chapters 5 and 6 of this thesis was to examine various aspects of the putting vision strategy. Chapter 5 dealt specifically with the factors associated with skill and success, and Chapter 6 examined the relationship between training and competition, as well as the influence of ocular dominance. The Skill-Success analysis presented in Chapter 5 was the principle analysis of the study, and its results affected which parameters were included in the subsequent analyses. As such, the mixed model development focused on obtaining an appropriate basic model for the Skill-Success analysis. This model was then used in the subsequent Training-Competition and Ocular Dominance analyses. [Note: A generalised linear mixed model is a type of regression analysis in which the linear predictor contains random effects in addition to fixed effects. Its is an extension of the generalised linear model.]

D.1 Skill-Success Model Development

The principle explanatory variables included in the Skill-Success were Skill, Putt Length and Putt Result. Subjects were identified by a Player ID variable. The repeated measures variable was Putt Trial, which was identified by the Player ID, Eye and Putt Length variables; Eye and Putt Length were nested within Player ID to precisely identify the repeated measures data. Eye was also included in the model as an explanatory variable to account for any variations in these parameters which could affect the final results.

In addition to identification of the explanatory and repeated measures variables, the decision needed to be made regarding whether or not random intercept and random slope factors should be included in the model. The covariance structure of the repeated measures term also needed to be decided upon. In order to make these decisions, the quantitative variables, Duration T_{FAQ} and Total Fixation Duration in Address were chosen as sample variables to be examined in detail. It was felt that the behaviour of these two variables represented the behaviour of all of the parameters of interest.

Figures D.1 to D.4 display scatter plots with best fit lines for each skill group (Figure D.1, D.2) and each player (Figure D.3, D.4). Based on these figures it can be seen that the intercepts of each group and each individual were quite different, but the best fit lines were relatively linear in most cases. In particular the y-intercepts appeared to be higher in the Top Professional golfers (Figure D.1, D.2) for both T_{FAQ} duration and Total Fixation Duration in Address. The near-linear slopes of the best fit lines suggested that T_{FAQ} duration was relatively consistent in all of the putts measured. The Total Fixation Duration in Address also appeared relatively constant on all putts in the Club Professionals and Amateurs. In Top Professionals there appeared to be a slight trend towards Total Fixation Duration in Address being shorter on latter putts, but the difference does not appear to be clinically significant. Based on these results, it was decided to include a random intercept in the model, but not a random slope.

Figure D.1 Duration T_{FAQ} on (A) 6 and (B) 10 foot putts with fit lines for each skill.

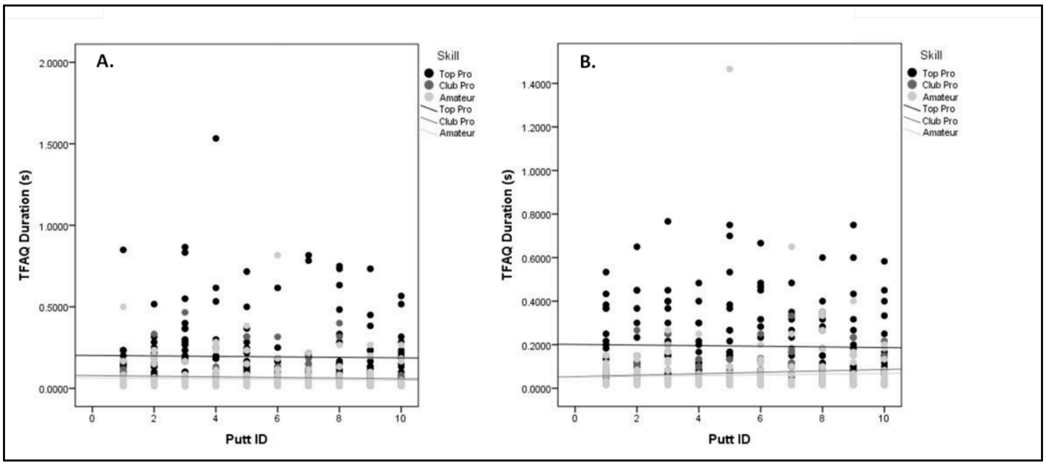
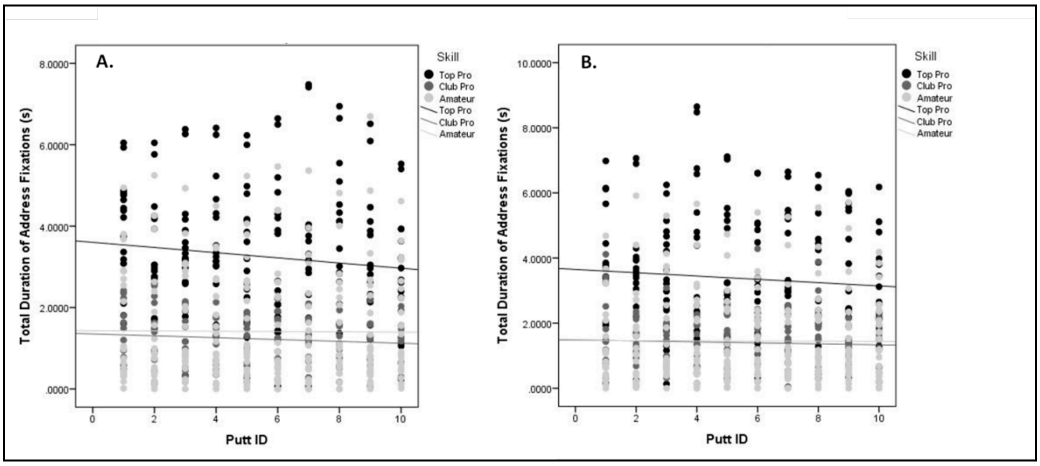


Figure D.2 Total Fixation Duration in Address on (A) 6 and (B) 10 foot putts with fit lines for each skill.



In individual players (Figures D.3, D.4) the y-intercepts of T_{FAQ} duration and the Total Fixation Duration in the Address both vary significantly, but again the slopes appear to be relatively linear in most individuals; these results support the random intercept model design without the use of a random slope.

Figure D.3: Duration T_{FAQ} on (A) 6 and (B) 10 foot putts with fit lines for each player.

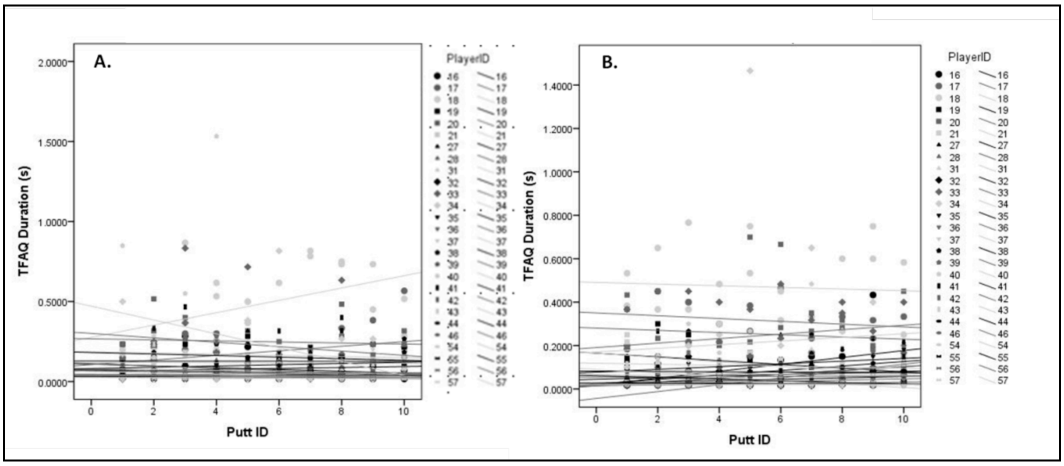
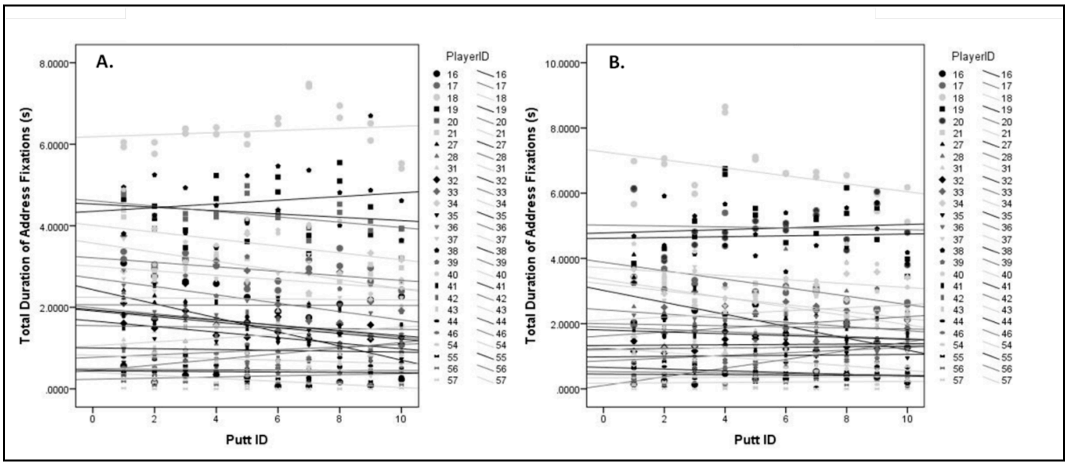


Figure D.4: Total Fixation Duration in Address on (A) 6 and (B) 10 foot putts with fit lines for each player.



Tables D.1 to D.12 display the correlation, variance and covariance estimates for T_{FAQ} Duration and Total Duration of Fixations in Address for the Top Professional (Tables D.1 to D.4), Club Professional (Tables D.5 to D.8) and Amateur (Tables D.9 to D.12) skill groups. These results were used to determine the appropriate covariance structure for the repeated measures terms of the linear mixed model.

D.1.1 Top Professionals

For the most part, the duration of T_{FAQ} was correlated between individual trials, although the correlations ranged in strength (r=0.012 to 0.986). There was no consistent pattern in the strength of the correlations between trials, as demonstrated below the diagonal in the following tables, which display the correlation analysis results in the Top Professionals at 6 feet (Table D.1) and 10 feet (Table D.2). The Total Duration of Fixations in Address was highly correlated between all trials (r=0.712 to 0.989); these results can be found in Tables D.3 and D.4 below the diagonal.

The variance estimates for T_{FAQ} duration and Total Duration of Fixations in Address on 6 foot and 10 foot putts are displayed along the diagonal in Tables D.1 to D.4, and covariance estimates are displayed above the diagonal. Variance values were relatively constant for each parameter examined (T_{FAQ} duration: 6 foot, range 0.016 to 0.060, 10 foot, range 0.018 to 0.050; Total Address Fixation Duration: 6 foot, range 2.008 to 3.657, 10 foot, range 2.223 to 6.228), although there was still a small amount of variation. Covariance varied greatly between putts at all distances, and there was no consistent pattern in its variation.

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**0.035**	*0.004*	*0.006*	*0.003*	*0.007*	*0.002*	*-0.004*	*0.002*	*0.003*	*0.000*
Putt 2	0.486	**0.016**	*0.016*	*0.022*	*0.010*	*0.002*	*0.007*	*0.018*	*0.008*	*0.014*
Putt 3	0.391	0.680*	**0.060**	*0.045*	*0.044*	*0.014*	*0.036*	*0.054*	*0.040*	*0.022*
Putt 4	0.253	0.347	0.504*	**0.132**	*0.018*	*0.028*	*0.045*	*0.041*	*0.042*	*0.028*
Putt 5	0.212	0.589	0.904**	0.523*	**0.036**	*0.015*	*0.023*	*0.040*	*0.025*	*0.011*
Putt 6	0.052	0.492	0.261	0.723*	0.429	**0.019**	*0.030*	*0.030*	*0.017*	*0.010*
Putt 7	-0.077	0.771**	0.529	0.898**	0.475	0.722**	**0.056**	*0.044*	*0.041*	*0.024*
Putt 8	0.044	0.930**	0.801**	0.827**	0.810**	0.736**	0.781**	**0.058**	*0.041*	*0.028*
Putt 9	0.068	0.440	0.659*	0.953**	0.585*	0.579*	0.844**	0.825**	**0.035**	*0.023*
Putt 10	0.012	0.520	0.425	0.754**	0.305	0.401	0.572*	0.655**	0.779**	**0.025**

*correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.1 Correlation, variance and covariance estimates for T_{FAQ} durations on each putt for Top Professional golfers on 6 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**0.027**	*0.024*	*0.039*	*0.016*	*0.037*	*0.028*	*0.013*	*0.019*	*0.028*	*0.033*
Putt 2	0.749*	**0.034**	*0.032*	*0.021*	*0.039*	*0.037*	*0.013*	*0.022*	*0.038*	*0.033*
Putt 3	0.755*	0.722*	**0.038**	*0.031*	*0.037*	*0.022*	*0.015*	*0.012*	*0.029*	*0.030*
Putt 4	0.740*	0.826**	0.815*	**0.018**	*0.022*	*0.015*	*0.005*	*0.012*	*0.032*	*0.023*
Putt 5	0.795**	0.768**	0.717**	0.605*	**0.050**	*0.039*	*0.010*	*0.026*	*0.039*	*0.038*
Putt 6	0.777**	0.784**	0.394	0.505	0.808**	**0.041**	*0.010*	*0.030*	*0.024*	*0.029*
Putt 7	0.370	0.415	0.528*	0.198	0.316	0.284	**0.020**	*0.005*	*0.004*	*0.013*
Putt 8	0.591*	0.659*	0.345	0.493	0.756**	0.845**	0.231	**0.026**	*0.027*	*0.019*
Putt 9	0.634*	0.803**	0.567	0.915**	0.648*	0.546*	0.125	0.700**	**0.043**	*0.021*
Putt 10	0.891**	0.819**	0.818**	0.758*	0.777**	0.794**	0.521*	0.602*	0.576*	**0.026**

*correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.2 Correlation, variance and covariance estimates for T_{FAQ} durations on each putt for Top Professional golfers on 10 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**2.269**	*1.482*	*2.708*	*2.928*	*2.442*	*2.948*	*2.309*	*2.249*	*2.216*	*1.990*
Putt 2	0.930**	**2.152**	*1.317*	*1.858*	*2.067*	*0.786*	*1.488*	*2.000*	*1.438*	*1.344*
Putt 3	0.957**	0.940**	**2.036**	*2.211*	*2.468*	*4.024*	*3.381*	*3.164*	*3.389*	*2.933*
Putt 4	0.983**	0.978**	0.941**	**2.713**	*2.848*	*4.286*	*3.774*	*3.871*	*3.683*	*3.220*
Putt 5	0.970**	0.942**	0.963**	0.960**	**2.598**	*3.625*	*3.245*	*3.166*	*3.058*	*2.810*
Putt 6	0.899**	0.953**	0.984**	0.975**	0.986**	**3.343**	*3.996*	*3.505*	*3.002*	*2.620*
Putt 7	0.860**	0.963**	0.974**	0.939**	0.942**	0.989**	**3.657**	*3.320*	*3.171*	*2.818*
Putt 8	0.907**	0.964**	0.940**	0.993**	0.951**	0.985**	0.942**	**3.400**	*2.904*	*2.598*
Putt 9	0.860**	0.975**	0.987**	0.986**	0.925**	0.926**	0.926**	0.941**	**2.705**	*2.254*
Putt 10	0.946**	0.979**	0.978**	0.989**	0.977**	0.946**	0.944**	0.966**	0.967**	**2.008**

*correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.3 Correlation, variance and covariance estimates for Total Fixation Duration in Address on each putt for Top Professional golfers on 6 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**3.375**	*1.540*	*4.949*	*2.924*	*4.024*	*3.214*	*4.842*	*3.394*	*3.155*	*3.136*
Putt 2	0.729*	**3.088**	*2.119*	*4.189*	*2.015*	*3.686*	*3.634*	*2.778*	*3.081*	*3.383*
Putt 3	0.965**	0.934**	**2.847**	*4.810*	*3.665*	*3.487*	*2.684*	*2.975*	*3.081*	*2.393*
Putt 4	0.712**	0.898**	0.887**	**6.228**	*5.008*	*4.143*	*4.078*	*4.033*	*3.171*	*2.377*
Putt 5	0.931**	0.876**	0.962**	0.967**	**3.758**	*3.448*	*3.668*	*3.245*	*3.327*	*3.608*
Putt 6	0.904**	0.934**	0.974**	0.948**	0.965**	**3.325**	*4.260*	*3.064*	*3.368*	*3.138*
Putt 7	0.947**	0.932**	0.956**	0.938**	0.988**	0.986**	**3.413**	*3.637*	*3.793*	*2.811*
Putt 8	0.908**	0.859**	0.961**	0.921**	0.932**	0.970**	0.934**	**3.327**	*3.118*	*3.126*
Putt 9	0.880**	0.826**	0.903**	0.808**	0.914**	0.948**	0.960**	0.924**	**3.519**	*2.862*
Putt 10	0.883**	0.935**	0.953**	0.811*	0.977**	0.972**	0.971**	0.944**	0.928**	**2.223**

* correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.4 Correlation, variance and covariance estimates for Total Fixation Duration in Address on each putt for Top Professional golfers on 10 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

D.1.2 Club Professionals and Amateurs

The Club Professional (Tables D.5 to D.8) and Amateur (Tables D.9 to D.12) results can be found below. The duration of T_{FAQ} was correlated between some individual putts in the Club Professional group, and between most individual putts in the Amateurs, although the correlations ranged in strength (Club Professionals, r= -0.553 to 1.000; Amateurs, r= -0.469 to 0.958). There was no consistent pattern in the strength of the correlations between putts. The Total Duration of Fixations in Address was highly correlated between most putts in the Club Professionals (r=0.183 to 1.000) and Amateurs (r= -0.210 to 0.995). There were more strong correlations between putts in the Amateur group. Again there was no consistent pattern in the strength of the correlations between putts.

Tables D.5 to D.12 also display the variance and covariance estimates for T_{FAQ} duration and Total Duration of Fixations in Address on 6 foot and 10 foot putts. Variance estimates are displayed along the diagonal, and covariance estimates are displayed above the diagonal. Variance values were relatively constant for each parameter examined in both Club Professionals (T_{FAQ} duration: 6 foot, range 0.000 to 0.009, 10 foot, range 0.001 to 0.009; Total Address Fixation Duration: 6 foot, range 0.181 to 0.561, 10 foot, range 0.303 to 1.328) and Amateurs (T_{FAQ} duration: 6 foot, range 0.001 to 0.0027, 10 foot, range 0.002 to 0.087; Total Address Fixation Duration: 6 foot, range 1.585 to 2.674, 10 foot, range 1.504 to 2.288). The covariance estimates varied greatly between putts at all distances in both skill groups, and there was no consistent pattern in its variation.

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**0.001**	*0.000*	*0.000*	*0.000*	*0.001*	*0.000*	*0.000*	*0.002*	*0.000*	*0.000*
Putt 2	-0.045	**0.009**	*0.015*	*0.003*	*0.005*	*0.009*	*0.002*	*0.000*	*0.000*	*0.000*
Putt 3	0.157	0.893**	**0.016**	*0.000*	*0.008*	*0.010*	*0.006*	*0.000*	*0.000*	*0.001*
Putt 4	0.105	0.939**	0.349	**0.005**	*0.000*	*0.000*	*0.000*	*0.002*	*0.001*	*0.000*
Putt 5	0.405	0.696*	0.563	0.009	**0.009**	*0.005*	*0.003*	*0.000*	*0.000*	*0.000*
Putt 6	0.578	0.838**	0.888**	0.521	0.524	**0.007**	*0.030*	*-0.001*	*-0.002*	*0.005*
Putt 7	-0.149	0.397	0.848**	0.763	0.925**	0.899**	**0.003**	*0.000*	*0.000*	*0.000*
Putt 8	0.447	0.246	-0.261	0.453	0.060	-0.321	0.002	**0.017**	*0.000*	*0.000*
Putt 9	0.401	0.063	-0.137	0.518	-0.156	-0.162	-0.081	0.181	**0.001**	*0.000*
Putt 10	0.087	0.152	0.602	-0.003	0.080	0.471	0.086	-0.222	0.353	**0.000**

* correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.5 Correlation, variance and covariance estimates for T_{FAQ} durations on each putt for Club Professional golfers on 6 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**0.002**	0.002	0.000	-0.001	0.000	0.000	0.000	-0.001	0.002	-0.002
Putt 2	0.921**	**0.005**	-0.001	-0.001	0.000	0.002	-0.001	0.007	0.008	0.001
Putt 3	-0.290	-0.449	**0.006**	-0.001	0.000	-0.001	0.007	0.001	0.005	0.002
Putt 4	-0.402	-0.489	-0.346	**0.002**	0.000	[c]	0.000	0.000	-0.001	0.001
Putt 5	0.195	-0.159	-0.034	-0.291	**0.001**	0.011	0.001	0.000	0.001	0.001
Putt 6	-0.166	0.206	-0.086	[c]	1.000**	**0.004**	0.002	0.001	0.003	0.000
Putt 7	0.199	-0.075	0.822	-0.011	0.183	0.489	**0.009**	-0.002	0.004	[c]
Putt 8	-0.217	0.986*	0.485	0.107	-0.553	0.627	-0.263	**0.003**	0.005	0.000
Putt 9	0.834*	0.987**	0.950*	-1.000**	1.000**	0.828*	0.986*	0.871	**0.005**	-0.001
Putt 10	-0.502	1.000**	0.248	0.241	0.201	0.345	[c]	0.004	-0.282	**0.007**

* correlation is significant at p<0.05; **correlation is significant at p<0.01; [c] cannot be computed because at least one of the variables is constant

Table D.6 Correlation, variance and covariance estimates for T_{FAQ} durations on each putt for Club Professional golfers on 10 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**0.561**	0.188	0.521	0.260	0.141	0.204	0.270	0.154	0.236	0.202
Putt 2	0.612	**0.563**	0.469	0.260	0.242	0.431	0.290	0.009	0.177	0.233
Putt 3	0.857**	0.839**	**0.424**	0.404	0.247	0.216	0.465	0.147	0.317	0.404
Putt 4	0.630	0.920**	0.839*	**0.288**	0.360	0.287	0.260	0.162	0.372	0.384
Putt 5	0.253	0.551	0.559	0.943**	**0.394**	0.290	0.231	0.122	0.259	0.281
Putt 6	0.473	0.856**	0.572	0.916*	0.805**	**0.335**	0.453	0.110	0.270	0.301
Putt 7	0.593	0.625*	0.860**	0.647	0.529	0.932**	**0.382**	0.094	0.243	0.271
Putt 8	0.454	0.081	0.761	0.569	0.615	0.737	0.719	**0.181**	0.052	0.086
Putt 9	0.577	0.466	0.758*	0.952**	0.727*	0.718*	0.645*	0.405	**0.307**	0.310
Putt 10	0.436	0.558	0.907**	0.883*	0.713*	0.752*	0.653*	0.547	0.914**	**0.375**

* correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.7 Correlation, variance and covariance estimates for Total Fixation Duration in the Address on each putt for Club Professional golfers on 6 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**1.382**	0.339	0.909	0.201	0.841	0.161	0.411	0.524	0.284	0.429
Putt 2	0.686	**0.467**	0.334	-0.020	0.093	0.623	0.318	0.166	0.578	0.366
Putt 3	0.893*	0.935**	**0.537**	2.769	2.584	0.199	1.049	0.332	0.078	0.353
Putt 4	0.927**	-0.091	0.732*	**0.480**	0.146	[c]	0.105	0.597	0.085	0.316
Putt 5	0.735*	0.238	0.473	0.490	**0.506**	0.027	0.324	0.482	0.133	0.226
Putt 6	0.183	0.913*	0.920	[c]	1.000**	**1.220**	0.969	1.352	0.339	0.208
Putt 7	0.574	0.648*	0.831	0.421	0.960**	0.838**	**0.579**	0.704	0.392	[c]
Putt 8	0.963*	0.442	0.205	0.917**	0.999**	0.895*	0.888*	**1.191**	0.274	0.174
Putt 9	0.828*	0.973**	0.628	1.000**	1.000**	0.792*	0.990**	0.940	**0.303**	0.147
Putt 10	0.842*	1.000**	0.738*	0.747	0.933**	0.560	[c]	0.797	0.677	**0.338**

* correlation is significant at p<0.05; **correlation is significant at p<0.01; [c] cannot be computed because at least one of the variables is constant

Table D.8 Correlation, variance and covariance estimates for Total Fixation Duration in Address on each putt for Club Professional golfers on 10 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**0.011**	*0.001*	*0.004*	*0.008*	*0.010*	*0.000*	*0.002*	*0.011*	*0.000*	*0.004*
Putt 2	0.514	**0.006**	*0.000*	*0.000*	*0.001*	*0.005*	*0.003*	*0.001*	*0.003*	*0.002*
Putt 3	0.883**	-0.059	**0.001**	*0.002*	*0.004*	*0.000*	*0.001*	*0.003*	*0.000*	*0.001*
Putt 4	0.718**	0.012	0.694**	**0.006**	*0.004*	*0.002*	*0.001*	*0.005*	*0.000*	*0.005*
Putt 5	0.933**	0.523	0.810**	0.570*	**0.007**	*0.000*	*0.002*	*0.008*	*0.000*	*0.003*
Putt 6	-0.190	0.300	-0.089	0.743**	-0.028	**0.027**	*0.000*	*0.001*	*0.014*	*0.000*
Putt 7	0.659**	0.422	0.641**	0.217	0.444	0.221	**0.002**	*0.001*	*0.000*	*0.002*
Putt 8	0.984**	0.241	0.958**	0.688**	0.851**	0.331	0.225	**0.003**	*0.002*	*0.002*
Putt 9	0.030	0.557*	0.504	0.102	-0.582*	0.754**	-0.187	0.792**	**0.004**	*0.001*
Putt 10	0.407	0.379	0.371	0.646*	0.924**	-0.242	0.628	0.403	0.512	**0.004**

* correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.9 Correlation, variance and covariance estimates for T_{FAQ} durations on each putt for Amateur golfers on 6 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**0.002**	*0.000*	*0.001*	*0.001*	*0.000*	*0.000*	*0.002*	*0.001*	*0.000*	*0.000*
Putt 2	-0.278	**0.002**	*0.000*	*0.000*	*0.020*	*0.000*	*0.006*	*0.001*	*0.004*	*0.001*
Putt 3	0.627	-0.110	**0.005**	*0.003*	*0.001*	*0.000*	*0.001*	*0.003*	*0.000*	*0.002*
Putt 4	0.327	0.320	0.727**	**0.002**	*0.000*	*0.000*	*0.000*	*0.003*	*0.000*	*0.001*
Putt 5	-0.016	0.824*	0.376	0.729**	**0.086**	*0.004*	*0.061*	*0.000*	*0.053*	*0.014*
Putt 6	0.169	0.182	-0.265	0.107	0.178	**0.002**	*0.001*	*0.002*	*0.000*	*0.001*
Putt 7	0.635*	0.774**	0.855**	0.430	0.938**	0.153	**0.018**	*0.000*	*0.025*	*0.011*
Putt 8	0.316	0.223	0.415	0.528*	0.045	0.393	0.049	**0.010**	*-0.001*	*0.003*
Putt 9	-0.295	0.621	-0.257	-0.271	0.967**	0.019	0.858**	-0.469	**0.007**	*0.007*
Putt 10	-0.037	0.579*	0.531	0.595	0.629**	0.180	0.958**	0.560*	0.791**	**0.004**

* correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.10 Correlation, variance and covariance estimates for T_{FAQ} durations on each putt for Amateur golfers on 10 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**2.105**	*3.452*	*1.936*	*2.142*	*1.160*	*-0.053*	*1.923*	*2.599*	*3.039*	*1.985*
Putt 2	0.917**	**2.169**	*4.448*	*2.533*	*0.178*	*1.574*	*3.369*	*2.121*	*3.397*	*2.486*
Putt 3	0.954**	0.991**	**1.725**	*1.867*	*1.001*	*0.400*	*1.884*	*2.198*	*3.007*	*1.783*
Putt 4	0.926**	0.984*	0.965**	**1.574**	*0.899*	*0.877*	*1.661*	*1.907*	*2.289*	*1.991*
Putt 5	0.823**	0.821**	0.931**	0.945**	**2.058**	*3.084*	*0.703*	*1.163*	*0.622*	*0.969*
Putt 6	-0.210	0.969**	0.897**	0.975**	0.989**	**2.384**	*1.108*	*1.059*	*1.492*	*0.720*
Putt 7	0.844**	0.979**	0.949**	0.934**	0.903**	0.954**	**1.940**	*2.140*	*2.720*	*2.277*
Putt 8	0.903**	0.989**	0.984**	0.974**	0.984**	0.985**	0.967**	**1.585**	*2.978*	*2.111*
Putt 9	0.891**	0.969**	0.971**	0.952**	0.867**	0.950**	0.949**	0.968**	**2.674**	*3.418*
Putt 10	0.950**	0.928**	0.949**	0.976**	0.911**	0.910**	0.956**	0.939**	0.993**	**1.638**

* correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.11 Correlation, variance and covariance estimates for Total Fixation Duration in Address on each putt for Amateur golfers on 6 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

	Putt 1	Putt 2	Putt 3	Putt 4	Putt 5	Putt 6	Putt 7	Putt 8	Putt 9	Putt 10
Putt 1	**1.797**	*0.630*	*1.479*	*2.318*	*1.911*	*2.175*	*2.046*	*1.204*	*2.604*	*0.714*
Putt 2	0.924**	**2.288**	*2.893*	*0.038*	*0.863*	*0.996*	*1.214*	*2.806*	*0.484*	*1.951*
Putt 3	0.931**	0.975**	**2.102**	*1.295*	*1.026*	*0.498*	*0.453*	*1.988*	*1.251*	*2.574*
Putt 4	0.944**	0.888*	0.934**	**2.192**	*2.555*	*2.543*	*2.347*	*0.945*	*3.303*	*1.103*
Putt 5	0.939**	0.947**	0.967**	0.982**	**1.645**	*2.213*	*2.190*	*0.679*	*3.116*	*0.962*
Putt 6	0.960**	0.910**	0.950**	0.988**	0.966**	**1.819**	*1.943*	*0.669*	*3.184*	*0.990*
Putt 7	0.961**	0.968**	0.906**	0.979**	0.973**	0.951**	**1.869**	*0.474*	*3.946*	*1.065*
Putt 8	0.883**	0.955**	0.897**	0.836**	0.859**	0.848**	0.930**	**2.004**	*3.946*	*1.065*
Putt 9	0.845**	0.549	0.992**	0.957**	0.952**	0.915**	0.995**	0.993**	**2.223**	*2.213*
Putt 10	0.731**	0.879**	0.949**	0.951**	0.916**	0.892**	0.912**	0.963**	0.909**	**1.504**

* correlation is significant at p<0.05; **correlation is significant at p<0.01

Table D.12 Correlation, variance and covariance estimates for Total Fixation Duration in Address on each putt for Amateur golfers on 10 foot putts; variances on diagonal (bold text), covariances above diagonal (italic text), correlations below diagonal (plain text).

D.2 Conclusion

Based on the above results, an unstructured repeated measures covariance structure was initially chosen for use in all analyses. The unstructured covariance structure allowed for the correlations and the variances to vary independently. Unfortunately, the computational load of the unstructured covariance matrix was too great; as it was trying to estimate numerous individual covariance parameters the analysis could not be run. For this reason, an alternative covariance structure needed to be chosen, and the next most appropriate structure was the scaled identity covariance structure. This structure assumed that the variances were equal across all repeated measures, but that the correlations varied independently. As this model did not try to estimate as many covariance parameters, there were no computational load issues, and this covariance structure was used successfully for all of the mixed model analyses completed in this thesis.

Appendix E
Chi-Square Automatic Interaction Detection

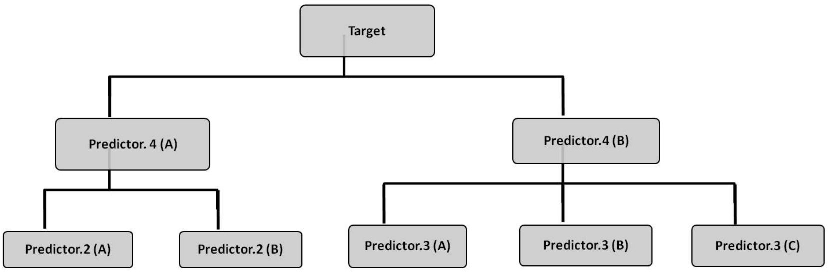
Chi-Square Automatic Interaction Detection, otherwise known as CHAID analysis, is a method which partitions a data set into decision trees through the determination of how predictor (independent) variables are best combined to explain the outcome of a given target (dependent) variable. Originally, it was recommended for use with categorical dependent variables only, but has since been adapted to allow for the inclusion of continuous dependent variables as well.[5, 6]

CHAID was developed by Kass in 1980, and was designed to improve upon the Automated Interaction Detection (AID) analysis. CHAID is a stepwise decision tree analysis; each step in the tree is created through the determination of the most significant predictor variable at that level. In order to determine the most significant predictor variable, CHAID first determines the best categorical partitions for each predictor variable. For example, if a predictor variable contained values from 0 to 100, CHAID could split it into the following groups: 0-19, 20-39, 40-59, 60-79, 80-100 or 0-35, 36-70, 71-100, or any other combination of categories depending on what best described the data. The best predictor, which is the most significant at that level of the decision tree, is then used to partition the data set into sub-groups. Each sub-group is then re-analysed independently, following the same principles to further sub-divide the analysis (Table E.1, Figure E.1).[5, 6]

Table E.1: Example of variables and their corresponding significance used in creating a decision tree (Figure D.1) based upon CHAID Analysis

Variable	Data Categories	Significance at (1)	Significance at (2.1)	Significance (2.2)
Target				
Predictor.1	2 (A, B)	0.61	0.02	0.03
Predictor.2	3 (A, B, C)	0.05	0.56	0.01
Predictor.3	4 (A, B, C, D)	0.83	0.93	0.07
Predictor.4	2 (A, B)	0.02		

Figure E.1: Example of a decision tree created using the variables listed in Table A.1 and CHAID Analysis



CHAID is unique in that it is not binary, in other words, it can produce more than two categories at any level of the tree. The statistical significance test used to determine the levels depends upon the measurement level of the target variable. If the target variable is categorical a chi-squared test is used, but if the target variable is continuous, an F-test is used instead. This test works for all types of variables, and it accepts both case weights and frequency variables. Missing variables are treated simply as their own category and do not create any problems for this type of analysis. CHAID has the further advantage of not forming a single predictive model for a data set; the second level predictors can be different for different branches of the tree. This approach best reflects clinical decision making.

Appendix F
Putting Vision Strategy Training

The videos included in this appendix demonstrate the habitual and post-training gaze behaviours of G2. The corresponding gaze data for these videos is presented in Chapter 7, Case 2. The green and blue dots in these videos correspond to the relative position of the right and left eyes (green = right, blue = left).

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