Attention, Gaze, Response Programming: Examining the Cognitive Mechanisms Underpinning the Quiet Eye

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Abstract

The quiet eye (QE) - the final fixation or tracking gaze on a specific location that has an onset prior to the start of a final, critical movement (Vickers, 2007) - has emerged as a key predictor of proficient performance in targeting and interceptive tasks over the last 20 years. Since Vickers’ seminal study in golf putting, the QE has been examined in over 28 different motor tasks, with a longer QE duration often referred to as a characteristic of superior performance and a measure of optimal visuo-motor control. However, the underpinnings of QE are not fully understood, with many researchers advocating the need to better identify and understand the mechanisms that underlie the QE (Williams, 2016; Gonzalez et al., 2015). Consequently, the overriding goal of this thesis was to examine the function of the QE duration, what it represents and how it exerts an influence, by exploring the attentional underpinnings of the QE and the prominent cognitive mechanism of response programming. In study 1 (chapter 4), the manipulation of different parameters of golf putting and the examination of different response programming functions (pre-programming vs online control) during the QE enabled me to build on previous explorations of the response programming function by investigating QE’s response to specific iterations of increased task demands. Experienced golfers revealed that longer QE durations were found for more complex iterations of the task and more sensitive analyses of the QE proportions suggest that the early QE (prior to movement initiation) is closely related to force production and impact quality. While the increases in QE were not functional in terms of supporting improved performance, the longer QE durations may have had a positive, insulating effect. In study 2 (chapter 5), a re-examination of Vickers’ seminal work in golf putting was performed, taking into account an error recovery perspective. This
explored the influence of trial-to-trial dependence on the functionality of the QE duration and the possible compensatory mechanism that assists in the re-parameterisation of putting mechanics following an unsuccessful trial. The results reveal that experienced golfers had consistently longer QE durations than novices but there was no difference in QE between randomly chosen hits and misses. However, QE durations were significantly longer on hits following a miss, reflecting a potential error recovery mechanism. Importantly, QE durations were significantly lower on misses following a miss, suggesting that motivation moderates the adoption of a compensatory longer QE strategy. These findings indicate that the QE is influenced by the allocation of attentional effort. To explore this notion further, in study 3 (chapter 6), two experiments were undertaken. Experiment 1 examined the QE’s response to attentional effort that is activated via goal motivation and experiment 2 examined the effect of disrupting the allocation of attentional effort on the QE using a dual-task paradigm. The early proportion of the QE was sensitive to motivation, indicating that the QE is not purely determined by the demands of the task and golfers have the ability to apply attentional effort, and therefore QE, strategically (exp. 1). The results also support the assumption that QE reflects overt attentional control but question the sensitivity of QE to detect movements in the locus of attentional effort that does not activate shifts in gaze (covert attention) (exp. 2). The results in this thesis conclude that, while significant contributions to understanding what the QE represents and how it may exert its influence are made, there still remains unanswered questions and tensions that require exploration.
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Chapter 1: Introduction
Vision is arguably one of the most important senses, not only in simple tasks, such as grasping and pointing, but also in complex sporting tasks (Hesse & Deubel, 2011). While physical attributes, such as height and strength, indicate sporting ability, there is considerable evidence that has shown the importance of perceptual cognitive components of elite performance (Abernethy, Maxwell, Masters, van der Kamp, & Jackson, 2007; Mann, Williams, Ward, & Janelle, 2007). Through the advances in eye tracking technology, it has been consistently shown that being able to direct gaze to select perceptual cues is a characteristic of sports expertise (Mann et al., 2007). The visual information that is acquired by directing gaze to the right locations informs the motor systems of how to respond and produce goal-directed actions (Land, 2009). The processing of such information occurs when the eye is steady or fixated - when information is brought into high foveal acuity. In a sports context, Joan Vickers was the first to comprehensively examine gaze behaviour, noticing that specific visual fixations seemed important to putting performance and skilled golfers. In her seminal golf putting study, Vickers (1992) found that lower handicap golfers attaining superior performance demonstrated longer final fixations on the ball throughout all phases of the movement. Having found similar effective gaze strategies in basketball (Vickers, 1996), the final fixation on the ball prior to movement was termed the Quiet Eye (QE), which has since has been accepted within the literature as an objective measure of visual control during the performance of motor skills (Vickers, 2007). Over the past 25 years, the QE has been examined in approximately 28 different motor skills, frequently differentiating inter-individual (expert vs. novice) and intra-performance (hit vs. miss) motor skill variability (Lebeau, et al., 2016). Furthermore, researchers have seen the opportunity to use the QE as a way to improve performance; by
coaching performers to adopt an optimal QE duration, performance accuracy can be significantly improved (Moore, Vine, Cooke, Ring, & Wilson, 2012).

Despite the extensive examination, researchers in the field suggest that the QE is at a “critical crossroads” where many paths of investigation remain (Vickers, 2016). In particular, relatively little is known about the cognitive processes that underpin its suggested benefits. While QE training is reported to have significant benefits, it is being used without full understanding of how it works and what exactly is being trained (Williams, 2016). Consequently, the overriding goal of this thesis is to examine the function of the QE duration, what it represents and how it exerts an influence, by exploring attentional underpinnings and the prominent cognitive mechanism of response programming.

1.1 Structure of the thesis
The second chapter of this thesis reviews the relevant literature, covering topics such as gaze behaviour, attentional control, visuo-motor control, QE mechanisms and expertise. Chapter 3 examines the research methodology, including eye tracking, data coding and measures of attention. Chapters 4-6 present 4 experimental studies that make up this project, all of which include an introduction, methods, results, discussion and areas of future research. Finally, chapter 7 brings the 4 studies together in the general discussion, considering the implications of the findings and then identifying areas of future research that could contribute to the progression of this field of research.
1.2 List of publications and conference abstracts


[This paper is my undergraduate research project]


Examining the response programming function of the Quiet eye: Do tougher shots need a quieter eye? *Cognitive processing, (In press).*

[This paper is presented as study 1 in the thesis]


[Presented data was from study 1 of this thesis]


[This paper is presented as study 2 in the thesis]
Chapter 2: Review of the Literature
2.1 Gaze behaviour, visuo-motor control and visual perceptual expertise

Successful sports performance involves knowing where and when to look. Ultimately, being able direct gaze, pick up relevant perceptual cues and inhibit irrelevant perceptual cues from often complex visual displays is a characteristic of sports expertise (Mann et al., 2007). Mann et al. (2007) demonstrated across a variety of sporting domains that more expert performers could control gaze more efficiently and effectively than their lesser skilled counterparts.

However, experts need more than just the ability to see to be successful. They have to be able to direct vision and process the information gathered by the eyes to then inform and guide the actions they take. Land (2009) describes this ability as 'visuo-motor control', highlighting interlinking systems that are responsible for the process of vision to action (Figure 2.1). The gaze system is responsible for coordinating eye movements to locate the appropriate stimuli, enabling the image to be brought into high focal acuity. The motor system is responsible for task execution and action, i.e. controlling and directing limbs (after approx. 0.5 second delay from gaze movement). The visual system is responsible for identifying targets that have been located by the gaze systems and providing the motor system with information to perform the motor response and execution. The three systems are controlled by an executive system, or schema system, which represents goal direction and is used to specify the current task in a top-down fashion. It specifies what stimuli need to be identified, what information the visual system needs to supply and what action will be taken.
Overall, being able to direct gaze to the right location means that the visual system is able to inform the motor system of how to respond (Land, 2009). Through the advances in eye tracking technology, research has been able to examine gaze behaviour during sports performance, identifying a particular gaze strategy called the Quiet Eye (QE; Vickers, 1996) that has been adopted in the literature as an objective measure of visuo-motor control and a characteristic of superior performance (Vickers, 2016).

2.2 The Quiet Eye

Vickers (1992) was the first to comprehensively examine gaze behaviour in golf putting, highlighting associations between visual fixations, performance accuracy and expertise. Participants of high and low handicaps completed putts of 3 meters until 10 successful and unsuccessful putts were achieved. Low handicap participants demonstrated more efficient gaze behaviour, with fewer fixations per trial and longer final fixations on the ball throughout all phases of the movement. In contrast, high handicap participants had the opposite gaze strategy with shorter final fixations and more fixations per trial. Vickers (1992) suggested that the gaze strategy of low handicap golfers allowed for superior
performance by maintaining task focus, coordinating movement precision and minimising distraction. Following Vickers’ initial findings, the specific gaze strategy of the final fixation was termed the QE.

The QE period consists of 5 perceptual-motor characteristics that can be captured objectively. **QE location** – QE is the final fixation where gaze is situated on a specific location of interest and remains steady (within 3° of a visual angle). **QE onset** – the onset of QE occurs prior to the initiation of task execution. **QE movement phase** – the QE is relative to the motor skill, with the onset timed to occur before the critical movement phase. **QE offset** – the QE concludes when gaze deviates off the object or location by more than 3° of a visual angle. The offset is not constrained to a particular movement phase. **QE duration** – the duration of the final fixation has a minimum duration of 100ms with no explicit maximum duration. Together, the QE is defined as the final fixation, directed to a single location or object, occurring prior to initiation of movement and concluding when gaze deviates off the object by more than 3° of a visual angle and for more than 100ms (Vickers, 2007). The characteristics, and consequently the definition, of the QE is dependent on the motor skill/sport due to the variation in movement phases.

Before I examine the QE literature in detail, I first want to take a step back to explain the foundations and fundamentals of where the QE came from as a variable. I start by explaining vision, types of vision and what eye movements mean in terms of fixations leading to the QE.

### 2.3 Vision

Vision is arguably the most important form of sensory information. This is not to say that other forms of sensory information are insignificant however visual information is what we rely upon the most (Williams, Davids, & Williams, 1999).
In order for us to see, light energy reflected from an object is transformed into images. As the reflected light from the image enters the eye through the cornea it is rotated and positioned upside down and backwards on the retina, an area at the back of the eye. The light energy then activates receptors on the retina, called Rods and Cones, which have different functions. Cones are located in the fovea, near the centre of the retina, and are responsible for colour and light detection; if the line of sight is aligned with the fovea images can be viewed with high acuity. In contrast, Rods are in the periphery of the retina and are responsible for detecting low light and motion. Once features of the sense are detected, the retina transforms the light energy into electrical signals, a process called transduction. Electrical signals then exit the back of the eye through the optic nerve and are processed by the brain to create coherent images. The world is usually perceived with input from both eyes – binocular vision – with the brain creating one cohesive image through binocular fusion – the merging of two slightly different images from each eye.

2.4 Types of Vision

The human visual field spans approximately 220° with three main regions: foveal, parafoveal and peripheral regions. Visual information is primarily registered through the foveal region, representing 1-2° degrees or 8 % of the visual field but contributing 50% of the information the brain receives via the optic nerve. Due to the Cone receptors, the foveal region registers high acuity information, providing clear and detailed images. In contrast, the large peripheral region (representing 6-200°) has very poor acuity due to the Rod receptors and, consequently, is only good for picking up on movements and contrasts. Between the two areas is the parafoveal region, representing 2-5° of the visual field, where there is a transition from high to low acuity. Due to the
optic characteristics of the eye, if we want to maximise our visual processing resources on a specific area we have to move our eyes to focus on that image or object. In doing so, the foveal region of the eye is aligned with the area of interest, providing the brain with the greatest amount of detail.

2.5 Eye movements

Eye movements have three main functions: to enable tracking of a moving object; to prevent perceptual fading; and, to enable information of interest to be viewed under foveal vision.

The tracking of an object requires the eyes to move in order to keep the image on the retina. Such movements are often called smooth pursuits. However, when an object is moving at high speed, a squash ball for instance, it is difficult to visually track objects (Haywood, 1984). As such saccadic eye movements are used to make predictions on where the object will travel (Hayhoe, McKinney, Chajka, & Pelz, 2012). Saccades are rapid movements of the eye to a new location or fixation point and range in duration from 60 – 100ms. Saccades typically occur 3 or 4 times each second and are essential to the process of gaining new information under foveal vision (Vickers, 2007). Specifically, during a targeting task, saccades enable task-relevant information to be given focus (Vickers, 2007). However, during saccades and other eye movements, such as blinks, information is suppressed (Stevenson, Volkmann, Kelly, & Riggs, 1986; Nakano, Kato, Morito, Itoi, & Kitazawa, 2012).

A pause in eye movements, a fixation, (and consequently the QE) permits processing of visual information under high foveal acuity (Williams et al., 1999). However, it is important to note that, during a fixation, microsaccades and other fixational eye movements are needed to refresh the image and stop
retinal fatigue (Martinez-Conde, Macknik, & Hubel, 2004), and to prevent perceptual fading due to neural adaption. As such, the eye is rarely still (0° of movement) during a fixation. A fixation is defined as being a minimum of 100-120ms, the minimum amount of time it takes to gain conscious awareness of stimuli. However, speed of consciousness can vary depending on skill and experience (Vickers, 1992). There is typically no maximum duration yet extended fixation durations (QE) can be accompanied by attentional fatigue (Behan & Wilson, 2008). Cognitive researchers typically define the visual angle of a fixation as within 1-3° (Vickers, 1992; Vickers, 2009; Wilson & Pearcy, 2009) though the measurement criteria used by vision researchers is more stringent, permitting eye movement within approximately 0.3° in reading tasks (Liversedge, Rayner, White, Findlay, & McSorley, 2006).

2.6 QE, Performance and Expertise

Since Vickers’ seminal work, the QE has frequently been associated with inter-individual (expert vs. novice) and intra-performance (hit vs. miss) motor skill variability (Lebeau et al., 2016). Wilson and Pearcy (2009) found that QE was the only gaze variable to distinguish between successful (hit) and unsuccessful (miss) golf putts in skilled golfers, with successful putts associated with longer QE durations than unsuccessful putts. Such proficiency related differences in the QE have also been found in a variety of other targeting tasks, including billiards (Williams, Singer, & Frehlich, 2002), shooting (Causer, Bennett, Holmes, Janelle, & Williams, 2010), table tennis (Rodrigues, Vickers, & Williams, 2002) and football (Piras & Vickers, 2011).

The QE has also been shown to be trainable, with recent studies demonstrating improved performance for participants using QE training interventions (Vine, Moore, & Wilson, 2014, for a review). Typical QE training
protocols aim to prolong the QE period through coaching performers to adopt the same gaze strategies as expert performers. The process involves participants viewing and discussing footage of an elite prototype demonstrating optimal QE (feed-forward) and viewing their own eye tracking footage (feed-back). Participants are then given a structured pre-performance routine focusing on visual control. Such training techniques have demonstrated that performance accuracy in both expert and novice golfers can be significantly improved when compared to traditional technical instruction (Moore et al., 2012). Similar effects have been reported in research adopting different sports skills, such as basketball (Vine & Wilson, 2011) and shooting (Causer, Holmes, & Williams, 2011). In addition, beneficial effects of QE have been transferred to real competitive performance (Vine, Moore, & Wilson, 2011). However, as recently highlighted by Williams (2016), it is clear that QE training can change the characteristics of the QE at a behavioural level (longer QE duration) yet it is unclear what is being trained at a mechanistic level (e.g. better programming of movements or control online, arousal control). As such, with knowing more about how the QE works there is the potential to understand what is being trained and, therefore, edit training protocols accordingly (Williams, 2016).

Typically, the QE duration is found to decrease under heightened levels of state anxiety (e.g. Behan & Wilson, 2008; Nibbeling, Oudejans, & Daanen, 2012; Vine, Lee, Moore, & Wilson, 2013). Wilson, Vine and Wood (2009) demonstrated that the QE is sensitive to elevated cognitive anxiety associated with competitive pressure; the gaze control of basketball players was adversely affected, resulting in reduced QE duration. However, the prolonging of the QE has been shown to be an effective intervention for dealing with pressure. Vine and colleagues have demonstrated that, through QE training, the adverse
effects of anxiety when performing under pressure, can be ‘buffered’ through maintaining the QE (Vine & Wilson, 2011; Moore et al., 2012). Despite such observations, the QE literature lacks clarity on how and why such findings occur (see section 2.7 for further discussion).

Although much research has found support for the association between longer QE durations and better performance (Lebeau et al., 2016), the QE-performance relationship is not always present. For instance, while Horn Okumura, Alexander, Gardin and Sylvester (2012) demonstrates that QE is sensitive to response programming demands, dart throwing performance was unaffected by the QE. Authors posit that QE can only reflect a responsive factor to task demands, rather than a facilitating factor in performance. Furthermore, in the study by Mann, Coombes, Mousseau, and Janelle (2011), several subjects from both the low handicap and high handicap group did not display differences in QE between their hits and misses. Moreover, van Lier, Kamp, Savelsbergh (2008) found that longer final fixations on the ball, during the preparation phase of the swing (before moving the putter), were not related to more accurate performance. It must be noted, however, that for Mann et al. and van Lier et al. the correct and full definition of the QE was not adopted. Finally, while Moore et al. (2012) revealed longer QE durations and more accurate putting performance for participants that received training to improve the QE, subsequent mediation analysis revealed that the QE duration did not mediate differences in performance between QE trained and control groups (see also Rienhoff, Baker, Fischer, Strauss, & Schorer, 2012, in a dart throwing task). Such findings ultimately question whether the mechanisms underpinning the QE are, in fact, functional or whether QE does reflect such mechanisms.
Vickers recently proposed that the lack of relationship between QE and performance in some cases is due to researchers adopting performance measures that examine the average error scores rather than hit-miss comparisons, which present definitive accuracy measures (Vickers, 2016). However, even the examination of definitive performance measures reveals inconsistency, as demonstrated by Mann et al. (2011) and van Lier et al. (2008). Either way, QE researchers frequently adopt block designs of grouping a selection of trials, yet performance over trials can exhibit dependence (see Iso-Ahola & Dotson, 2014, for a review). Cooke et al. (2015) demonstrates that previous unsuccessful putts influence the response programming of the following putts in attempts to recover performance. As such, ‘performance dependence’ could explain why QE effects are not always found in blocked designs. Overall, further research is warranted to examine the QE performance relationship and the QE’s function, particularly as there is a risk of being overly reliant on the seminal work in the field (Vickers, 1992; 1996). Even though such work is far-reaching in its impact, studies were carried out with dated equipment and methodological flaws (power related).

In terms of QE and different levels of skill, expert performers in their respective sports have been found to possess longer final fixations than their lesser skilled counterparts (e.g. Panchuk & Vickers, 2006; Panchuk & Vickers, 2011; Vickers, 1996; Williams et al., 2002; Mann et al., 2007 for a review). Specifically, research indicates that experts possess more efficient gaze behaviour, having a single, long, final fixation to the target rather than serval fixations around the target (Wilson, Causer, & Vickers, 2015). For instance, Panchuk and Vickers (2011) found that elite ballet dancers had superior gaze
strategies, with fewer fixations of longer durations, including a significantly longer final QE fixation when compared to a control group.

Although there is extensive evidence across many motor skills to support the QE duration as being a predictor of expertise, we have to question the evidence for QE as a predictor of expertise within specific skills. For instance, in golf putting there is limited examination of expert-novice differences in the QE duration. Vickers (1992), Mann et al. (2011), Campbell and Moran (2014) and van Lier et al. (2008) have examined skill level difference but this was within a competent sample of golfers. Furthermore, the findings were mixed, and consistent definitions were not used between the studies. Therefore, skill level differences (particularly expert novice differences) in golf putting are often assumed on the basis of extensive research examining different skills and, consequently, such assumptions are not validated.

Furthermore, this leads onto question whether comparisons and assumptions from the QE can be drawn between findings of different skills. Different skills hold different perceptual, cognitive and motor requirements and therefore a QE of the same definition has the potential to represent a different function for different skills or tasks. For instance, Moran et al. (2016) examined QE during a stimulated equestrian task, requiring a button press response, and the same definition was used in a football penalty shooting task (Wood & Wilson, 2010). Furthermore, even with definitions that are similar in terms of skill classification (darts vs shooting), there are still differences in task parameters that require specific forms of visuo-motor control (Vine & Klostermann, 2017). Therefore, one universal definition does not account for what the QE may represent in different tasks.
Nonetheless, the consistency of expert performers possessing longer QE durations (Lebeau et al., 2016) is of contrast with the widely-accepted notions of expertise and motor control paradigms, which generally support a neural efficiency hypothesis (Haier et al., 1988). Experts are suggested to require minimal energy expenditure and more efficient brain processes that elicit reduced cortical activity corresponding with performance automaticity and efficiency (Mann, Wright, & Janelle, 2016). For instance, Beilock, Wierenga, and Carr (2002) was able to demonstrate that expert golfers were able to maintain their putting performance under conditions of reduced attentional resource allocation as their putting skill is more autonomous, requiring less resources compared to novice participants. Therefore, increasing the QE duration for the reasons of providing more time for movement parameterisation appears difficult to rationalise, with the ‘longer is better’ approach appearing to reflect a more inefficient strategy. These suggested contradictions have recently been termed the ‘efficacy paradox’ (Mann et al., 2016). Mann et al. summarise the paradox by posing this rhetorical question, “If efficiency, strictly speaking, enables experts to perform greater, more detailed work in relation to the total energy expended, how then does the QE represent and/or enable efficiency?” (p. 2). However, recent EEG findings of Cooke et al. (2014) and Bablioni et al. (2008) suggest that expertise – at least in self-paced tasks - is not reflective of processing efficiency. Specifically, the pattern of high-alpha power activation in Cooke et al.’s study indicates that, upon addressing the ball, experts are more relaxed, expending fewer resources. Yet, the clear reduction in high-alpha power in the final seconds preceding and during the movement reflects experts’ greater mobilisation of programming resources, specifically in motor areas of the brain (Gallicchoi, Cooke, & Ring, 2017). Klostermann, Vater and Kredel
(2016) offer the ‘Inhibition hypothesis’ as an explanation for the longer QE possessed by expert performers, suggesting that experts have a greater repertoire of knowledge and that means there are more possible movement variants to inhibit before and during the movement. Considering the different areas of research surrounding expert performance, it is again unclear the function that the QE holds. However, overall, it seems that a lot is inferred from the duration of time someone is looking at a particular object.

2.7 QE mechanisms

The greatest failing in this area is the paucity of research that has attempted to better identify and understand the mechanisms that underpin the QE (Williams, 2016; Gonzalez et al., 2015). Several potential mechanisms have been proposed that largely fall into either a cognitive or ecological perspective, yet mechanisms remain mostly uncorroborated (Gonzalez et al., 2015).

2.7.1 Ecological perspective

Research from an ecological perspective suggests QE operates through a mechanism that advocates that the beneficial effects of a prolonged final fixation are due to performers being able to pick up information and attune the execution of movements (Oudejans, van de Langenberg, & Hutter, 2002). The fixation is suggested to enable direct optic flow so that the performer can optimise orientation of movements to that specific task. Such attunement is via a subconscious, continuous feedback process not requiring cognitive processing but rather through generating relationships between body or limb location and the target. Oudejans’ and colleagues found that, depending on functional aspects of a task, for example basketball jump shot style, different visual control strategies were utilised. In particular, players using the high shooting style, where the ball and hands are above the player’s head prior to
ball release, utilise late visual information to control their movement (online), whereas low shooting style players use early visual information. Oudejans’ and colleagues’ work highlights that the timing of ‘when’ athletes' pick-up information is important, not necessarily the total fixation duration. However, this perspective is dated, receiving little to no investigation and, consequently, support.

2.7.2 Cognitive perspective

Alternatively, the cognitive perspective, rooted in the concept of the brain acquiring and processing information, advocates that the QE reflects “the time needed to process cognitively the information that is being fixated or tracked and to focus attention on the demands of the task” (Vickers, 2009; p. 283).

2.7.2.1 The programming hypothesis

Cognitive psychologists believe that the human being operates as an information processor, gathering information and then processing it, eventually resulting in movement output. The continuous process from input to output is suggested to involve three stages: stimulus-identification; response-selection; and, response programming (Schmidt, 1991). Stimulus-identification is primarily a sensory stage, assessing information from all senses to produce a representation of stimuli, which is then passed to the next stage of response-selection. At this stage, information regarding the stimuli is interpreted and decisions about the movement are made. Finally, the response programming stage has the role of organising and programming the motor system to respond with the correct movement parameters in the right order to produce the movement effectively. It is this final stage that is most widely reported as the mechanism underlying the QE, suggesting that the QE duration therefore provides a sufficient period for the effective parameterization of the subsequent
movement (Williams et al., 2002). It is during this period when sensory information is synthesized with the mechanisms necessary to both plan (pre-programme) and control (online) the appropriate motor response. For example, in golf putting, the golfer must be able to hold information about the desired line of the putt in working memory while fixating the ball, and call upon a suitable motor programme to hit the ball with the requisite force and direction to achieve the desired outcome (Mann et al., 2011). Consequently, the QE duration needs to be long enough to accommodate the processing and coordination of a motor response (Vickers, 2009).

Drawing upon the work of Henry and Rogers (1960), which demonstrated that more complex movements have longer reaction times, research has focused on manipulating the task and, subsequently, the response programming requirements. By doing so, QE’s sensitivity to changes in response programming can be examined. One example is the study by Williams et al. (2002), which investigated task complexity in billiards. The task was manipulated to include three levels of complexity (easy, intermediate, and hard), requiring different shots and changes in movement parameters. Results revealed that QE duration increased proportionally with task complexity. Furthermore, increases in QE duration were also associated with expertise and superior performance, highlighting the importance of the QE period. The second part of the study confirmed this proposal by imposing time constraints, revealing that the linear decrease in QE duration was associated with poorer performance. Authors, therefore, proposed that QE reflects and accommodates the increases in response programming related to increases in complexity.

Horn et al. (2012) provide further support for a response programming function of the QE by using a context interference paradigm. Participants were
asked to perform dart throws in constant and variable practise conditions under
the hypothesis that the inter-task processing and rescaling of movement
parameters required during variable, compared to constant, practice conditions
would need greater cognitive programming and, consequently, longerQE
durations. Indeed, they found an increase in QE duration for a variable practice
condition, inferring that more time was needed to process new task information
than for familiar tasks.

Nonetheless, researchers have emphasised that it is not just the duration
of QE that is important for response programming but also its timing relative to
postulated that QE reflects a pre-programming function by demonstrating that
QE was initiated during the preparation of a movement (basketball free-throw)
and, once adequate motor programming had occurred, the QE was suspended
prior to movement execution by blinking or saccadic eye movements. This
supports the view that skills can be executed without visual guidance online
using pre-structured motor programmes (Schmidt, 1991). In addition,
neurological evidence supports the timing of such response programming
(Janelle et al., 2000; Babiloni et al., 2008; Baumeister, Reinecke, Liesen, &
Weiss, 2008; Cooke et al., 2014, 2015). For instance, Mann et al. (2011)
demonstrated that QE was closely associated with neural correlates of
movement preparation. Specifically, the QE was related to the
Bereitschaftspotential (BP), an index of pre-motor readiness and movement
preparation. While authors inferred a preparatory function of the QE, allowing
for the coordination of neural structures, they only considered the proportion of
QE prior to execution.
Furthermore, Cooke et al. (2014), adopting an electroencephalogram methodology, found reductions in high-alpha power during the final seconds preceding golf putting performance. Due to high-alpha power being inversely related to cortical activity in regions of motor planning (premotor and motor cortex; e.g., Pfurtscheller, 1992), such reductions are suggested to reflect an increase in resources applied to response programming (see also Babiloni et al., 2008). However, Cooke et al. (2014) also reveal that the suppression of high-alpha power continues during the putting execution, indicating the maintenance of response programming.

Particularly in golf putting, optimal QE durations continue throughout preparation, execution and, often, once the ball has gone (Vickers, 1992, Vickers, 2007; Vine et al., 2013). The continued fixation is suggested to allow response programming online, where performance is continuously adjusted through constant feedback during the skill execution (Vine et al., 2015). For instance, any differences between the actual and desired putter head parameters (i.e. direction and speed) are sensed as errors from which corrections are implemented to bring the putter back into line. This form of control is also referred to as online control (Vine et al., 2013) or prospective control (Panchuk & Vickers, 2009). Although the terms come from different approaches (cognitive vs. ecological) and are used in different contexts, they both focus on how actions are guided online, throughout the entire movement. The effect of online control can be seen in movement kinematics. Functional variability enables movements to be adjusted and tailored towards the end goal (striking the ball) (Langdown, Bridge, & Li, 2012). Craig, Delay, Grealy, and Lee (2000) demonstrated that golfers constantly regulate and spatially scale club
head motion, making adjustments and alterations to ensure the optimal motor response.

By dividing the QE into early (prior to the critical movement) and late (during movement execution) proportions, Vine and colleagues have demonstrated that late QE duration and the active visual processing that occurs during the late QE is critical to performance. Vine et al. (2013) found that the late QE duration was cut short at the point of performance failure during a putting shoot-out task aiming to induce anxiety. Furthermore, by occluding late visual information (from initiation of backswing using liquid-crystal smart glass), Vine et al. (2015) found putting performance suffered. Although the late QE did not change, such findings demonstrate the importance of processing visual information during this period to aid motor performance. However, it isn't clear exactly what information is being processed during this time. Overall, a longer QE duration is suggested to support information processing during both movement preparation (Vickers, 1996, 2007; Panchuk & Vickers, 2009; Williams et al., 2002; Mann et al., 2011) and movement execution (Vine et al., 2013; 2015), resulting in optimized movement parameterisation (Klostermann, Kredel, & Hossner, 2014).

However, the programming hypothesis is not without its limitations and inconsistencies. As discussed above, the suggested efficiency of expert performers, who require minimal energy expenditure and more efficient brain processes that elicit reduced cortical activity (Haier et al., 1988; Beilock et al., 2002), is of contrast to the increase in response programming that is suggested to accompany longer QE durations of expert performers (Mann et al., 2011). Furthermore, limitations can also be found in the QE research that has manipulated the task demands to explore the response programming function.
Although Williams et al. (2002) manipulated the difficulty of well-known billiards shots that involved the programming of different shot angles, the QE’s responses (increased duration) may not have reflected the influence of other relevant parameters, such as changes in force production. In addition, such research also did not examine the contribution of the early and late QE proportions and their contrasting functions. However, this is not just the case for billiards; the precise information that is important during performance and the specific contribution of the different QE proportions during different tasks is not fully understood (Gonzalez et al., 2015).

In addition, Klostermann, Kredel and Hossner (2013) experimentally manipulated the onset of the QE duration and the predictability of the throwing target location. While authors indicate that the QE was sensitive to increased processing demands, increasing in duration when the final target location was unpredictable, the increased processing requirements of the task actually occurred prior to the initiation of the QE duration. This means that, in this instance, the increase in QE was not a consequence of manipulated task demands.

Moreover, the QE duration does not always respond to tasks where response programming requirements have been increased. For instance, Chia, Chow, Kawabata, Dicks and Lee (2016) found that QE was unaffected by different levels of difficulty in a ten-pin bowling task. Wilson and Pearcy (2009) found that QE duration in golf putting was not associated with changes in the slope of the putting surface. Moreover, van Lier et al. (2008) found that final fixations on the ball, during the preparation phase of the swing (before moving the putter) did not change with the introduction of sloping putting surfaces. Such studies not only question the validity of task difficulty manipulations but also
ultimately question whether the mechanisms underpinning the QE are, in fact, functional or whether QE does reflect a response programming mechanism. Seeing as though response programming is found to influence performance (Cooke et al., 2014; 2015) and based on the assumption that increased resources and response programming is functional (Norman & Bobrow, 1975), we have to question what longer QE durations represent in the cases above.

2.7.2.2 Attentional mechanisms

Efficient eye movements are critical in a sporting environment in order to select task relevant information and, ultimately, make the correct response. The control of gaze occurs through attention, with the pre-motor theory of attention (Rizzolatti, Riggio, Dascola, & Umilta, 1987) demonstrating, through saccadic programming and the suppression of eye movements, that attention precedes and cues shifts in gaze. As such, the QE, a gaze behaviour, is suggested to have attentional underpinnings, meaning that its parameters are determined and controlled by attention. Consequently, the QE is frequently adopted as a measure of attentional control (Moore et al., 2012).

While defining and explicitly measuring such an abstract construct as attention is challenging, there is broad agreement that attention involves the process of inhibiting and selecting the information that is then put forward for further processing (Smith & Kosslyn, 2007) and is suggested to be the mechanism that “turns looking into seeing” (p. 1484, Carrasco, 2011). Attention is suggested to have three dimensions: selective attention, divided attention, and, sustained attention (Lavallee, Kremer, Moran, & Williams, 2004). Selective attention refers to the perceptual skill of being able to focus, or ‘zoom in’, on one aspect of the environment while ignoring potentially distracting and irrelevant stimuli. Divided attention refers to an athlete’s ability to attend and respond to
more than one stream of information that occur simultaneously. Typically, while attention is directed towards one stream of information, attentional control is needed to split attention between stimuli. Finally, sustained attention, also referred to as concentration, is the process of exerting mental effort on stimuli for an extended period of time. To sustain attention, an element of effortful persistence and control is required, sometimes referred to as the act of ‘paying attention’. A common theme with the dimensions of attention highlighted above is that they all require an element of control that determines what, where and how much attention is given to a particular task, object, or location.

**Attentional control**

In terms of attention-based research in the QE literature, researchers have focused on two aspects of attention to explain QE’s suggested beneficial effects: attentional focus and attentional control. Attentional control refers to the ability to direct attentional resources to only goal relevant stimuli. The QE period is suggested to reflect the efficient control of attention needed to perform skills accurately (Vickers, 2009). Vickers (1996) explained the beneficial effects of QE as being related to the optimal control of visual attention via three neural networks: orienting attentional network, executive network; and, the vigilance network (Posner & Raichle, 1997). The orienting network guides the attentional resources to relevant cues. The executive network determines the relevance of a cue for the goal in hand. The vigilance network maintains attention. The QE is suggested to reflect the function of the vigilance network by coordinating and maintaining attention on the critical cues.

Corbetta and Shulman’s (2002) model of attention reflects the balance between top-down, goal directed (dorsal) and bottom up, stimulus-driven (ventral) attentional systems, which is used to explain the beneficial effects of
the QE (Vickers, 2009). The top-down system of attention (dorsal / goal-directed system) is mediated by cognitive goal-directed factors, including previous knowledge and current goals that guide the voluntary allocation of attention and, ultimately, gaze. This system is centred in the dorsal posterior parietal and frontal cortex. In contrast to the top-down system, the bottom-up system of attention (ventral / stimulus driven system) is mediated by sensory factors that are typically unattended, unexpected stimuli that often trigger sudden shifts of attention. This system is centred on the temporoparietal and ventral frontal cortex and has been referred to as the ‘act now think later system’. The QE is suggested to help maintain the allocation of attention towards task relevant cues, while suppressing any distraction from exogenous stimuli (goal driven attentional control) (Vickers, 1996). Furthermore, when the sensitivity of the stimulus-driven attentional system is increased, under conditions of anxiety (causing increased distractibility and impaired task relevant processing) for instance, it acts as a ‘circuit breaker’ for the top-down systems, directing attention away from goal-directed factors and towards salient stimuli. Under these circumstances the QE duration is often found to reduce (Behan & Wilson, 2008; Wilson et al., 2009). Consequently, several studies reveal a longer QE may be a useful measure of optimal attentional control (e.g. Moore et al., 2012).

However, such assertions are based on the assumption that gaze and attention are tightly coupled, for which there is substantial evidence. Interdependence theories (pre-motor theory of attention) show that gaze and attention share common resources (Corbetta, 1998) and, under certain conditions, shifts in gaze cannot occur without preceding shifts in attention (Murry & Giggey, 2006). Furthermore, Nobre, Gitelman, Dias and Mesulam
(2000) demonstrated that fronto-parietal areas of the brain were primarily involved in both saccades and covert attention allocation.

However, this is a controversial assumption to make as it is also well established that attention can relocate without shifting gaze (Williams et al., 1999; Piras & Vickers, 2011), meaning that the locus of gaze can be dissociated from the locus of attention (covert orientation). For instance, research has demonstrated that information can be extracted and processed from the periphery by means of a visual pivot, where gaze is fixated and attention can move selectively (Williams & Elliot, 1999; Piras & Vickers, 2011). As such, in these instances, gaze does not reflect the locus of processing and a continuous overt association between attention and gaze cannot always be assumed. This demonstrates that changes in covert parameters of attention may not be reflected in gaze behaviour (Horowitz, Fine, Fencsik, Yurgenson, & Wolfe, 2007). As the current measurement of QE is not able to assess changes in the location of attention, using peripheral vision for instance (Klostermann, Vater, & Kredel, 2016), the potential for gaze-attention dissociation has significant implications for how the QE can be interpreted.

**Attentional focus**

Attentional focus refers to the direction and orientation of attention. By focusing attention externally, on the effects of the task (e.g. swing trajectory), performance is suggested to be improved by the means of less effortful automatic control processes, rather than eliciting conscious step-by-step monitoring of movement control associated with an internal focus of attention (for a review see Wulf, 2013). In line with the theory of reinvestment (Masters & Maxwell, 2008), focusing internally elicits a conscious self-awareness. This causes performers to over think their performance, disrupting the natural fluidity
of movement and consequently causing performance to suffer. Moore et al. (2012) suggest that the beneficial effects of QE training are a consequence of participants producing an external focus of attention. Research that aimed to examine the link between QE and focus of attention has found mixed results. For example, Ziv and Lidor (2015) found that, while eliciting an external focus via instructional sets increased the QE duration, putting was unaffected. Yet, Klostermann et al. (2014), Rienhoff, Fisher, Strauss, Baker, and Schorer (2014) and Querfurth, Schucker, Lussanet and Zentgraf (2016) found the QE increased during internal (or movement) focus of attention conditions. Klostermann et al. and Querfurth et al. discuss their findings in relation to the inhibition hypothesis, suggesting that an external focus means automatic movement programming and, therefore, little inhibition demand during the QE. In contrast, an internal focus directs attention towards individual movement variants, thus the QE is prolonged to deal with the greater inhibition demands.

**Attentional effort – attention as a ‘resource’**.

One area of attentional research that is under-represented in the QE literature is attentional effort, also known as mental effort or cognitive effort (Kahneman, 1973; Burge et al., 2013; Piquado, Isaacowitz, & Wingfield, 2010; Wilson, Smith, & Holmes, 2007), referring to the quantity of attentional resources that are allocated to a task. While attention has been referred to and explained through the use of different metaphors that reflect different theories of attention, including a ‘filter’ (Broadbent, 1958) a ‘spotlight’ or ‘zoom lens’ (Cave & Bichot, 1999), this thesis will focus on attention as a ‘resource’. Consequently, paying attention to a task or stimuli is seen as a matter of degree rather than ‘all or none’. For example, you could be attending to the same task each day (e.g.
making a cup of tea) but, from one day to another, the amount of effort and consequently resources allocated to that task may change.

According to Kahneman’s (1973) capacity ‘resource’ model of attention, attentional effort, and hence the allocation of resources, can be flexibly allocated depending upon the system demands. Resources can be increased to meet task demands until a point at which the demands outweigh the limited resource capacity and performance then suffers (Kahneman, 1973). Attentional effort is typically cited in the literature as a way of explaining performance in difficult tasks. For instance, Beilock and colleagues demonstrated using a dual-task paradigm that, when experienced golfers had to putt with a novel ‘funny putter’ and perform a secondary word recognition task, showed putting performance suffered as a result of the demands exceeding the required attentional resources (Beilock et al., 2002). Consequently, task difficulty is often considered to determine attentional effort.

Indirect evidence that highlights QE’s relationship with attentional effort is provided by studies where task difficulty has been manipulated. For example, as discussed in an earlier section, in billiards (Williams et al., 2002) and ball throwing (Klostermann et al., 2013), performers extended their QE duration as task demands and subsequent processing requirements increased. Such findings support the response programming argument however this is not a passive relationship. The amount of information processing occurring during the QE is mediated by the effortful allocation of attentional resources (Klostermann et al., 2013). Attention is suggested to be a mechanism for controlling information processing (Smith & Kosslyn, 2007), accounting for the selectivity in the information we process (Rensink, 2013; Findlay & Gilchrist, 2003). Accordingly, longer QE durations seem to reflect a greater application of
attentional effort, in line with task and, consequently, response programming
demands. A recent study by Moran et al. (2016) is the first to measure
attentional effort during the QE using pupillometry. Pupillometry findings during
the show-jumping related task not only provide an independent index of
cognitive processing but also imply that a longer QE duration was related to an
increase in exerted attentional effort, reflected by increased pupil dilation.
However, the study was not without its limitations. For instance, the findings
have limited generalisability, due to the small sample size, and the study has an
absence of performance measures, meaning that attentional differences
between performance outcomes (decisions) cannot be established.

Furthermore, research indicates that QE reduces under anxiety related
attentional disruptions (e.g., Wilson et al., 2009). However, it is unclear whether
the QE is sensitive to disruptions in attentional effort (resources) or attentional
control (distraction task-irrelevant stimuli). Worrisome thoughts created by
anxiety are suggested to consume attentional resources, impairing the task
processing efficiency (e.g. Behan & Wilson, 2008; Nibbeling et al., 2012) but
also heighten the sensitivity of the stimulus driven bottom-up system, making
performers more susceptible to distraction at the expense of the goal-directed
task (Eysenck & Wilson, 2016). Despite this speculative relationship between
QE and attentional effort, both the QE literature and Kahneman’s work
overlooks the notion of intention and motivation to perform.

Sarter and colleagues provide a conceptualisation of attentional effort,
which incorporates internal factors, indicating that attentional effort is the
function of motivation to achieve a personal goal in response to performance
challenges (Sarter, Gehring, & Kozak, 2006). In other words, the degree of
attention paid also seems to be a matter of intention. As stated by Cohen (2014)
there is a distinction between the tendency of tasks to need effort and the tendency of an individual to generate effort; “a task may have minimal processing demands, and yet the individual may exert much attentional effort as a result of motivation to perform well” (p. 99). However, Sarter and colleagues acknowledge the influence of task demands and performance as critical stimuli for potentially adjusting the amount of attentional effort. However, adjustments are considered to depend on cost-benefit analysis. Kanfer and Ackerman (1989) highlight that distal motivation processes impact the engagement of resources or efforts allocated to the task. Performers are suggested to make judgments of perceived performance utility, effort utility and performance-resource relation; evaluating the expected performance benefits relative to expected cost of investing effort. This ultimately determines the motivation and intended level of effort to be devoted to the task. While motivation has not explicitly been examined during the QE duration, Mann et al. (2011) demonstrates that QE is related to neurological activation (BP) that is not only an index of premotor readiness but also associated with enhanced motivation (Andreassi, 1980). The examination of QE’s response to motivated performance could develop further understanding surrounding QE’s function.

Interestingly, the contrasting views of what drives attentional effort are reflected in two theoretical accounts of effort, which are explored in this thesis, providing the potential for greater explanatory power of the QE duration. Although not a complete theory of effort, the conflict monitoring hypothesis (CMH; Botvinick, Braver, Barch, Carter & Cohen, 2001) outlines an evaluative control process of conflict or error monitoring by which effort is allocated and experienced. Through the examination of the relationship between anterior cingulate cortex (ACC) activation in the brain, cognitive control and connecting
feedback loops, the theory is able to explain strategic behavioral phenomena relating to performance recovery. McGuire and Botvinick (2010) suggest effort arises from unmet demand (poor performance / a more difficult task), which results in the detection of conflict that drives the engagement of compensatory adjustments in processing and control. This theory is supported by Cooke et al. (2015), who examined neural responses following successful and unsuccessful golf putts. It was found that following unsuccessful putts there were reductions in high alpha power, indicating more response programming due to high-alpha, being inversely related to cortical activity in regions of motor planning (premotor and motor cortex; e.g., Pfurtscheller, 1992). Such responses were suggested to reflect effort to recover performance.

On the other hand, the motivational intensity theory (MIT; Wright, 1996; Richter, 2013) acknowledges the influences of incentive and intention and is based on the idea that when there is an optimal balance between resource mobilisation (ability) and task difficulty, coupled with motivation and task engagement, more effort and energy is invested to complete that task. While this mirrors Kahneman’s description, the theory also iterates that humans will avoid wasting energy and, therefore, effort is predicted to be invested proportionally with task demands until chances of success become low, at which point efforts will be withdrawn.

The interaction between such theories has recently been captured by Harris and colleagues in a proposed model that highlights the difference in the subjective experience of feeling like they had invested great effort in a difficult task compared to the objective effort response of withdrawing effort from a task where demands outweigh expertise (Harris, Vine, & Wilson, 2017).
Overall there is an incomplete understanding of what the QE represents. While the research has demonstrated that QE is a functional gaze behaviour adopted by expert performers, and which can also be trained, there is no consensus surrounding how and why it seems to be of benefit. Further examination of the response programming function, together with attentional effort that goes into more depth regarding the QE response to experimental manipulations of response programming demands and motivation, could explain the functionality of the QE.

2.8 Scope & outline of the thesis

The literature review demonstrates that, while QE is often referred to as a characteristic of superior performance, the functional mechanisms that underpin the QE are not fully understood. Many researchers advocate the need to better identify and understand the mechanisms that underlie the QE (Williams, 2016; Gonzalez et al., 2015). Williams (2016), in particular, highlights the importance of understanding the function of QE from an applied perspective because, at present, QE training is being used without full understanding of how it works and what exactly is being trained. Consequently, the overriding goal of this thesis is to examine the function of the QE duration, what it represents and how it exerts an influence.

Cognitive mechanisms are arguably the most widely investigated and reported, with response programming being the most prominent. However, there is little research investigating the means by which response programming occurs, i.e. the allocation of sufficient attentional resources. While QE’s relationship with attention is often assumed, the investigation of the effortful aspect of attention during the QE is important if we are to better understand the extent to which the location of attentional focus (measured by an eye tracker)
represents effortful processing of movement parameters and, ultimately, how QE influences performance. Four studies were undertaken that examine QE’s functionality.

Study 1 will examine QE’s relationship with task difficulty, building on previous research by manipulating three elements of task difficulty that correspond with different parameters of golf putting performance: force production; impact quality; and, target line. Furthermore, the parameters’ influence on different proportions of the QE duration (early-QE, late-QE) can be examined. The different parameters also provide more precise manipulations of task difficulty, enabling the influence of specific parameters to be investigated. If the QE reflects the response programming function, increasing the complexity of movement parameters should increase the QE duration.

Study 2 will move on to re-examine Vickers seminal work in golf putting, exploring the recovery from putting errors and the potential influence of trial-to-trial dependence on the functionality of the QE duration. Based on recent findings (Cooke et al., 2015; Botvinick et al., 2001) showing that motor planning in putting is dependent upon the outcome of a previous attempt and errors in performance elicit compensatory adjustments in processing, recovering from unsuccessful performance would require a greater mobilisation of attentional resources. As such, QE may aid performance recovery.

While the first two studies elicit increases in attentional effort and response programming the first experiment of the third study explores QE’s relationship with attentional effort further by examining the influence of attentional effort that is activated by goal motivation rather than putting demands. Attentional resources are suggested to be allocated in accordance with distal motivation processes (Kanfer & Ackerman, 1989), making the
allocation of attentional effort strategic rather than purely structural (task dependent).

To further probe QE’s relation with attentional effort experiment 2 uses a dual-task paradigm that aims to manipulate task demands by limiting the allocation of attentional resources to putting rather than making the putting more difficult. It is often assumed that QE and attention are associated yet QE can also reflect a visual pivot from which information in the peripheral can be utilised (Piras & Vickers, 2011). An examination of the utility of the QE’s duration measure is therefore warranted.

Overall, the thesis has the goal of aiding understanding of the QE by exploring what the duration of QE can actually tell us about its function. Furthermore, such knowledge can only aid the application of the QE in performance settings.

In summary, this series of studies will aim to:

1. Examine the influence of increasing the complexity of task parameters on the QE duration;

2. Re-examine Vickers’ Seminal work and the potential performance recovery function of the QE;

3. (Exp.1) Examine the role of motivation and the potential strategic nature of the QE; and

3. (Exp. 2) Examine the influence that disrupting attentional effort, using task demands, has on the QE duration.
Chapter 3: Methodology
3.1 Golf putting

Golf is one of the most popular sports world-wide, appealing to all ages and abilities. It requires the use of a number of different strokes in order to sink the ball in each of the holes in as few shots as possible. The putting stroke is the shortest and most simple stroke. It is used when the ball reaches the putting green in the final efforts to place the ball in the hole (Pelz, 2000). Although the putting green represent a small proportion of the course (approx. 2 %) an estimated 40 % of all strokes are made on the green (Professional Golfers Association website, 2016), making putting arguably the most important shot in a golfer’s repertoire.

The putting stroke is often divided on four phases: backswing; downswing; contact; and’ follow through (Pelz, 2000). The backswing is the movement of the putter backwards and upwards in relation to and away from the ball. The downswing is the movement of the putter downwards and towards the ball, and reflects the acceleration phase of the swing. This starts when the backswing ends and finishes immediately prior to the putter making contact with the ball. The contact, or impact point, is when the putter makes contact with the ball. The follow through is the final phase, starting immediately after contact where the putter decelerates moving upwards and away from the ball. Pelz (2000) describes the putting swing as a pendulum movement, where the putter path is linear and the clubface square to the path throughout the swing. However, this view can be criticised for not considering the biomechanical limitations that a golfer executing the pendulum movement must involve an element of movement compromise (Karlsen, Smith, & Nilsson, 2008).

Despite the principle of putting being simple “rolling a small ball into a large, round hole” (Pelz, 2000) many golfers find it the most difficult part of the
The complexity of the putting stroke lies in the precision of motor control (Pelz, 2000). The ball has to be directed on the correct line, using the correct force (judging specific ball speed) in order to gain the required distance and direction to land the ball within the hole (Pelz, 2000). The intended direction and distance of putts are determined by many factors including the putter face angle, path, impact point, acceleration and stroke length. Golfers do not often struggle with gaining enough distance on putts however, compared with a full swing, slight inaccuracies in directional factors (e.g. putter face angle) have significant performance implications (Karlsen et al., 2008). Added complexity is also provided by task, environment and player factors that include grass texture of the green (task), wind (environment) and psychology (e.g. motivation or anxiety) (Newell, 1986). Therefore, it is not surprising that elite golfers only successfully hole approximately 29% of putts from 10-15 feet (PGA website, 2016).

### 3.2 Why golf putting?

Golf putting was chosen as the targeting skill in this thesis for a number of reasons. Firstly, in order to understand the functional mechanisms of QE, the chosen skill has to accommodate the QE duration. In the case of putting the clear onset, offset and critical movement (backswing) of trials means QE duration can be calculated. Furthermore, putt durations are long enough to examine QE’s contribution to both the offline and online control of movements. Second, putting is frequently used as a targeting skill in the QE literature and in the examination of QE’s function. Therefore, my findings will be applicable to research in the field. Third, as stated above, golf is popular worldwide and with that comes interest from an applied perspective. Although the focus of the research is to understand the QE phenomena, our findings also aim to aid the
application of QE training into competitive performance. Finally, from a practical perceptive, the equipment and facilities needed for putting were easily accessible to me.

3.3 Participants
In order to examine QE as a characteristic of expertise, both high and low level golf participants were selected in order to draw expertise comparisons (study 2, 3 exp1, exp. 2). Novice golfers possessed no handicap and had no official golf experience. Golfers that I have termed “experienced” or “highly skilled” reported a handicap. 70% of the experienced golfers had handicaps of 6 or less. The majority of participants were university students, however experienced golfers were also recruited from local golf clubs due to the limited availability of some university golfers.

3.4 Ethical considerations
All experiments gained ethical approval from the institutional ethics committee prior to participant recruitment. Participants performed the golf putting tasks within a controlled environment (indoor laboratory) where the risks of harm were low. Participants were informed of the task procedures prior to giving informed consent. It was also made clear that participants had the right to withdraw from participating in the study. Participants were kept anonymous via a coding system (initials and participant number) and data was stored securely in locked facilities at the institution until completion of the project, when raw video files will be destroyed.

3.5 Data collection and analysis
The tracking of eye movements has been used by researchers to understand cognition and behaviour for many years. Previous eye tracking equipment was
labour intensive and immobile yet, through the advances in technology, eye tracking is now automated and mobile, meaning gaze can be assessed under ecologically valid set-ups.

3.5.1 The ASL mobile eye

The ASL mobile eye (ME) eye tracker incorporates: lightweight spectacles, a hot mirror combiner, which reflects the eye image and corneal reflection between the user and the monocular eye camera; a spectacle mounted unit (SMU), containing a scene camera that records the environment being observed and an eye camera recording the eye being tracked; a recorder mounted unit; and, an analysis computer.

In order to compute gaze within a scene ME uses dark pupil tracking, which captures the relationship between two features: the pupil and corneal reflection. Three infra-red lights are projected on the eye through light emitting diodes (LEDs) only visible to the eye camera. The LEDs illuminate the eye resulting in the pupil appearing dark and the surrounding iris bright. The contrast enables the eye tracker to identify the pupil. The LEDs are also reflected by the cornea and appear to the camera as a triangle of three dots (spot cluster). Due to the pupil moving relative to the head but corneal reflection remaining in the same position, the angle and distance (vector) between the two is compared to compute the eye position.

By informing the system of how these vectors relate to a participant’s environment, through fixating several specific locations in the environment (5 balls positioned at their feet) in turn, the eye tracker can be calibrated to establish the point of gaze. Images from both cameras are interleaved, creating one image (functional sampling 30Hz) that shows the environment being observed and the point of gaze reflected by a cursor. The cursor, either
represented as a cross or circle, was set to reflect 1° of visual angle (spatial accuracy of ± 0.5° visual angle; 0.1° precision). Eye vision data processing software installed on a computer system is the operating software that attunes the corneal refection image, calibrates the scene image and records the data/video stream for offline analysis. The data output consists of an avi. video file and a Microsoft office excel file of the raw gaze coordinates (x and y co-ordinates of the master spot and pupil centre in eye image pixels, pupil radius in eye image pixels, eye direction and mouse cursor position).

Despite ME trackers allowing such flexibility in the location of data collection there are concerns regarding the capture rate of 30 Hz (data captured every 33.33ms) and the accuracy of such data collection, compared to higher capture rates. However, recent studies indicate no differences in gaze behaviour that could be attributed to changes in the captured rate (30 Hz, Panchuk & Vickers, 2009; Panchuk, Vickers, & Hopkins, 2017; or 60 Hz, Panchuk & Vickers, 2006) of data.

In terms of the practicalities and ease of data collection, there were problems throughout the studies in this thesis. In some instances, despite using the adjustments available on the eye tracker, it was not possible to capture the eye. Anatomical factors (e.g. position of eyes within the face and stance adopted to take a golf putt) contributed to the poor calibration and reduced participant numbers. It was found on occasions that, when standing upright and looking ahead, the eye could be captured clearly. On adopting a putting stance, which involves looking down at the ball, the eye was obstructed by the eyelid and, despite considerable efforts to adjust the eye-tracker, it would not capture the eye.
3.5.2 Analysis and coding

The data captured by the eye-tracker was analysed offline using Quiet Eye Solutions Vision-in-Action software (Quiet Eye Solutions Inc., Calgary, CA) (see figure 3.1). In order to calculate the QE duration, analysis of the movement phases is required first. The onset and offset of the four golf putt movement phases were coded. The preparation phase started when the putter was placed behind the ball, with the end of preparation and start of backswing coded on the first initiation of putter head movement away from the ball. Fore-swing starts (also typically the end of backswing) on the first initiation of putter head movement back towards the ball, ending at putter ball contact. Finally, the follow-through phase starts at putter ball contact and ends when the movement of the putter head following the ball stops. Following the coding of the movement phases, gaze behaviour can be assessed. From trial onset, the location (e.g. ball, green, putter, hole), type (e.g. fixation, saccade) and duration (clicking onset offset bottoms) of gaze behaviour can be coded by watching the cursor reflecting the point of gaze.
Figure 3.1. A screen shot of the Quiet Eye Solutions software analysis; coding entry field (right), interleaved video showing the environment being observed and the point of gaze reflected by a cursor (left).

Specific criteria are used to code gaze behaviours, including fixations, saccades, and tracking pursuits, however the analysis in this thesis focused on coding fixations. The static nature of the ball before execution means that tracking pursuits are not required in putting. While saccades do occur in a putting trials (typically looking between the ball and the hole) information processing is suppressed during their duration. The focus of fixations is primarily due to the aim of examining the QE duration and determining which fixation in a trial meets the criteria of a QE duration.

Fixations were observed when gaze was steady on one location for more than 100ms and within 1° of a visual angle. The duration of 100ms is thought to reflect the minimum duration that information can be gathered and processed (Vickers, 2007). Previous research has classified movement within 3° of a visual...
angle as a fixation however, research by Dalton (2013) demonstrates that other short duration eye movements (e.g. saccades) can occur within 3°. Furthermore, saccades can reflect shifts in attention and interruptions in visual processing (Murry & Giggey, 2006). Consequently, the 3° classification has the potential to misclassify and misinterpret a fixation and its underlying processes (Dalton, 2013). The more stringent fixation criteria therefore allows for a more accurate representation of a fixation. Once fixation parameters have been identified and coded (onset, offset, location) together with the movement phases, the QE solutions software is able to compute the QE duration (assuming that QE is present). If the QE is not present a zero duration scores appears.

3.5.3 Defining the QE

The Quiet Eye period is generally defined as the final fixation, directed to a single location or object, occurring prior to the initiation of the final movement and concluding when gaze deviates off the object by more than 3° of a visual angle and for more than 100ms (Vickers, 2007). For golf putting, the final movement is the initiation of backswing. However, the fixation criteria of movement within 3° of a visual angle could misclassify gaze behaviours, such as short duration saccades, as a fixation (Dalton, 2013). Consequently, the QE was operationally defined for golf putting in this thesis as the final fixation on the ball, within 1° visual angle and for more than 100ms (Vine et al., 2015). The onset occurs prior to initiation of movement (backswing) and the offset occurs when gaze deviates from the ball by more than 1° visual angle or more than 100ms (3 frames). While other putting studies have used different operational definitions of the QE (e.g. Mann et al., 2011; van Lier et al., 2008), this is the
standard definition that is used for the term QE. A consistent definition enables comparisons to be made between studies.

The QE solutions software (www.quieteyesolutions.com) provides a data sheet of the five QE characteristics (onset, offset, duration, location, and movement phase) that can be used for further statistical analysis. However, the software does not provide calculations for the early and late QE proportions relative to movement phases. Such calculations are carried out separate to QE solutions. The early phase of the QE (QE-early) has an onset prior to backswing (the same as QE duration) and an offset that occurs on backswing onset. The late phase of the QE (QE-late) has an onset at the initiation of the backswing and finishes when the putter contacts the ball, or at QE offset (if prior to ball contact; Vine et al., 2015).

3.6 Measurement and manipulation of attentional effort

3.6.1 Measurement

Measuring attention is not easy, in part due to its ill-defined nature and the difficulty in explicitly measuring such an abstract construct. Therefore, attention is assessed by measuring artefacts of attention. Within the QE literature, gaze behaviour is frequently used as a measure of spatial attention, with few alternatives.

The Rating Scale of Mental Effort (RSME; Zijlstra, 1993) was used in this thesis to assess attentional effort. The scale consists of rating invested effort by putting a cross on a continuous line with several anchor points that relate to statements of invested effort, e.g. ‘almost no effort’ or ‘extreme effort’ and corresponding scores (see appendix 2). This scale has been shown to have acceptable reliability in various laboratory settings (r = .88) (Zijlstra, 1993). Furthermore, the RSME has been used successfully in golf putting to assess
mental effort (Wilson, Smith & Holmes, 2007; Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011).

3.6.2 Manipulation

In order to establish QE’s relationship with the intensive element of attention, various manipulations were used to induce different intensities of attention and response programming.

3.6.2.1 Task demands

The demands of a task have long been suggested to drive the allocation of attentional resources (Kahneman, 1973). The established findings of Henry and Rogers (1960) demonstrate that more complex movements induced longer reaction times. Thus, because movement complexity was the only factor that varied, the increased reaction time was interpreted to reflect the increased time required for response programming. Attention is suggested to be a mechanism for controlling information processing (Smith & Kosslyn, 2007), accounting for the selectivity in the information we process (Rensink, 2013; Findlay & Gilchrist, 2003). As such, complex tasks require a greater allocation of attention resources to allow for such programming to take place. In accordance with Kahneman (1973), greater attentional effort is mobilised to meet the increased demands of complex tasks. Such findings are supported by pupillometry studies that have found pupil size increases (reflecting greater processing load) when solving more complex multiplication problems (Hess & Polt, 1964). Study 1 manipulated the task (putting) demands to further understand QE’s function.

3.6.2.2 Goal setting

A less invasive method of manipulating attentional effort is using goals. A goal is the aim of an action or task, e.g. attaining a standard of proficiency (Locke & Latham, 2002). Setting goals is often suggested to be a conscious process that
influences motivation and, consequently, invested effort, both physical and mental, with the sources of motivation derived from the desire and intention to reach the goal (Locke & Latham, 2002). The Achievement goal theory (Nicholls, 1984) suggests that an individual’s source of motivation comes from a central motive to either develop or demonstrate competence, with individuals adopting a task (mastery) or ego (performance) involvement.

Despite the motive or reason the individual has for eliciting motivation, there are many factors that determine how motivated and, consequently, how much effort is actually given to pursuing the goal. Effort is found to vary with goal difficulty, with more difficult goals suggested to create greater, prolonged, and more efficient allocation of effort than easier goals (Locke & Latham, 2002). While the response to goal difficulty may be similar to that of task difficulty (e.g., increase movement complexity), goal difficulty is distinct in that the actual task typically remains the same but the proficiency level one must attain varies. Nonetheless, as highlighted by the motivational intensity theory, effort does not consistently increase with task difficulty. A central assumption is that humans avoid wasting energy and therefore, on perceiving low chance of success (i.e., for difficult task/goal), effort is withdrawn (Wright, 1996; Richter, 2013).

Furthermore, effort is found to vary with goal commitment, the amount of determination used to achieve a goal (Locke & Latham, 2002). Goal importance is suggested to be a key contributor to goal commitment. According to Kanfer and Ackerman’s (1989) resources allocation model, when a task is perceived as important, individuals will invest more effort into observing their performance. Furthermore, findings of Seijts, Meertens and Kok (1997) indicates that the reduced performance for difficult and unimportant goals was due to the reduced allocation of attentional resources. Moreover, while self-set
goals are suggested to aid goal commitment (Erez, Earley, & Hulin, 1985). Locke & Latham suggest that if the rationale and importance of assigned goals is emphasised, performance does not differ between self-set or assigned goals. Study 3 (exp. 1) manipulated goal difficulty to understand the influence of attentional effort on the QE durations relationship with attentional effort that is active by motivation, rather than task demands.

### 3.6.2.3 Dual-task paradigm

A dual-task paradigm (used in study 3 (exp. 2)) can be used to manipulate, as well as measure attentional effort. The technique encompasses a range of methods whereby participants perform a primary task, such as reading or executing a motor skill, alongside a secondary task of responding to a tone or light flash, or performing mental arithmetic, for example. Capacity models of attention suggest that attentional capacity (the allocation of effort) is limited and, therefore, performance will suffer when insufficient resources are available (Kahneman, 1973). A dual-task paradigm intends to increase the attentional load whereby the cognitively demanding secondary task would consume and limit the availability of attentional resources to perform the primary task, often resulting in a deterioration of performance. Such deterioration of performance then provides a measure of the allocation of attentional resources. However, performance is dependent on other factors, including the demands and similarity of each task and participant factors, including practice and skill level. For instance, Leavitt (1979) found that expert ice hockey players were more proficient at stick-handling a puck through a slalom course under dual-task conditions that more novice players. The dual-task design has also been used in a variety of other sports skills to manipulate and assess attentional
requirements, including soccer (Smith & Chamberlin, 1992), golf (Beilock et al., 2002; Chauvel et al., 2012) and rugby (Gabbett, Wake, & Abernethy, 2011). Overall, the attentional effort allocated to a particular task can be manipulated via a demanding secondary task, with performance measures providing an indication of attentional requirements. To the best of my knowledge, a dual task paradigm has not been used to explicitly assess attentional requirements during the QE of sports performance.
Chapter 4: Study 1 - Examining the response programming function of the Quiet eye: Do tougher shots need a quieter eye?

4.1 Introduction

The Quiet Eye (QE; Vickers 1996) - defined as the final fixation directed to a single location or object prior to initiation of movement - has become a well-established characteristic of expertise and proficiency (see Lebeau et al., 2016 for a recent meta-analysis and review). However, there is a lack of clarity in the literature regarding the potential mechanisms through which it exerts its influence. The predominant explanation is that the QE reflects a period of response programming, where task parameterisation (e.g., force and direction) occurs as a result of the consolidation of information from the QE duration itself, as well as previous fixations and performance attempts for a recent overview see Gonzalez et al., 2015).

Several noteworthy attempts have been made to experimentally examine the response programming function of the QE by manipulating task difficulty in billiards shooting (Williams et al., 2002), and in ball (Klostermann et al., 2013) and dart (Horn et al., 2012) throwing tasks. In each case longer QE durations were found when tasks place greater demands on response programming. However, as well as some equivocal findings - Wilson and Pearcy (2009) found that QE duration in golf putting was not associated with changes in the slope of the putting surface - previous research has been imprecise in how task difficulty has been manipulated. For instance, Williams et al. (2002) focused on manipulating the complexity of well-known billiards shots that involved the programming of different shot angles, which may not reflect QE’s response to other relevant parameters such as changes in force production.

The first aim of this experiment was therefore to examine the influence of manipulations of task difficulty that correspond with different parameters of golf putting performance, e.g., force production, impact quality and target line (Pelz,
2000) on the QE duration adopted by experienced golfers. Vickers (2012) suggests that the length of a QE duration will depend on the length of the putt. We predict that more complex tasks, requiring more detailed and specific parameterisation, should be associated with longer QE durations.

The second aim was to adopt a more sensitive analysis relating the different proportions of the QE (early and late; Vine et al., 2013) to specific manipulations. Previous research has demonstrated that reductions in the late QE duration result in participants missing critical information regarding putter location and the putter-ball contact, leading to inferior performance (Vine et al., 2013). As such, the late QE is suggested to be responsible for the online control of movements (Vine et al., 2015). While exploratory, we suggest that a manipulation related to increasing the difficulty of making an optimal putter-ball impact (a putter insert) will likely influence the late proportion of the QE (online guidance of impact quality).

Historically research has focused on the QE’s relation to the pre-programming of movement parameters (Mann et al., 2011; Williams et al., 2002; Vickers, 1996). Vickers (1996) postulated that movement parameters, including force and velocity, were programmed in the final fixation during the preparatory phase of movement. We suggest the manipulation of force production (length of putt) may influence the early portion of the QE (pre-programming swing length parameters). However, as stated above such investigation and hypotheses are largely exploratory due to the novelty of this work and limited examination of the QE proportions and specific movement parameters.
4.2 Methods

4.2.1 Participants

Thirty-four golfers (M age = 21.35, SD = 4.04) with an average self-reported handicap of 7.2 (SD = 6.44) volunteered to take part in the experiment. All participants provided written informed consent and local ethics committee approval was granted prior to testing.

4.2.2 Manipulation of Task Difficulty

We manipulated the target size (large, 10cm (3.9in) vs. small, 5cm (1.9in)), length of the golf putt (short, 4ft (1.2m) vs. long, 8ft (2.4m)), and the size of the effective putter face using magnetic inserts (contact point: large, 1.7cm (0.7in), 24g vs small, 0.6cm (0.2in), 14g). Varying these manipulations in a systematic fashion lead to the creation of eight conditions of increasing difficulty. The order of these 8 conditions was randomised and a Latin squares design was used to avoid order effects\(^\text{1}\).

4.2.3 Apparatus

Participants putted using a standard length 90cm steel-shafted blade style putter and standard size (4.27cm diameter) white golf balls. In order to measure gaze behaviour, a lightweight Applied Science Laboratories (ASL; Bedford, MA) Mobile Eye Tracker XG was used to capture gaze behaviour at 30Hz (spatial accuracy of ± 0.5° visual angle; 0.1c precision). The Mobile Eye tracks the translation and rotation of the participant’s eye movement by means of the corneal reflection technique that get superimposed as a fixation on the video footage of a scene camera. The gaze location is represented by a circular cursor, reflecting 1° of a visual angle. The QE was calculated using Quiet Eye

\(^{1}\) No significant main effects were found for the condition order \(F(7,203) = 0.76, p = 0.551, \eta_p^2 = 0.03\)
Solutions vision-in-action software (www.QuietEyeSolutions.com). The putting movement (recorded by the mobile eye’s scene camera) and gaze location are used to calculate the QE duration. Specifically, the QE onset was required to occur prior to the initiation of backswing and the offset then occurs when gaze deviated from the ball by more than 1° visual angle or more than 100ms (3 frames, i.e. 99.9 ms) (Vine et al., 2015).

4.2.4 Procedure

Participants read an information sheet, completed a demographic questionnaire, were fitted with an eye tracker and were allowed five familiarisation putts from 8 feet. Putts were taken on an artificial green and aimed towards a circular target projected onto the surface of the green using a Hitachi LCD mobile projector and Powerpoint software. A projected target (rather than a hole) requires more precision in pace judgement than a normal sunken hole and was used to further increase task difficulty. The participants were provided with details relevant to each condition and were instructed to try to stop the ball on the projected target. In order to reduce a learning effect, and to maintain the novelty of the task for each putt the target was moved to one of three positions (left, centre or right). We also restricted feedback by removing the projected target just after putter-ball contact. Participants were then asked to face away from the target while the target re-appeared and putts were measured. A total of 10 putts were executed in each condition and rest periods were provided between conditions. The first five putts were then selected for gaze analysis in order to limit the potential for participants from making adjustments to overcome the manipulation of the task difficulty (e.g., Moore et al. 2012).
4.2.5 Measures

**Performance.** The radial error (the distance that the ball finished from the target in cm; from top of the ball to the edge of the target) was recorded using a tape measure after each putt. Radial error scores were then averaged (mean radial error) for each condition as a measure of performance.

**Quiet eye (QE).** The QE was operationally defined for golf putting as the final fixation on the ball, with an onset prior to initiation of movement (backswing) and an offset when gaze deviates from the ball by more than 1° visual angle and for more than 100ms (Vine et al., 2015). The early phase of the QE (QE-early) started at QE onset and ended with the initiation of the backswing. The late phase of the QE (QE-late) started at the initiation of the backswing and finished when the putter contacted the ball, or at QE offset (if prior to ball contact; Vine et al., 2015). Duration measures were averaged for each participant’s five trials. Due to technical errors in the data collection four participants had to be removed and were not considered in data analyses. In the case where participants demonstrated no QE fixation a zero value was entered for that trial (Williams et al., 2002). No fixation occurred due to the fixation onset starting after the backswing onset. However, if no QE fixation occurred due to technical difficulties the trial was excluded from further analysis.

4.2.6 Data and Statistical analysis

QE and performance data were subjected to 2 (target size) x 2 (length) x 2 (putter face) factorial analyses of variance (ANOVAs), with the alpha level set to .05.

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2 For 2 participants all tracking data was lost due to technical errors, and 2 different participants lost tracking data for one condition also due to technical issues. As such these participants were not entered into the ANOVA for all variables and this is reflected in the degrees of freedom in the results section. In addition, across conditions 1, 2 and 3 there were 7 participants that had average QE durations taken from less than 5 putts (no less than 3; again due to technical errors).

3 Out of the possible 620 trials no fixations occurred for 10 trials (1.6%). Levels of significance were unaffected when removing zeros from QE and QE-late analysis. QE-early analysis brought the significance of the length manipulation to > .05 ($p = 0.047$).
<.05 and Greenhouse-Geisser corrections applied if sphericity assumptions were violated. Spearman's Rank-Order Correlations were also performed on QE duration and performance error measures in each of the eight conditions. Three univariate outliers classified as values more than 3.3 standard deviation units from the grand mean (Tabachnick & Fidell, 1996) were Winsorized by changing the extreme raw score to a value 1% larger or smaller than the next most extreme score (as in Shimizu, Seery, Weisbuch, & Lupien, 2011). Effect size was calculated using partial eta squared (η²) for omnibus comparisons. All data analyses were conducted using SPSS 20.0.

4.3 Results

4.3.1 Performance

ANOVA revealed significant main effects for target size \( [F(1,29) = 7.78 , p = 0.009, \eta^2_p = 0.21] \), length \( [F(1,29) = 90.11 , p = 0.001, \eta^2_p = 0.76] \) and putter face size \( [F(1,29) = 15.94 , p = 0.001, \eta^2_p = 0.39] \). Participants’ error scores were higher for the more difficult iteration of each manipulation (See figure 4.1). No significant interactions were found (\( p’s > .062 \)).

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It is possible that the different target sizes contributed to the differences in radial error. When the target sizes were accounted for (ie. Putts that stopped within the circumference of the large target were excluded, for both target iterations) additional analysis reveals participants were still significantly less accurate in the small target condition (large target \( M = 17.36cm, SD = 1.06 \); small target \( M = 21.00cm, SD = 1.21 \) \( [F(1,29) = 19.56 , p = .001, \eta^2_p = .40] \). We thank an anonymous reviewer for this suggestion.
**Figure 4.1:** Performance error of the target size, length and putter face manipulations (mean ± s.e.m.). Significant differences are denoted, **p < .01.**

### 4.3.2 Quiet Eye

For overall QE duration ANOVA revealed non-significant main effects for target size \[F(1,29) = 1.72, p = 0.200, \eta_p^2 = 0.06\] and putter face size \[F(1,29) = 0.53, p = 0.473, \eta_p^2 = 0.02\]. However, a significant main effect for length \[F(1,29) = 13.68, p = 0.001, \eta_p^2 = 0.32\] was found (see Figure 4.2a). A significant interaction was found for length and putter face \[F(1,29) = 6.40, p = 0.017, \eta_p^2 = 0.18\]. Follow up t-tests revealed that in the conditions where the putter face was small the longer putt had a significantly longer QE duration \[t(29) = -4.20; p = 0.001\]. No other significant interactions were found \(p's > 0.169\).

For QE-early, ANOVA revealed non-significant main effects for target size \[F(1,29) = 0.19, p = 0.668, \eta_p^2 = 0.01\], putter face size \[F(1,29) = 0.32, p = 0.579, \eta_p^2 = 0.01\] and for the length manipulation \[F(1,29) = 4.06, p = 0.053, \eta_p^2 = 0.12\] (See Figure 4.2b). An interaction effect was found between length and putter face \[F(1,29) = 7.12, p = 0.012, \eta_p^2 = 0.20\]. Follow up t-tests revealed that in the conditions where the putter face was small the longer putt had a significantly longer QE duration \[t(29) = -3.50; p = 0.002\]. In long putting distance conditions a small putter face had longer QE-early durations \[t(29) = 2.18; p = 0.037\]. No other significant interactions were found \(p’s > 0.096\).
For QE-late, ANOVA revealed non-significant main effects for target size \( [F(1,29) = 0.21, \ p = 0.654, \ \eta^2_p = 0.01] \) and putter face \( [F(1,29) = 0.03, \ p = 0.862, \ \eta^2_p = 0.01] \). There was a significant main effect for length \( [F(1,29) = 13.02, \ p = 0.001, \ \eta^2_p = 0.31] \) (See Figure 4.2c). No significant interactions were found (\( p's > 0.223 \)).
**Figure 4.2:** Total QE (a), QE-Early (b) and QE-Late (c) durations for each manipulation of target size, putt length and putter face size (mean ± s.e.m.). Significant differences are denoted, * p < .05, ** p < .01.

4.3.3 Quiet Eye – Performance relationship

In four conditions there were weak negative correlations (Con3. large target, long length, large putter; Con5. small target, short length, large putter; Con6. small target, short length, small putter; Con7. small target, long length, large putter), which were not statistically significant \([r_s’s > -.01, p’s > .308]\). In the remaining conditions, there were weak positive correlations, three of which were not statistically significant (Con1. large target, short length, large putter; Con2. large target, short length, small putter; Con8; small target, long length, small putter) \([r_s’s > .15, p’s > .184]\) and one was statistically significant (Con4. large target, long length, small putter) \([r_s = .39, p = .032]\).

4.4 Discussion

The aim of this study was to examine the response programming explanation of the QE by manipulating the difficulty of a golf-putting task. Task difficulty was successfully manipulated in all three manipulations (force, impact, target line), as performance error was higher with more difficult iterations of each manipulation. The lack of any significant interaction effects would suggest a floor effect for performance.

The results for the QE measures were more complex, reflecting the fact that performance and QE measures might not necessarily have a monotonic relationship. The manipulation of target size had no impact on QE, perhaps because the aiming point (the centre of the target circle) was the same in both
conditions. We did find that the QE was sensitive to changes in requirements for accurate force production; as the length of putts increased so did overall QE and QE-late durations. This strategy does provide more time for online control of movements (e.g., Lam, Masters, & Maxwell, 2010), however, it may be a side effect of the longer putting stroke used to propel the ball to the further target (Williams et al., 2002). Yet, increased force demands does not necessarily require a longer swing, swing durations can be maintained while increasing force and amplitude (Delay, Nougier, Orliaguet, & Coello, 1997). Extended swing durations could reflect an intentional strategy to provide more time for online control of movements (Fitts, 1954; Corben et al., 2011; Lam et al., 2010).

Nonetheless, the most notable finding is the length by putter face interaction for overall QE and QE-early durations, while not fully supporting our initial hypotheses the findings do support Vickers’ (1996) proposition that movement parameters are programmed prior to movement initiation. Taken together the findings suggest that participants took longer QE-early durations to prepare for the most difficult tasks (long putt and small putter face). It is unclear from the results whether QE and QE-early increased due to the need for an objective rescaling of movement parameters or due to a subjective need to pause and prepare psychologically for the task, both provoking the allocation of additional cognitive resources.

Recent research has focused on the importance of QE-late durations for controlling movements online (Vine et al. 2013; Vine et al. 2015), however, these findings refute this idea, and provide support for the pre-programming of movements (as proposed by Vickers, 1996). However, it is possible that the

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5 QE duration relative to swing duration revealed non-significant main effects for target size \[F(1,29) = .24, p = .627\], putter face size \[F(1,29) = .01, p = .957\] and for the length manipulation \[F(1,29) = .01, p = .930\]. No significant interactions were found \((p's > .303)\).
mechanisms causing changes in QE in this study (in response to task difficulty) are different to the mechanisms that cause changes to QE in this previous research from Vine and colleagues, which focused on manipulating state anxiety. Such differences perhaps provide the opportunity for future research to explore more theoretical explanations for the role of QE in supporting performance. For example, Vine et al. (2013, 2015) suggested that anxiety made it more difficult to maintain goal-directed focus (based on the prediction of Eysenck et al.’s (2007) Attentional Control Theory) and that this control was most likely to break down late in the swing, as target related disruptions became most salient. Also, contrary to previous research (e.g. Vine et al., 2013, 2015), the longer QE durations found in the more difficult conditions were not associated with superior performance. One condition revealed that longer QE durations were related to less accurate performance, suggesting that increased QE in response to task difficulty was not functional for these experienced golfers. More specifically, the additional task parametrisation before movement did not translate into better movements.

Nevertheless, the increased cortical investment allocated to movement preparation that accompany longer early QE durations (Mann et al., 2011), may have prevented even greater performance decrements. As such, the longer QE durations may in fact have had a positive, insulating effect, although this is difficult to determine using the current research design. It is impossible to unpick the cumulative and opposing influences that extended QE durations and increased task demands have on performance. Future research is needed to better understand precisely why increased difficulty causes a change in QE duration and to decipher how the QE can be associated with more difficult (and
hence less accurate) performance on the one hand and superior performance on the other.

To conclude the current study builds on previous research by indicating that QE is sensitive to the programming of specific task parameters, supporting the response programming function of the QE. Specifically, the importance of the early QE rather than late QE proportions, indicates that different mechanisms may be at play when putting under different circumstances, such as anxiety. Nonetheless, the increases in QE do not seem functional in terms of supporting improved performance but may provide an insulating effect. Further research is needed to explore QE’s relationship with performance under conditions of increased difficulty.

4.5 Directions for future research

The results from study 1 lend support to the response programming function of the QE, increasing for more difficult putting parameters of force production and impact quality. Yet, in this instance such increases in QE did not aid putting accuracy, however, due to the experimental design it is not possible to understand this QE-performance relationship because of the opposing influences that longer QE durations and increased task demands have on performance. If the importance of the putting task was changed rather than the difficulty, the confound associated with trying to make sense of the QE-performance relationship is removed and the functions of the QE can still be examined.

One way to further examine the relation between the QE’s underpinnings and its functional relevance to performance without the confounding influence of difficulty is to take a more considered approach of examining trial-to-trial influences in a sequence of trials. Together, Cooke et al. (2015) and Botvinick
et al. (2011) demonstrate that motor planning in putting is dependent upon the outcome of a previous attempt, and errors in performance elicit compensatory adjustments in processing. Recovering from unsuccessful performance would therefore require a greater mobilisation of attentional resources. As such, QE may aid performance recovery. This examination could have practical applications and offer more clarity on the relationship between longer QE durations, response programming and difficult or unsuccessful performance. Therefore, the next study examined recovering from putting errors and assessed the influence of trial-to-trial dependence on the functionality of the QE duration.
Chapter 5: Study 2 - The Quiet Eye supports error recovery in golf putting

5.1 Introduction

The quiet eye (QE) - the final fixation or tracking gaze on a specific location that has an onset prior to the start of a final, critical movement (Vickers, 2007) - has emerged as a key predictor of proficient performance in targeting and interceptive tasks over the last 20 years. Indeed, a recent meta-analysis (Lebeau et al., 2016) found a large inter-individual mean effect size ($\bar{d} = 1.04$; between experts’ and novices’ QE durations), and a moderate intra-individual effect size ($\bar{d} = .58$; between QE durations on successful and unsuccessful performance attempts) across 27 studies with 38 effect sizes. We sought to further our understanding of why the intra-individual effects are weaker than the inter-individual ones by revisiting Vickers’ (1992) seminal study in golf putting that started this field of enquiry. We suggest that it might be overly simplistic to consider the QE - performance relationship for a trial in isolation, without considering the potential effect of the preceding attempt.

Vickers’ (1992) seminal study examined the gaze behaviour of five low handicap (LH: 0-8) and seven higher handicap (HH: 10-16) golfers as they putted from 3 m. Although not yet defined as the QE (see Vickers, 1996) she found that LH golfers fixated the ball for significantly longer than the HH group during all phases of the putt. Furthermore, fixations on the ball were longer when the golfers achieved hits compared to misses (since supported by Wilson & Pearcey, 2009). However, QE’s relationship with performance is not always so clear-cut. For example, in the study by Mann et al. (2011) several subjects from both the low handicap and high handicap group did not display differences in QE between their hits and misses. Moreover, van Lier et al. (2008) found that longer final fixations on the ball, during the preparation phase of the swing (before moving the putter), were not related to more accurate performance.
Although it must be noted that for both of the above studies the correct definition of the QE was not adopted. Finally, while Moore et al. (2012) revealed longer QE durations and more accurate putting performance for a QE trained group, subsequent mediation analysis revealed that the QE duration did not mediate differences in performance between QE trained and control groups (see also Rienhoff et al., 2012 in a dart throwing task). As such, it is clear that future research is warranted to qualify the results with regards to hit vs miss comparisons in golf putting.

There also appears to be a lack of consensus in the literature with regards to the mechanisms that explain the performance enhancing effect of the QE. While several potential mechanisms have been proposed (see Gonzalez et al., 2015 for a review), the response programming argument is probably the most widely reported: QE provides a sufficient period for the effective parameterization of the subsequent movement (Williams et al., 2002). It is during this period when sensory information is synthesized with the mechanisms necessary to both plan (pre-programme) and control (online) the appropriate motor response. For example, in golf putting, the golfer must be able to hold information about the desired line of the putt in working memory while fixating the ball, and call upon a suitable motor programme to hit the ball with the requisite force and direction to achieve the desired outcome (Mann et al., 2011).

Explicit support for the response programming explanation in golf putting came from Moore et al. (2012). These authors found that more accurate performance could be attributed not only to longer QE durations, but also greater cardiac deceleration. Cardiac deceleration has been associated with greater external information processing during the preparatory phase of motor
skill performance (Neumann & Thomas, 2009). Cooke et al. (2014) adopting an electroencephalogram methodology found that reductions in high alpha power during the final seconds preceding performance predicted successful putts. Due to high-alpha power being inversely related to cortical activity in regions of motor planning (premotor and motor cortex; e.g., Pfurtscheller, 1992), such reductions are suggested to reflect an increase in resources applied to response programming (see also Babiloni et al., 2008). Taken together, the findings of Moore et al. and Cooke et al. suggest that increased response programming is related to successful performance.

However, of particular interest to the current study, a follow up re-analysis of Cooke et al.’s (2014) original data found that the degree of response programming was greater (reduced high alpha power) following a miss compared to a successful putt (Cooke et al., 2015). The authors proposed that additional resources are devoted to motor planning when there is a need to correct for previous errors, indicating that putts are influenced by prior performance. When considering the actual game of golf this process seems highly relevant. If golfers miss the birdie putt there is the opportunity to try and recover performance and maintain par. Furthermore, missing a makeable putt on one hole is likely to affect how the golfer approaches a putt with similar parameters later in the round. These conclusions are supported by previous research from Lam et al. (2010), who also found that golfers allocate more resources to response programming – as indexed by elongated probe reaction times during the putt - following a missed putt. Such attempts to recover performance have been proposed to occur through an evaluative control process of conflict or error monitoring, where conflicts in information processing
(an error or miss) result in compensatory adjustments in processing (Botvinick et al., 2001).

While QE researchers frequently adopt block designs and take an average, or compare random hits to misses, performance over trials can exhibit dependence (see Iso-Ahola & Dotson, 2014, for a review). Furthermore, as we have described above, the relationship between QE and performance is not entirely clear from the existing literature. As such, we propose that ‘performance dependence’ could explain why QE effects are not always found. More specifically, if the QE can be associated with Cooke et al.’s (2015) reduced alpha power measure (see Wilson, Cooke, Vine, Moore, & Ring, 2012 for a rationale) then we would expect the QE duration to be influenced by the outcome of the preceding trial as well as in turn influencing the outcome of the current trial. Furthermore, the different response programming functions of the QE (pre-programming and online control) present an additional area of exploration. Considering Cooke et al. (2015) found significant increases in response programming in the final seconds prior to taking putts that followed an unsuccessful putt, examining the QE’s response in further detail - involving the early and late QE proportions - may uncover specific response programming contributions.

The overall aim of this experiment was to use a re-examination of Vickers’ original study as a launchpad to then examine a more nuanced exploration of the QE’s relationship with performance and expertise. In line with Vickers (1992) and much of the literature (Lebeau et al., 2016), we first hypothesised that experienced golfers will have a longer QE than their less expert counterparts. Second, based on our proposed compensatory error recovery function for QE, we hypothesised that any intra-individual effect for
putt outcome will be greater when examining QE on a trial-to-trial basis (i.e. a miss-hit sequence) compared to randomly selected comparisons (averaged hits and misses; cf. Vickers, 1992). Third, we predicted that longer QEs should be found when golfers are successful in recovering from an error rather than unsuccessful: responding to a miss with a hit compared to another miss.

5.2 Methods

5.2.1 Participants

We recruited 18 experienced single figure handicap golfers' (Age: $M = 28.4, SD = 14.5$) (Handicap: $M = 5.7, SD = 3.9$). We received 21 responses to take part from Novice golfers with zero years of experience (Age: $M = 23.9, SD = 7.1$). Power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that based on an effect size ($\eta^2_p = .21$) from gaze measures found by Lebeau et al. (2016), thirty-four participants were considered sufficient to achieve a power of 0.8 in a F test, given $\alpha = .05$. We therefore elected to test all 21 novice volunteers as previous experience has revealed that gaze data can be lost from novice participants particularly. Participants volunteered to take part and all provided written informed consent. University ethical approval was obtained prior to recruitment.

5.2.2 Design

A two proficiency (experienced vs novice) x two performance outcome (miss vs. hit) design was adopted. Participants performed a golf putting task on a flat artificial green from ten foot to a standard size sunken hole. The task required participants to achieve five unsuccessful putts (misses) and five successful putts (hits); however, participants were unaware of this achievement criterion (Vickers, 1992).
5.2.3 Apparatus

Participants putted using a standard length 90 cm steel-shafted blade style putter and standard size (4.27 cm diameter) white golf balls. Gaze behaviour is captured using a lightweight Applied Science Laboratories (ASL; Bedford, MA) Mobile Eye Tracker. The eye-tracking system used pupil and corneal reflection to calculate and record the momentary point of gaze (at 30Hz). A circular cursor, showing location of gaze in a video image of the scene (spatial accuracy of ± 0.5° visual angle; 0.1° precision), could be viewed in real time on a laptop screen installed with Eyevision (ASL). QE duration was calculated offline using Quiet Eye Solutions (QES) Vision-in-Action software (Quiet Eye Solutions Inc., Calgary, CA). QES uses the putting movement (recorded by the mobile eye’s scene camera) and point of gaze to calculate the QE duration. This software automatically determines the frame of video when a final fixation is observed on the ball, prior to the frame signalling the beginning of the backstroke. This is the QE onset. The QE offset then occurs when the fixation deviates off the ball by more than 1° for 100 ms. Thus, QE offset minus QE onset equals QE duration.

5.2.4 Measures

**Quiet Eye duration.** The QE was operationally defined for golf putting as the final fixation towards the ball (Vickers, 2007). The onset of the QE occurs prior to initiation of movement (backswing) and the offset occurs when gaze deviates from the ball by more than one 1° visual angle and for more than 100 ms (Vine et al., 2015). While other putting studies have used different operational definitions of the QE (e.g. Mann et al., 2011; van Lier et al., 2008), this is the standard definition that should be used for the term QE. A consistent definition enables clear comparison to be made between studies which aid understanding of QE effects and non-effects. For the analysis of the QE
proportions the early phase of the QE (QE-early) started at QE onset and ended with the initiation of the backswing. The late phase of the QE (QE-late) started at the initiation of the backswing and finished when the putter made contact with the ball, or at QE offset (if prior to ball contact; Vine et al., 2015). In the case where participants demonstrated no QE fixation a zero value was entered for that trial (Williams et al., 2002)\(^6\). Inter-rater reliability was assessed using the interobserver agreement method (see Thomas & Nelson, 2001). A second analyst scored 10% (39 trials) of QE duration data and revealed an adequate level of agreement at 82% (Moore et al., 2012).

5.2.5 Procedure

On attending the single testing session, participants read an information sheet and completed the demographics form containing questions regarding their name, age, gender and handicap (if applicable). The eye tracker was fitted and calibrated by asking participants to adopt their putting stance while being instructed to hold their gaze on the centre of each the five balls positioned at their feet in turn. Participants had five familiarisation putts from ten feet. On completion of the setup the task was explained. The experimenter emphasised that performance error was being measured and so unsuccessful putts should be left as close as possible to the hole. Participants were asked to continue putting until told to stop. Testing duration varied among participants depending on the number of shots it took to complete the attainment criteria. Following completion participants were thanked, debriefed and given the opportunity to discuss their performance with the experimenter.

\(^6\) Out of the possible 390 trials (5 hits and 5 misses) no fixations occurred for 10 trials all of which were novice participants (2.56%).

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5.2.6 Data Analysis

We first analysed the five successful and unsuccessful putts using a split-plot ANOVA with skill level (experienced vs. novice) as the between-subjects factor and performance outcome (hit vs. miss) as the within-subject factor, with the alpha level set to < .05. In order to test our hypotheses regarding error recovery, we also analysed the QE duration on occasions where two specific pairs of putts occurred: a missed putt followed by a successful putt (miss-hit), and two consecutive missed putts (miss-miss). While the occurrence of these pairs of trials varied between participants (See appendix 7), a minimum of one and a maximum of five pairs for each trial combination was used. Outliers classified as values more than 3.3 standard deviation units from the grand mean (Tabachnick & Fidell, 1996) were Winsorized by changing the extreme raw score to a value 1% larger or smaller than the next most extreme score (as in Shimizu et al., 2011). Effect sizes were calculated using partial eta squared ($\eta_p^2$) for omnibus comparisons. All data analyses were conducted using SPSS 20.0.

5.3 Results

Experienced golfers achieved the success criteria of five successful attempts in significantly fewer putts ($M = 13.72$ putts, $SD = 9.88$) than their novice

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7 The analysis of pairs of putts was run post hoc after considering the functional relevance of trial to trial effects. Consequently, each participant didn’t attain consistent numbers of pair sequences, accounting for the variation in the numbers of pair sequences selected.

8 Four participants (one novice, three experienced) did not obtain two consecutive misses and were removed from analyses (see degrees of freedom).

9 One experienced participant had 6 univariate outliers for their QE duration scores across the different analyses.
counterparts ($M = 25.66$ putts, $SD = 10.33$), $t(37) = -3.67; \ p = .001$, CI [-18.53, -5.36]$^{10}.

**5.3.1 Averaged Random Miss v Hit**

ANOVA revealed a significant main effect for skill level, $[F(1,37) = 13.51, p = .001, \ \eta^2_p = .27$, 95% CI [305.1, 1055]]. Experienced golfers revealed significantly longer QE durations ($M = 1920.63$ ms, $SE = 135.79$) than novice golfers ($M = 1240.58$ ms, $SE = 125.72$). No significant main effect for performance outcome, $[F(1,37) = 1.05, p = .311, \ \eta^2_p = .03$, 95% CI [-43.23, 132.01]]; and no significant interaction effect between skill level and performance outcome, $[F(1,37) = 0.70, p = .407, \ \eta^2_p = .02]$, were found (see figure 5.1).

*Early QE.* ANOVA revealed a significant main effect for skill level, $[F(1,37) = 5.67, p = .023, \ \eta^2_p = .13$, 95% CI [48.06, 597.84]]. Experienced golfers revealed significantly longer early QE durations ($M = 808.77$ ms, $SE = 99.56$) than novice golfers ($M = 485.83$ ms, $SE = 92.17$). No significant main effect for performance outcome, $[F(1,37) = 1.24, p = .273, \ \eta^2_p = .03$, 95% CI [-122.34, 35.55]]; and no significant interaction effect between skill level and performance outcome, $[F(1,37) = 2.67, p = .110, \ \eta^2_p = .07]$, was found.

*Late QE.* ANOVA revealed a significant main effect for skill level, $[F(1,37) = 9.65, p = .004, \ \eta^2_p = .21$, 95% CI [72.58, 345.04]]. Experienced golfers revealed significantly longer late QE durations ($M = 872.50$ ms, $SE = 49.34$) than novice golfers ($M = 42.68$ cm, $SD = 15.12$) also had significantly lower mean radial error (cm) on their missed putts than their less expert counterpart ($M = 18.66$ cm, $SD = 9.24$) $t(37) = -5.86; \ p = .001$. 

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$^{10}$ Experenced golfers ($M = 18.66$ cm, $SD = 9.24$) also had significantly lower mean radial error (cm) on their missed putts than their less expert counterpart ($M = 42.68$ cm, $SD = 15.12$) $t(37) = -5.86; \ p = .001$. 

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golfers ($M = 663.69$ ms, $SE = 45.68$). However, ANOVA also revealed a significant main effect for performance outcome, $[F(1,37) = 5.46, p = .025, \eta^2_p = .13, 95\% CI [9.38, 131.69]]$. Unsuccessful putts had significantly shorter QE durations ($M = 732.83$ ms, $SE = 38.08$) than successful putts ($M = 803.36$ ms, $SE = 35.57$) (see figure 5.2). No significant interaction effect between skill level and performance outcome, $[F(1,37) = .22, p = .639, \eta^2_p = .01]$, was found.

![Figure 5.1](image-url)

**Figure 5.1.** QE duration of experienced and novice golfers during randomly selected unsuccessful (miss) and successful (hit) putts.
Figure 5.2. Late QE duration of experienced and novice golfers during randomly selected unsuccessful (miss) and successful (hit) putts.

5.3.2 Miss-Hit Pairs

ANOVA revealed a significant main effect for skill level, \( F(1,37) = 16.90, p = .001, \eta^2_p = .31, 95\% \text{ CI} [386.6, 1137.9] \). Experienced golfers again revealed significantly longer QE durations (\( M = 1902.39 \text{ ms}, SE = 136.05 \)) than novice golfers (\( M = 1140.15 \text{ ms}, SE = 125.46 \)). However, ANOVA also revealed a significant main effect for performance outcome, \( F(1,37) = 16.99, p = .001, \eta^2_p = .32, 95\% \text{ CI} [133.6, 391.8] \). Successful putts following misses had significantly longer QE durations (\( M = 1652.60 \text{ ms}, SE = 104.70 \)) than the preceding unsuccessful putts (\( M = 1389.93 \text{ ms}, SE = 90.86 \)). No significant interaction effect was found between skill level and performance outcome, \( F(1,37) = 0.01, p = .936, \eta^2_p = .00 \), (see figure 5.3).
Early QE. ANOVA revealed a significant main effect for skill level [$F(1,37) = 5.92, p = .020, \eta^2_p = .14, 95\% CI [56.53, 621.02]]$. Experienced golfers revealed significantly longer early QE durations ($M = 755.01$ ms, $SE = 102.22$) than novice golfers ($M = 416.23$ ms, $SE = 94.63$). However, ANOVA also revealed a significant main effect for performance outcome, [$F(1,37) = 4.61, p = .038, \eta^2_p = .11, 95\% CI [56.53, 621.02]]$. Successful putts following misses had significantly longer early QE durations ($M = 635.72$ ms, $SE = 75.14$) than the preceding unsuccessful putts ($M = 535.52$ ms, $SE = 71.72$). No significant interaction effect was found between skill level and performance outcome [$F(1,37) = 0.02, p = .905, \eta^2_p = .00]$.

Late QE. ANOVA revealed a significant main effect for skill level, [$F(1,37) = 16.10, p = .001, \eta^2_p = .31, 95\% CI [132.57, 403.10]]$. Experienced golfers again revealed significantly longer late QE durations ($M = 891.62$ ms, $SE = 48.98$) than novice golfers ($M = 623.80$ ms, $SE = 45.35$). However, ANOVA also revealed a significant main effect for performance outcome, [$F(1,37) = 9.78, p = .003, \eta^2_p = .21, 95\% CI [38.29, 179.26]]$. Successful putts following misses had significantly longer late QE durations ($M = 812.10$ ms, $SE = 40.54$) than the preceding unsuccessful putts ($M = 703.32$ ms, $SE = 34.49$) (see figure 5.4). Furthermore, a significant interaction effect was found between skill level and performance outcome, [$F(1,37) = 5.25, p = .028, \eta^2_p = .12]$]. Follow up analysis revealed experienced golfers had significantly longer late QE durations than novices for both unsuccessful [$t(37) = 5.04; p = .001$] and successful [$t(37) = 2.32; p = .026$] putts. Furthermore, successful putts revealed significantly longer late QE durations than unsuccessful putts for novice [$t(20) = 3.30; p = .004$] but not experienced golfers [$t(17) = .85; p = .409$].
Figure 5.3. QE duration of experienced and novice golfers during unsuccessful followed by successful putts (miss-hit).

Figure 5.4. Late QE duration of experienced and novice golfers during unsuccessful followed by successful putts (miss-hit).
5.3.3 Miss-Miss pairs

ANOVA revealed a significant main effect for skill level \([F(1,33) = 15.98, p = .001, \eta^2_p = .33, 95\% \text{ CI } [398.31, 1223.98]]\). Experienced golfers revealed significantly longer QE durations \((M = 1905.81 \text{ ms, } SE = 153.39)\) than novice golfers \((M = 1094.67 \text{ ms, } SE = 132.84)\). However, ANOVA also revealed a significant main effect between the QE duration of two consecutive missed putts \([F(1,33) = 4.24, p = .047, \eta^2_p = .11, 95\% \text{ CI } [1.51, 243.78]]\). Following the first missed putt the QE duration got significantly shorter on the following missed putt \((\text{Miss 1 } M = 1561.56 \text{ ms, } SE = 114.34; \text{ Miss 2 } M = 1438.92 \text{ ms, } SE = 96.36)\). No significant interaction effect was found between skill level and performance outcome \([F(1,33) = 0.13, p = .724, \eta^2_p = .01]\), (see figure 5.5).

*Early QE.* ANOVA revealed a non-significant main effect for skill level \([F(1,33) = 3.93, p = .056, \eta^2_p = .11, 95\% \text{ CI } [-7.32, 551.11]]\) and for the early QE duration of two consecutive missed putts \([F(1,33) = .83, p = .368, \eta^2_p = .03, 95\% \text{ CI } [-71.67, 188.43]]\). No significant interaction effect was also found between skill level and performance outcome \([F(1,33) = 0.59, p = .449, \eta^2_p = .02]\).

*Late QE.* ANOVA revealed a significant main effect for skill level \([F(1,33) = 15.70, p = .001, \eta^2_p = .32, 95\% \text{ CI } [153.99, 479.11]]\). Experienced golfers revealed significantly longer QE durations \((M = 926.39 \text{ ms, } SE = 60.40)\) than novice golfers \((M = 609.85 \text{ ms, } SE = 52.31)\). However, ANOVA revealed a non-significant main effect between the late QE duration of two consecutive missed putts \([F(1,33) = 1.10, p = .307, \eta^2_p = .03, 95\% \text{ CI } [-35.21, 108.66]]\). No significant interaction effect was found between skill level and performance outcome \([F(1,33) = 0.01, p = .968, \eta^2_p = .00]\).
Figure 5.5. QE duration of experienced and novice golfers during consecutive unsuccessful putts (miss-miss).

5.4 Discussion
The broad aim of this experiment was to establish the basis of QE’s relationship with performance and expertise, by examining the influence of previous putts on subsequent QE durations and outcome. This is the first study to have examined QE duration in relation to functionally relevant pairs of shots. Although much research has found support for the association between longer QE durations and better performance (Lebeau et al., 2016) this is not always the case (Moore et al., 2012; van Lier et al., 2008; Rienhoff et al., 2012). The reason for different findings may be because performance does not occur in a vacuum and that previous trials may influence subsequent response programming. The current investigation was particularly interested in the role of previous errors on subsequent motor planning and performance, given the fit to recent theoretical accounts (Botvinick et al., 2001; Eysenck & Wilson, 2016).
5.4.1 Reinvestigating Vickers’ (1992)

In common with Vickers (1992) and much of the literature (Lebeau et al., 2016) the QE proved to reflect a characteristic of expertise; Experienced golfers had significantly longer QE durations than novice golfers ($\eta^2_p = .27$), an effect that is in keeping with Lebeau et al. ($\bar{d} = 1.04$, $\eta^2_p = .21$) and required fewer putts to achieve the success criteria. It seems that with experience and through training, experts learn to strategically direct their gaze control system to maximise relevant information acquisition (via the QE) to support subsequent motor response planning (Wilson et al., 2015). Furthermore, such increases in the QE duration are a cumulative increase of both early and late QE durations. The increased QE duration and QE proportions also indicate that experienced golfers do not strive for efficient processing, but rather process what is needed to be accurate. Furthermore, results support the EEG findings of Cooke et al. (2014) and Bablioni et al. (2008) and suggest that expertise – at least in self-paced tasks - is not reflected in processing efficiency (also see Klostermann et al., 2014).

However, contrary to Vickers (1992) outcome findings, QE durations did not significantly differ between the randomly selected five successful and unsuccessful putts. The recent meta-analysis by Lebeau et al. (2016) also found that inter-individual effects of QE duration were stronger than intra-individual effects. The examination of QE proportions reveals that while the early QE corresponded with the non-significant effects of the total QE, the late QE duration was significantly shorter for the unsuccessful putts. While such findings are in accordance with previous research that has demonstrated reductions in late QE at the point of performance (Vine et al., 2013), the effect was not great enough to warrant changes in the total QE duration. However,
grouping trials by outcome may miss some functional variability in QE duration associated with the pattern of putting success. Previous research has revealed that blocked putting trials are not in fact independent of previous attempts and more processing occurs following a miss due to compensatory error recovery mechanisms (Cooke et al., 2015). We therefore sought to differentiate between QE durations and QE proportions of successful putts that occurred directly following a miss (miss-hit) as opposed to randomly occurring hits and misses.

5.4.2 Error recovery

When the trial sequence was considered, a functional benefit of having a longer QE was uncovered. First, contrary to the previous analysis (figure 5.1) hits that followed immediately after a miss did have longer QE durations (figure 5.3) with a larger intra-individual effect ($\eta^2_p = .31$) compared to the intra-individual effect of randomly selected outcomes ($\eta^2_p = .03$). Furthermore, both the early and late QE durations contributed to the overall increase in QE duration for successful putts. However, the interaction effect for the late QE duration reveals that for experienced golfers, the increase in total QE duration for successful putts originates exclusively from the increase in early QE, with late QE duration remaining consistent from unsuccessful to successful putts. While these findings are of contrast to the random trial analysis above and previous findings (Vine et al., 2013), it seems that, when examining the functional variability within a sequence of trials, the response programming suggested to occur during the early QE duration, aids error recovery. Such findings coincide with the findings of Cooke et al. (2015), Babiloni et al. (2008) and Lam et al. (2010) who find that experts significantly increase response programming in the final seconds prior to taking putts that follow unsuccessful putts.
While these differences overall suggest a response programming increase in QE following an error, we found a more nuanced effect than uncovered by Cooke et al. (2015) by examining occasions when a miss was followed by another miss. In these cases, although no differences were found in early and late QE duration, we found that total QE durations actually dropped on the second attempt (figure 5.3). In essence the results provide additional support for a functional role of longer QE durations in supporting trial-to-trial putting performance, particularly when trying to recover from an unsuccessful attempt.

Furthermore, the inhibition hypothesis (Klostermann et al., 2014) offers a potential explanation for the increase in QE duration when recovering from an error. Following a miss one could speculate that inhibition demands would increase and consequently the QE duration increases to ensure optimal movement variants are parametrised and successful performance follows. However, the inhibition hypothesis holds little explanatory power when considering the decrease in QE duration on consecutive misses.

As such the important question from both a practical and theoretical viewpoint is why did participants not always try to increase their QE durations following an error? Botvinick and colleague’s conflict monitoring hypothesis (CMH; Botvinick et al., 2001), suggests that unmet demand (poor performance) results in the detection of conflict, which drives the engagement of compensatory adjustments in control. This theory would therefore support Cooke et al.’s (2015) findings, but it does not explain why on some occasions, performers decided to not apply compensatory control processes (i.e. lengthening their QE duration). To potentially explain these occasions we draw from a model recently proposed by Harris et al. (Harris et al., 2017) that pairs
the CMH with Wright’s (1996) motivational intensity theory (MIT). Based on the idea that humans will avoid wasting energy, MIT predicts that effort will be invested proportionally to task demands until chances of success become low, at which point resources will be withdrawn. As such, it is possible that the attenuated QE on the consecutive miss occurrences reflects participants’ withdrawal of effort from immediate task goals. Interestingly, this effect was consistent across both experienced and novice golfers in the current study. However, future research could further probe the extent to which the application of effort differs between novice and experienced golfers, in relation to successful and unsuccessful putts.

A complementary, albeit relatively speculative, explanation for the reduction in QE following a miss comes from Eysenck and Wilson’s (2016) updated version of attentional control theory (ACT; Eysenck et al., 2007); ACT: Sport. Eysenck and Wilson (2016) indicate that unsuccessful performance can increase pressure on subsequent performance attempts, potentially causing an increase in anxiety. The experience of anxiety is determined by whether or not a performer exhibits attentional and/or interpretational biases under competitive pressure. An increased attentional bias might cause a performer to pay more attention to threat cues (e.g., errors they have made) and an interpretive bias might cause a performer to interpret errors as having an impact on how they will perform subsequently. We describe this explanation as speculative simply because anxiety was not measured in the current study. However, it is likely that following missed putts, participants would have experienced an increase in pressure, and the anxiety that results from such pressure has been reliably shown to disrupt the allocation of attentional resource (e.g. the QE, Vine et al., 2013). As such, it is possible that fluctuations in momentary anxiety might
explain the differences in how participants responded to errors, and future research should examine these contentions.

Finally, although experienced golfers have a longer QE duration than novices across the different analysis, the QE proportions revealed similar early QE durations for experienced and novice golfers when performing two consecutive misses. In contrast, the other analysis found that all QE measures were longer for experts. Together with the interaction effect for miss-hit pairs, revealing the importance of the early QE for experienced golfers and successful putts, it seems that early QE is most sensitive to performance changes. Furthermore, unlike Cooke et al. (2015), we did not find any QE duration interaction effects. While skill level did moderate the performance outcome differences in late QE duration, experts were not more sensitive to errors than novices. In contrast, Cooke et al. suggested that experts are more sensitive to errors than novices, because they have a greater bank of performance-relevant resources to allocate to the task. However, as we have suggested, other psychological factors (motivation, anxiety) might be more important in the interpretation of errors than simply the degree of declarative knowledge available. It is also possible that QE is not as sensitive a measure of response programming as alpha power, and indeed, it has been proposed that the QE serves additional functions that are relevant to performance, for example an external focus of attention (Gonzalez et al., 2015; Vine, Moore, & Wilson, 2014).

Clearly future research needs to explore the effect of errors on participants’ momentary state anxiety and also on their motivational intensity and applied mental effort in subsequent attempts. The extent to which QE is a measure of effortful compensatory processes (e.g., Harris et al., 2017; Moran et al., 2016) also needs to be clarified. Moreover, the number of data points that
could be used to compare trial-to-trial sequences varied for each participant and were limited in some cases. Consequently, future research may wish to set explicit targets for the number of these specific sequences of trials (e.g. miss-hit) that are achieved, rather than simple hit v miss success criteria.

Furthermore, although the number of hit and miss trials in the present study is in keeping with similar research examining the QE in golf (Moore et al., 2012) the impact of varying trial numbers on the efficacy of the findings relating to QE and performance warrants further investigation.

5.4.3 Conclusions

This is the first study to have examined QE duration as a consequence of prior performance. While previous research has examined the QE in a sub selection of shots (e.g. Vine et al., 2013), here we have specifically examined the influence of performance failure on subsequent performance. Our findings extend understanding of the QE by demonstrating that when the influence of previous trials is considered, the QE duration is able to differentiate performance outcomes. Furthermore, while both early and late QE proportions contribute to the increases in QE for novice golfers, experienced golfers seem to rely on the early pre-programming proportion following unsuccessful putts. However, the fact that differences in the QE and QE proportions were found on the basis of a particular trial selection strategy highlights methodological and conceptual considerations for QE research, particularly regarding the false assumption of trial independence and a possible compensatory error recovery function for the QE. These findings also have applied implications, in particular for golfers. Golfers should increase their QE duration following a miss to ensure that they don’t compound their error and miss again. In terms of skill level, experienced golfers tended to display longer QE durations, confirming that the
QE is a characteristic of expertise (Wilson et al., 2015). The study provides a novel insight into the functional relationship between QE durations and golf putting performance and further supports the response programming function of the QE. However, additional research is needed to further our understanding of how the QE’s relationship with performance recovery attempts is moderated by the performer’s psychological state (e.g. anxiety, motivation).

5.5 Directions for future research
The results from study 2 support the response programming function of the QE and its relationship with attentional effort, providing practical, methodological and conceptual implications for QE research. While previous research has examined QE’s response to task demands (Williams et al., 2002; Chapter 4) and explored the role of motivation in recovering from an error on the QE (Chapter 5), research has not explicitly examined the influence of attentional effort on the QE that is activated by the psychological factor of motivation. To gain a more comprehensive representation of the contingencies that influence the QE the first experiment of study 3 follows on from study 2 by creating blocked conditions where motivational intensity and subsequently attentional effort is manipulated using goal setting.

In order to further test the extent to which QE is influenced by attentional effort experiment 2 aims to use a dual-task paradigm that manipulates task demands by limiting the allocation of attentional resources to putting rather than making putting harder as used in study 1. As such task demands are manipulated from a processing rather than functional perspective. While research indicates that QE reduces under anxiety related attentional disruptions (e.g., Wilson et al., 2009) it is unclear whether the QE is sensitive to disruptions in attentional effort (resources) or attentional control (distraction task-irrelevant
stimuli). Without a clear indication of QE response to both increases and decreases in attentional resources, there is a risk of wrongly assuming that all QE durations reflect attentional resources and a response programming function. As such, an assessment of QE under conditions of disrupted attentional effort is warranted.
Chapter 6: (Study 3 - experiment 1 & 2): Vision and attention during aiming performance: Understanding the functionality of the Quiet Eye
6.1 Introduction

The Quiet Eye (QE) – the final fixation to a target – has previously been found to underpin inter- and intra-individual differences in far aiming performance (see Lebeau et al., 2016, for a recent meta-analysis). It has been suggested that a longer QE supports this performance advantage via a response programming function, providing more time to extract the relevant visual information and programme the subsequent movement (Williams et al., 2002). However, this function relies on the optimal allocation of attention towards relevant cues (Klostermann et al., 2013). While the construct of attention encompasses many facets, the QE literature has investigated two distinct areas of attention, attentional focus and control, in order to explain the relationship between QE and performance.

Firstly, attentional focus refers to the direction and orientation of attention. By focusing attention externally, on the effects of the motor response, performance is improved by means of less effortful, automatic control processes. In contrast, an internal focus of attention is suggested to impair performance by eliciting conscious step-by-step monitoring of movement control (for a review see Wulf, 2013). Moore et al. (2012) provided evidence that (at least some of) the beneficial effects of QE training are as a consequence of participants eliciting an external focus of attention. However, research that has examined the link between QE and focus of attention has found mixed results. For example, Ziv and Lidor (2015) found that, while eliciting an external focus (via instructional sets) increased the QE duration, putting was unaffected. Yet, Klostermann et al. (2014), Rienhoff et al. (2014), and Querfurth et al. (2016) found that the QE increased during internal (or movement) focus of attention conditions.
Second, attentional control refers to the ability to maintain top-down, goal-directed focus, while resisting distractions. Attention is controlled via two control systems: a top-down, goal-directed attentional system and a bottom-up, stimulus-driven attentional system (Corbetta & Shulman, 2002; Knudsen, 2007). It is suggested that the QE helps to maintain the allocation of attention towards task relevant cues, while suppressing any distraction from exogenous stimuli (Vickers, 1996). When the sensitivity of the stimulus-driven attentional system is increased, under conditions of anxiety for instance (causing increased distractibility), the QE duration is often attenuated (Behan & Wilson, 2008; Wilson et al. 2009). Consequently, several studies reveal a longer QE may be a useful measure of optimal attentional control (e.g., Moore et al., 2012). Nonetheless, these areas of research are muddled, with confusion surrounding QE’s relationship with attentional focus and the degree to which gaze represents attentional parameters. Furthermore, these areas alone do not tell the entire story surrounding the QE’s relationship with attention.

One area of attentional research that is under-represented in the QE literature is attentional effort, also known as mental effort or cognitive effort (Kahneman, 1973; Burge et al., 2013; Piquado et al., 2010), referring to the quantity of attentional resources that are allocated to a task. Attentional effort is suggested to be determined by two factors; task demands and motivation. As such, the expenditure of attentional effort is not only determined by the task demands imposed on the cognitive system, but is also a matter of intention. While the motivational intensity theory (MIT) advocates that effort increases proportionally with task demands, this is dependent upon the willingness and motives of individuals (see Brehm & Self, 1989; Wright, 1996). Sarter et al. (2006) propose that the allocation of attentional effort is a voluntary, motivated
response to achieve a personal goal. Kanfer and Ackerman (1989) also indicate that resources are allocated in accordance with distal motivation processes that involve evaluating the expected performance benefits relative to expected cost of investing effort. These processes ultimately determine the motivation and intended level of effort to be devoted to the task and make the allocation of attentional effort strategic rather than purely structural (task dependent).

Indirect evidence that highlights QE’s relationship with attentional effort is provided by studies where task demands have been manipulated. For example, in billiards (Williams et al., 2002), ball throwing (Klostermann et al., 2013) and golf putting (Chapter 4) performers extended their QE duration as task demands and subsequent processing requirements increased. Such findings support the response programming argument, however this is not a passive relationship. The amount of information processing occurring during the QE is mediated by the effortful allocation of attentional resources (Klostermann et al., 2013). Attention is suggested to be a mechanism for controlling information processing (Smith & Kosslyn, 2007), accounting for the selectivity in the information we process (Rensink, 2013; Findlay & Gilchrist, 2003). Accordingly, longer QE durations seem to reflect a greater application of attentional effort, in line with task and, consequently, response programming demands.

Recent research by Moran et al. (2016) measured attentional effort during the QE in a show-jumping related task using pupillometry. Findings not only provide an independent index of cognitive processing, but also imply that a longer QE duration was related to an increase in exerted attentional effort, reflected by increased pupil dilation. Furthermore, chapter 5 has provided additional support for the QE being related to attentional effort. Golfers exerted longer QE durations on successful putts directly following a missed putt,
indicating that, following an error, golfers invested more resources into response programming in order to resolve the error and recover performance (Cooke et al., 2015). However, QE durations were shorter on the second of consecutive missed putts, reflecting a withdrawal of effort from the task. Such efforts to recover performance are therefore likely to not only be a result of conflict resolution (conflict monitoring hypothesis (CMH; Botvinick et al., 2001) but also golfers’ motivation to maintain performance (Sarter et al., 2006). However, little is understood about the QE’s relationship with attentional effort that is activated by motivation. While motivation has not explicitly been examined during the QE duration, Mann et al. (2011) demonstrate that QE is related to neurological activation, which is not only an index of premotor readiness but also associated with enhanced motivation (Andreassi, 1980).

In this paper we present two experiments, both investigating the attentional effort underpinnings of the QE during golf putting. This research is the first to comprehensively examine the influence of attentional effort on the QE using experimental manipulations. Such research is important if we are to better understand the extent to which the location of attentional focus (measured by an eye tracker) represents effortful processing of movement parameters (occurring in relevant brain centres). Experiment 1 involved the manipulation of motivation (by setting task goals), with subsequent examination of QE’s response to changes in the allocation of attentional effort that is not activated by response programming requirements. Experiment 2 used a dual-task methodology (mental arithmetic), to further examine the relationship between QE and attention, exploring the influence of disrupting the attentional effort allocation and response programming functions that are proposed in the literature. Overall, the two studies aim to examine QE’s response to
manipulations that we are assuming (on the basis of previous research) influence attentional effort.

6.2 Experiment 1

While previous research has examined QE’s response to task demands (Williams et al., 2002; Chapter 4) and explored the role of motivation in recovering from an error on the QE (Chapter 5), the aim of experiment 1 was to explicitly examine the QE’s response to attentional effort that is activated by motivation, using performance goals rather than task demands. Such exploration of the QE’s attentional underpinning is important in order to understand its function (Gonzalez et al., 2015). Motivation and, consequently, effort have been found to be influenced by goals, particularly goal difficulty (Locke & Latham, 2002; Capa, Audiffren, & Ragot, 2008). Goals are suggested to have an energising, motivational function; more difficult goals create greater, prolonged, and more efficient effort allocation (both physical and mental) than easier goals (Locke & Latham, 2002). However, Harris et al. (2017) propose that, while difficult tasks may feel more effortful, as individuals engage in greater top-down attentional control (McGuire & Botvinick, 2010) the physiological (objective) mental effort allocated to the task and internal motive may be withdrawn, depending upon the chances of success. This notion is in line with the MIT (Wright, 1996; Richter, 2013). As such, Harris’s model indicates that subjective effort increases proportionally with perceived difficulty yet objective effort increases until a threshold, where task demands and personal ability is high, and then there is sharp decline in effort when perceived chances of success are low.

The present study used three performance putting goals of varying levels of difficulty (easy, moderate, and hard) in order to manipulate attentional effort
through motivation. Consequently, the effect of motivation to achieve performance goals (rather than task demands) on the QE can be assessed. This manipulation requires no disruption to attentional effort through the division of resources and therefore the results will not be influenced by differing strategies of attention allocation (covert vs. overt allocation). Furthermore, we aimed to explore the different proportions of the QE duration; early and late QE, to examine whether increases in motivation influenced a particular proportion of QE.

We first hypothesised, in line with Harris et al. (2017), that participants subjective mental effort will increase proportionally with goal difficulty. Second, considering that recent research has shown that QE responds in line with prediction of the MIT, rather than purely the task requirements (e.g. error recovery, Chapter 5), the QE would seem to be a measure of objective, rather than subjective, attentional effort application. As such, in line with MIT and Harris et al.'s model, QE duration was predicted to increase with goal difficulty until the hard goal, where demands become too great and the likely chances of success are lower, and consequently motivation, attentional effort, and QE, were predicted to reduce. Therefore, QE was predicted to be the longest in the moderate goal condition where demand and ability are matched and chances of success are still high.

6.2.1 Methods

6.2.1.1 Participants

Fifteen experienced (Age: \( M = 26.13, SD = 14.91 \)) (Handicap: \( M = 4, SD = 3.5 \)) and 15 novice golfers (Age: \( M = 27.93, SD = 9.32 \)) were recruited. Prior to completing this experiment participants were involved in a different experiment (experiment 2). Participants volunteered to take part and all provided separate
written informed consent. Power analysis using G*Power (Faul et al., 2007) indicated that based on an effect size ($\eta^2_p = .18$) from gaze measures found by Harris et al. (2017), however this was adjusted to ($\eta^2_p = .16$) to account for any effect related to completing experiment 2. As such, thirty participants were considered sufficient to achieve a power of 0.8 in a F test, given $\alpha = .05$.

6.2.1.2 Design

A two proficiency (experienced vs novice) x three goal condition (easy vs. moderate vs. hard) design was adopted. Participants performed a golf putting task on a flat artificial green from ten feet (experienced golfers) or five feet (novice golfers)\(^1\), to a 10.8 cm sunken hole. The task required participants to achieve 3 performance goals of varying difficulty, following a baseline performance measure of 10 putts (average baseline performance- Novice golfers: 3.8 putts, Experienced golfers: 3.2 putts). The easy goal condition required participants to achieve two less successful putts than their baseline performance, creating a goal that was not challenging and within their capability considering their baseline performance. The moderate condition required participants to achieve one more successful putt than their baseline performance, creating a goal that was challenging but was still within their capability. Finally, in order to create a distinctly different goal condition, the hard condition required participants to achieve five more successful putts (on occasions the target number of putts exceeded 10), creating a very challenging goal that is likely beyond participant’s capability considering their baseline performance. The three conditions were counterbalanced using a complete

\(^1\) The different distances enable the comparison of relative performance between experienced and novice golfers.
counterbalancing design, meaning there were six condition order possibilities. Each participant was assigned an order on their visit to the laboratory.

6.2.1.3 Apparatus

Participants putted using a standard length 90 cm steel-shafted blade style putter and standard size (4.27 cm diameter) white golf balls. Gaze behaviour was captured using a lightweight Applied Science Laboratories (ASL; Bedford, MA) Mobile Eye Tracker. The eye-tracking system used pupil and corneal reflection to calculate and record the momentary point of gaze (at 30Hz). A circular cursor, showing location of gaze in a video image of the scene (spatial accuracy of ± 0.5° visual angle; 0.1° precision), could be viewed in real time on a laptop screen installed with Eyevision (ASL). QE duration was calculated offline using Quiet Eye Solutions Vision-in-Action software (Quiet Eye Solutions Inc., Calgary, CA). This software uses the putting movement (recorded by the mobile eye’s scene camera) and point of gaze to calculate the QE duration.

6.2.1.4 Measures

Goal attainment. The number of successful putts was recorded per condition (with higher values indicating better performance). The difference between the number of successful putts and the required number of putts specified by the goal was recorded as a measure of goal attainment.

Quiet eye (QE). The QE was operationally defined for golf putting as the final fixation on the ball, with an onset prior to initiation of movement (backswing) and an offset when gaze deviates from the ball by more than 1° visual angle and for more than 100ms (Vine et al., 2015). The early phase of the QE (QE-early) started at QE onset and ended with the initiation of the

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12 Easy (1) Moderate (2) Hard (3) Order: 1 = 1 2 3, 2 = 1 3 2, 3 = 2 3 1, 4 = 2 1 3, 5 = 3 2 1, 6 = 3 1 2
backswing. The late phase of the QE (QE-late) started at the initiation of the backswing and finished when the putter made contact with the ball, or at QE offset (if prior to ball contact; Vine et al., 2015). Duration measures were averaged for each participant’s trials in each condition. Due to technical errors in the data collection one experienced participant had to be removed and was not considered in data analysis (see df). In the case where participants demonstrated no QE fixation, a zero value was entered for that trial (Williams et al., 2002)\textsuperscript{13}. However, if no QE fixation occurred due to technical difficulties the trial was excluded from further analysis\textsuperscript{14}. Intra-rater reliability was assessed using an observer agreement method (see Thomas & Nelson, 2001). The analyst reanalysed 10 % (90 trials) of QE duration data and revealed an adequate level of agreement at 90%.

**Attentional effort.** A self-report assessment of mental effort was measured following each condition using the rating scale of mental effort (RSME; Zijlstra, 1993). The RSME consists of rating invested effort on a vertical axis scale ranging from 0-150 with nine descriptive anchor points relating to statements of invested effort, e.g., ‘almost no effort’ or ‘extreme effort’. This scale has been shown to have acceptable reliability in various laboratory settings (r = .88) (Zijlstra, 1993) and golf putting studies (Wilson et al., 2007; Cooke et al., 2011).

**Cognitive anxiety.** It was thought that goal attainment may elicit anxiety, often associated with declines in performance and reduced QE durations. As such, an assessment of anxiety was measured using The Mental Readiness

\textsuperscript{13} Out of the total number of trials (907 putts) no QE fixation occurred for 67 trials all of which were novice participants (7.39%).

\textsuperscript{14} On 24 occasions (7 cases experienced 17 cases novice) averages were taken from less than 10 putts across all conditions (no less than 7 putts per averaged QE measure).
Form – Likert (MRF-L; Krane, 1994) to act as a control variable. The MRF-L consists of three bipolar, 11-point Likert scales which are anchored between worried and calm for the cognitive anxiety scale, tense and relaxed for the somatic anxiety scale and confident and scared for the self-confidence scale. Due to cognitive anxiety often being associated with disrupting attention (Eysenck et al., 2007), and the aim of the present study being to investigate attentional allocation, the cognitive anxiety scale of the MRF-L was the focus.

### 6.2.1.5 Procedure

On attending a single testing session, participants read an information sheet and completed a demographics form. The eye tracker was calibrated by instructing participants to hold their gaze on the centre of each of the five balls positioned at their feet in turn while adopting their putting stance. Participants had two familiarisation putts from their allocated distance (novice 5 ft, experienced 10 ft). On completion of the set-up, participants performed ten baseline putts followed by the three goal conditions. Prior to each condition the experimenter emphasised the importance of trying to achieve the specified target number of successful putts. Participants were instructed to keep putting even if the goal was achieved prior to the final putt or the goal was no longer attainable within the number of remaining putts. The measure of mental effort was completed after each condition. Performance and gaze data were recorded continuously throughout each condition. Finally, at the end of the study, participants were thanked, debriefed and given the opportunity to discuss their performance with the experimenter.

### 6.2.1.6 Data analysis

QE, performance, attentional effort, and anxiety measures were subjected to a split-plot ANOVA with skill level (experienced vs. novice) as the between-
subjects factor and goal condition (easy vs. moderate vs. hard) as the within-subjects factor with the alpha level set to < .05 and Greenhouse-Geisser corrections applied if sphericity assumptions were violated. Effect sizes were calculated using partial eta squared ($\eta_p^2$) for omnibus comparisons. All data analyses were conducted using SPSS 20.0.

6.2.2 Results

6.2.2.1 Goal attainment

ANOVA revealed no significant main effect for skill level [$F(1,27) = .29, p = .594, \eta_p^2 = .01, 95\% CI = -1.13, 1.93]$. A significant main effect was found for goal conditions [$F(2,54) = 130.59, p = .001, \eta_p^2 = .83]$. Participants exceeded their easy goals ($M = 2.2$ putts, $SE = .45$), equalled their moderate goals ($M = 0$ putts, $SE = .45$) and unachieved their hard goals ($M = -4.8$ putts, $SE = .45$). No significant interaction effect between skill level and goal condition [$F(2,54) = .38, p = .668, \eta_p^2 = .01]$, was found.

6.2.2.2 Quiet Eye

Quiet Eye duration. ANOVA revealed a significant main effect for skill level, [$F(1,27) = 44.86, p = .001, \eta_p^2 = .62, 95\% CI = 509.96, 960.45]$. Experienced golfers had significantly longer QE durations ($M = 1577.71$ ms, $SE = 78.95$) than novice golfers ($M = 842.52$ ms, $SE = 76.27$). No significant main effect for goal conditions, [$F(2,54) = .95, p = .395, \eta_p^2 = .03]$, and no significant interaction effect between skill level and goal conditions, [$F(2,54) = 1.06, p = .349, \eta_p^2 = .04]$, were found.\(^\text{15}\)

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\(^{15}\) Post-hoc analysis revealed similar QED and performance findings when examining putts taken only prior to the goal and when examining the first putt in each condition. Participants may have invested more effort leading up to the goal.
QE – Early. ANOVA revealed a significant main effect for skill level, [\(F(1,27) = 14.54, p = .001, \eta^2_p = .35, 95\% \text{ CI} = 177.33,590.38\)]. Experienced golfers had significantly longer QE-early durations (\(M = 728.44\) ms, \(SE = 72.39\)) than novice golfers (\(M = 344.59\) ms, \(SE = 69.94\)). No significant main effect for goal conditions was found \([F(2,54) = .43, p = .619, \eta^2_p = .02]\) (see figure 6.1). A significant interaction effect between skill level and goal condition \([F(2,54) = 4.03, p = .030, \eta^2_p = .13]\) was found. Follow up analysis revealed significant skill level differences in QE-early durations for easy \([t(27) = 2.70; p = .012, 95\% \text{ CI} = 67.30, 492.74]\), moderate \([t(27) = 4.27; p = .001, 95\% \text{ CI} = 259.76, 739.47]\), and hard \([t(27) = 3.39; p = .002, 95\% \text{ CI} = 146.98, 596.85]\), goal conditions. Furthermore, experienced golfers QE-early durations differed significantly across goal conditions \([F(2,26) = 3.56, p = .048, \eta^2_p = .22]\) with the QE-early duration significantly increasing from the easy to moderate goal condition \((p = .039, 95\% \text{ CI} = -238.03, -7.52)\). For novice golfers QE-early durations did not differ significantly across goal conditions \([F(2,28) = 1.52, p = .240, \eta^2_p = .10]\).

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QE Duration: Goal conditions: Pre-goal putts - \([F(2,54) = .84, p = .417, \eta^2_p = .03]\) and first putt only - \([F(2,48) = 1.21, p = .309, \eta^2_p = .05]\). Skill level differences remained consistent: Pre-goal putts - \([F(1,27) = 50.67, p = .001, \eta^2_p = .65]\) and first putt only - \([F(1,24) = 33.41, p = .001, \eta^2_p = .58]\).

Performance(cm): Goal conditions: Pre-goal putts \([F(2,54) = 2.87, p = .066, \eta^2_p = .09]\) and first putt only – \([F(2,48) = 1.65, p = .203, \eta^2_p = .64]\). Skill level differences remained consistent: Pre-goal putts - \([F(1,27) = 4.40, p = .045, \eta^2_p = .14]\) and first putt only - \([F(1,24) = 4.12, p = .054, \eta^2_p = .15]\).
Figure 6.1. Early QE duration (ms) of experienced and novice golfers during easy, moderate and hard goal conditions (mean ± s.e.m.).

QE – Late. ANOVA revealed a significant main effect for skill level \([F(1,27) = 22.12, p = .001, \eta_p^2 = .45, 95\% CI = 169.27, 431.21]\). Experienced golfers had significantly longer QE-late durations (\(M = 794.85\ ms, SE = 45.91\)) than novice golfers (\(M = 494.61\ ms, SE = 44.35\)). No significant main effect for goal conditions, \([F(2, 54) = 1.16, p = .314, \eta_p^2 = .04]\); and no significant interaction effect between skill level and goal condition, \([F(2, 54) = 0.78, p = .441, \eta_p^2 = .03]\), were found.

6.2.2.3 Attentional effort

ANOVA revealed no significant main effect for skill level \([F(1,27) = .35, p = .557, \eta_p^2 = .01, 95\% CI = -18.91, 10.42]\). A significant main effect was found for goal conditions \([F(2, 54) = 16.13, p = .001, \eta_p^2 = .37]\) (see figure 6.2). Pairwise comparisons revealed all conditions were significantly different, participants invested significantly less effort in the easy goal condition compared to both the
moderate ($p = .006, 95\% \text{ CI} = -22.85, -4.13$) and hard goal conditions ($p = .001, 95\% \text{ CI} = -36.12, -17.22$). Furthermore, participants invested significantly more effort in the hard goal condition compared to the moderate goal condition ($p = .012, 95\% \text{ CI} = -23.26, -3.1$). No significant interaction effect between skill level and goal condition was found $[F(2, 54) = .32, p = .713, \eta^2_p = .01]$.

![Figure 6.2. Reporting mental effort of experienced and novice golfers during easy, moderate and hard goal conditions (mean ± s.e.m.).](image)

**6.2.2.4 Cognitive anxiety**

ANOVA revealed no significant main effect for skill level $[F(1,27) = .10, p = .751, \eta^2_p = .01, 95\% \text{ CI} = -1.57, 1.15]$. A significant main effect was found for goal conditions, $[F(2,54) = 10.99, p = .001, \eta^2_p = .29]$ (See figure 6.3). Pairwise comparisons revealed all conditions were significantly different, participants reported being significantly less anxious in the easy goal condition compared to both the moderate ($p = .043, 95\% \text{ CI} = -1.5, -0.02$) and hard goal conditions ($p = .001, 95\% \text{ CI} = -2.46, -.92$). Furthermore, participants were significantly more
anxious in the hard goal condition compared to the moderate goal condition ($p = .013$, 95% CI = -1.65, -.21). No significant interaction effect between skill level and goal condition was found [$F(2,54) = .05$, $p = .955$, $\eta^2_p = .00$].

![Figure 6.3](image.png)

**Figure 6.3.** Reporting cognitive anxiety of experienced and novice golfers during easy, moderate and hard goal conditions (mean ± s.e.m.).

### 6.2.3 Discussion

While recent research implies a longer QE duration is associated with more attentional effort (Moran et al., 2016), responding to the increased response programming requirements of more demanding movements (Williams et al., 2002), it is unclear whether QE is related to attentional effort that is activated by motivation to achieve. Three performance putting goals of varying difficulty were used to manipulate attentional effort. It was predicted that, in conditions where individuals are motivated and effort increases, the QE duration would also increase.
As predicted, subjective effort increased proportionally with increased goal difficulty. However, the results reveal that the goal manipulation had no effect on the total QE duration. Nonetheless, the analysis of QE proportions revealed an interaction effect for the early QE duration, indicating that experienced golfers significantly increased their early QE duration from easy to moderate goals. Such increases in the early QE correspond with the feeling of increased effort and follow the predicted path of objective measures of effort that are suggested to be at their highest during moderate difficulty, when goal difficulty and capability are matched (Harris et al., 2017). Furthermore, early QE did not continue to increase for the hard goal. This demonstrates that QE is not purely responding to the task demands. While there was also no significant decrease in early QE from moderate to hard goals in line with the reduced chance of success, the similarity in the early QE duration for hard and easy goals is in line with predictions of the MIT that effort is reduced to avoid wasting energy (Wright, 1996; Richter, 2013). Furthermore, considering the association between a neurological indicator of pre-programming movements (Mann et al., 2011) and motivation (Andreassi, 1980), the changes in early QE, which are also suggested to reflect a pre-programming function, provide further support that early QE is a motivated response.

Considering that the putting parameters remained the same across the goal conditions, it seems the increase in early QE is strategic rather than purely task dependent, reflecting an insurance strategy that seemed to aid the correct pre-programming of movement parameters and attainment of a more difficult (moderate difficulty) goal. Furthermore, findings revealed anxiety increases proportionally with goal difficulty. While anxiety is typically found to disrupt attentional control and, therefore, reduce the QE duration, our findings reveal
the opposite. According to the attentional control theory, the allocation of additional attentional resources (effort) can compensate for the negative effects of anxiety (Eysenck & Calvo, 1992; Wilson et al., 2007). As such, the increase in effort could explain the increase in early QE duration and goal attainment under conditions of increased anxiety. Findings are in line with QE training studies that indicate an increase in QE can buffer against the effects of anxiety (Vine & Wilson, 2011; Moore et al., 2012). Furthermore, our findings reveal that, when anxiety is increased further (hard goal condition) but motivation does not match (and consequently no increases in early QE duration), goals are not attained.

The results also highlight the influence of goals on experienced, rather than novice, golfers QE. We consider that this likely reflects a circular process, whereby a performer that has an established gaze strategy (e.g. an expert that has a longer QE) will evaluate a task as more favourable, eliciting motivated states (Moore et al., 2013) that seem to increase the QE when performing (Moore et al., 2012). Furthermore, commitment to achieving a goal is facilitated by the added importance of goal attainment to the individual (Locke & Latham, 2002). For experienced golfers, goal attainment is likely to be a matter of integrity, holding more value compared to novice golfers with no previous golf experience. Although the rationale and importance of each goal was emphasised, the effects of assigned goals can be mediated by personal self-set goals (Locke & Latham, 2002). Novice participants in particular may have self-selected putting goals, accounting for their consistency in QE duration measures.

To conclude, our findings reveal that the early QE proportion is sensitive to attentional effort that is activated by the motivation to achieve a more difficult
goal. Although such increases were not enough to warrant changes in the QE duration, this effect reflects a specific pre-programming response from experienced golfers. Thus, QE seems to be a strategic response rather than purely task dependent.

6.3 Experiment 2
In light of the paucity of research examining QE’s relationship with attentional effort, experiment 2 aims to further examine this relationship to gain a better understanding of the extent to which QE is influenced by attentional effort. In study 1 of this thesis we see that QE is influenced by the task demands. However, in this study the aim is to manipulate task demands by limiting the allocation of attentional resources to putting, rather than making the putting more difficult. A dual-task paradigm is a method of changing the attentional resources allocated to a primary task by dividing the available resources between the primary task and an additional secondary cognitive (or motor) task simultaneously. Although dual-task designs are used to assess the attentional demands required for motor and sports skills (Beilock et al., 2002; Smith & Chamberlin, 1992; Leavitt, 1979), such a design also provides a novel way to disrupt the ability to apply attentional effort to response programming of a putt during the QE. However, a dual-task also increases the overall processing demand on the cognitive system (if the primary task allows).

While experiment 1, along with other previous research, indicates that QE is sensitive to increases in attentional effort that is activated by increased demands (perceived or actual) (Chapter 5; Williams et al., 2002), this has only been examined when completing a single goal-directed task. When performing under pressure, anxiety is suggested to create dual-tasking, where the task at hand and worrisome thoughts compete for attentional resources (Wilson, 2012;
Beilock & Carr, 2001; Ring, Cooke, Kavussanu, & McIntyre, 2015). Under these circumstances of divided attentional resources and reduced processing efficiency, the QE duration is found to reduce (e.g., Wilson et al., 2009) in line with the predictions of attentional control theory (Eysenck et al., 2007). As such, under dual-task conditions that both increase the overall application of attentional effort and processing demands, yet simultaneously disrupt the attentional effort allocated to putting, it is unclear how the QE duration will respond.

Two versions of a secondary task were designed to disrupt either gaze and motor processing (dual-visual condition) or motor processing alone (dual-audio condition). We also aimed to determine whether any possible changes in the QE duration were a function of attentional resources being allocated to different modalities. Due to proposed variations in QE durations and attentional requirements between skill levels (Lebeau et al., 2016; Beilock et al., 2002), we also explored expertise differences.

We first hypothesised that, based on previous dual-task studies involving golf putting (e.g. Beilock et al., 2002) and the influence of disrupting the processing of movement parameters, putting performance would be less accurate in both dual-task conditions compared to a control condition, but only for novice participants. Second, we predicted that, if the duration aspect of the QE reflects the attentional effort allocated to golf putting alone, the duration will decrease in line with the addition of a secondary task and consequential disruption of attentional effort and response programming applied to putting. Both secondary tasks were expected to disrupt the response programming function of the QE. The greatest reduction in QE duration was expected during the dual-visual condition, in accordance with the explicit change in gaze location.
required to perform the visual secondary task. Furthermore, due to the
temporal presentation of the secondary tasks during the execution phase of
putting, any changes in the QE duration were expected to occur during the late
QE proportion.

6.3.1 Methods

6.3.1.1 Participants

A total of 30 subjects, fifteen experienced (Age: $M = 26.13, SD = 14.91$)
(Handicap: $M = 4, SD = 3.5$) and 15 novice golfers (Age: $M = 26.13, SD = 5.89$),
were recruited for the study. Participants volunteered to take part and all
provided written informed consent. University ethical approval was obtained
prior to recruitment. Power analysis using G*Power (Faul et al., 2007) indicated
that based on an effect size ($\eta_p^2 = .16$) from gaze measures found by Nibbeling
et al. (2012), thirty participants were considered sufficient to achieve a power of
0.8 in a F test, given $\alpha = .05$.

6.3.1.2 Design

A two proficiency (experienced vs novice) x three condition (single vs. dual-
audio vs. dual-visual) design was adopted. The single task condition involved
participants performing the primary golf putting task on a flat artificial green from
ten feet to a circular target 10cm in diameter. The two dual-task conditions
(audio and visual) required participants to perform the primary task while
performing a secondary mental arithmetic task. Mental arithmetic was selected
as the secondary task because it is cognitively demanding. Although
multiplication of two digits represents a single step of computation (Winkel &
Schmidt, 1974), this task involves retaining a number in working memory,
identifying the presented number, computing the answer, and then providing the
response within a narrow temporal window, all of which diverts attentional resources away from the primary task.

_Dual-audio condition_. This condition involved performing the primary putting task with an audio secondary arithmetic task. The arithmetic task involved participants multiplying two numbers together; one number between 2 and 11 was selected at random by the participant (e.g. 5) prior to trial onset, with the second number (e.g. 2) presented acoustically (spoken aloud by the experimenter) at the onset of putter backswing. The presented numbers were predetermined and sums were consistent for all participants, reflecting simple multiplication (e.g. 7 x 2). Pilot testing revealed that more complex sums (e.g. 9 x 9) were too demanding (see appendix 8). Participants were required to calculate the sum and provide a verbal answer prior to putter-ball contact, ensuring that primary and secondary tasks are performed simultaneously.

_Dual-visual condition_. This condition was the same as the dual-audio condition in all respects apart from the second number was presented visually. A visual projection of the numbers was shown on the green in front of the participant using a Hitachi LCD mobile projector and Powerpoint software\textsuperscript{16}. Ten putts were performed in each condition. If participants did not provide an answer prior to putter-ball contact or changed their swing to provide more time to answer the sum the trial was repeated. For repeated trials the number given by the participant remained the same and the presented number was changed. The presented number for repeated trials were pre-determined. The three conditions were counterbalanced using a complete counterbalancing design,

\textsuperscript{16} The projected number appear in participant’s peripheral vision, more than approx. 7° of a visual angle from the ball.
meaning there were six condition order possibilities\textsuperscript{17}. Each participant was assigned an order on their visit to the laboratory.

\textbf{6.3.1.3 Apparatus}

Apparatus remain unchanged from experiment 1.

\textbf{6.3.1.4 Measures}

\textit{Quiet eye (QE)}. The definition of QE, early QE and late QE was the same as that used in experiment 1. Duration measures were averaged for each participant’s trials in each condition. Due to technical errors in the data collection two experienced participants had to be removed and were not considered in data analyses (see df). In the case where participants demonstrated no QE fixation a zero value was entered for that trial (Williams et al., 2002)\textsuperscript{18}. However, if no QE fixation occurred due to technical difficulties the trial was excluded from further analysis\textsuperscript{19}. Intra-rater reliability was assessed using an observer agreement method (see Thomas & Nelson, 2001). The analyst reanalysed 10\% (84 trials) of QE duration data and revealed an adequate level of agreement at 89%.

\textit{Attentional effort}. Measures of self-reported mental effort were the same as those employed in experiment 1; RSME; Zijlstra, 1993. While this measure does not assess the subjective effort of primary and secondary tasks respectively, the measure demonstrates collective engagement and overall load on the cognitive system. Attentional resource allocation in dual-task designs is shown through performance measures.

\textsuperscript{17} Single (1) Dual-audio (2) Dual-visual (3) Order: 1: 1 2 3, 2: 1 3 2, 3: 2 3 1, 4: 2 1 3, 5: 3 2 1, 6: 3 1 2
\textsuperscript{18} Out of the total number of trials analysed (840) no QE fixation occurred for 74 trials (8.81\%).
\textsuperscript{19} On 43 occasions (14 cases experienced 29 cases novice) averages were taken from less than 10 putts across all conditions (no less than 6 putts per averaged QE measure).
Performance. The radial error (the distance that the ball finished from the circular target in cm) was also recorded using a tape measure after each putt. Radial error scores were then averaged (mean radial error) for each condition as a measure of performance.

Cognitive anxiety. In keeping with experiment 1 it was thought that completing a dual-task may elicit anxiety. As such, an assessment of anxiety was measured using The Mental Readiness Form – Likert (MRF-L; Krane, 1994) (see experiment 1) again as a control variable.

6.3.1.5 Procedure

Following experiment 1 participants read an information sheet, provided informed consent and the eye tracker was re-calibrated using the same procedure reported in experiment 1. Participants then performed five familiarisation putts from 10 feet. Prior to the single task condition the experimenter emphasised the importance of putting accuracy, with the aim being to try to stop the ball within the circular target. Prior to the dual-task conditions the experimenter emphasised that participants should give equal priority to putting accuracy and the multiplication task, to ensure attentional capacity was loaded. Due to the self-paced nature of the tasks and the potential for task switching the experimenter also emphasised that the putting swing should not be extended to gain more time to answer the sum. If this was deemed to be the case the trial was repeated. Before each dual-task condition two practice putts were performed to confirm participants understood the task. Moreover, self-report measures of mental effort and anxiety were completed after each condition. Performance and gaze data were recorded continuously throughout each condition. Finally, at the end of the study, participants were thanked and debriefed.
6.3.1.6 Data analysis

QE, performance, attentional effort, and anxiety measures were subjected to a split-plot ANOVA with skill level (experienced vs. novice) as the between-subjects factor and condition (single vs. dual-audio vs. dual-visual) as the within-subjects factor, with the alpha level set to < .05 and Greenhouse-Geisser corrections applied if sphericity assumptions were violated. Effect sizes were calculated using partial eta squared ($\eta^2_{p}$) for omnibus comparisons. All data analyses were conducted using SPSS 20.0.

6.3.2 Results

6.3.2.1 Quiet Eye

**Quiet eye duration.** ANOVA revealed a significant main effect for skill level, $[F(1,26) = 19.91, p = .001, \eta^2_{p} = .43, 95\% CI = 333.54, 903.3]$. Experienced golfers had significantly longer QE durations ($M = 1601.01$ ms, $SE = 101.44$) than novice golfers ($M = 982.59$ ms, $SE = 94.43$). A significant main effect was also found for conditions $[F(2,52) = 5.00, p = .012, \eta^2_{p} = .16]$. Pairwise comparisons revealed that participants had significantly shorter QE durations during the dual-visual condition compared to both the single ($p = .029, 95\% CI = 29.04, 486.65$) and dual-audio ($p = .003, 95\% CI = 134.47, 572.94$) conditions (see figure 6.4). No significant interaction effect was found $[F(2,52) = .012, p = .985, \eta^2_{p} = .00]$. 
Figure 6.4. QE duration (ms) of experienced and novice golfers during single, dual-audio and dual-visual conditions (mean ± s.e.m.).

**QE-early.** ANOVA revealed a significant main effect for skill level, $[F(1,26) = 7.67, p = .010, \eta^2_p = .23, 95\% CI = 78.69, 532.37]$. Experienced golfers had significantly longer QE-early durations ($M = 863.73$ ms, $SE = 80.77$) than novice golfers ($M = 558.20$ ms, $SE = 75.19$). No significant main effect for conditions $[F(2,52) = .47, p = .602, \eta^2_p = .02]$; or interaction effect $[F(2,52) = .206, p = .788, \eta^2_p = .01]$ was found.

**QE-late.** ANOVA revealed a significant main effect for skill level, $[F(1,26) = 10.15, p = .001, \eta^2_p = .28, 95\% CI = 88.35, 409.76]$. Experienced golfers had significantly longer QE-late durations ($M = 656.64$ ms, $SE = 57.22$) than novice golfers ($M = 407.59$ ms, $SE = 53.27$). A significant main effect was also found for conditions $[F(2,52) = 17.99, p = .001, \eta^2_p = .41]$. Pairwise comparisons revealed that participants had significantly shorter QE-late durations for the dual-visual condition compared to both the single ($p = .001, 95\% CI = 178.29,$
415.14) and dual-audio ($p = .001$, 95% CI = 199.67, 408.05) conditions\textsuperscript{20}. No significant interaction effect was found [$F(2,52) = .97$, $p = .380$, $\eta^2_p = .04$].

**6.3.2.2 Performance**

**Putting performance.** ANOVA revealed a significant main effect for skill level, [$F(1,26) = 40.83$, $p = .001$, $\eta^2_p = .61$, 95% CI = -37.88, -19.44].

Experienced golfers were significantly more accurate ($M = 20.05$ cm, $SE = 3.28$) than novice golfers ($M = 48.71$, $SE = 3.06$). A significant main effect was also found between conditions [$F(2,52) = 4.30$, $p = .021$, $\eta^2_p = .14$]. Pairwise comparisons revealed that participants were significantly more accurate during the single task compared to both dual-task conditions (audio $p = .016$, 95% CI = -11.28, -1.26, visual $p = .008$, 95% CI = -10.43, -1.69) (see figure 6.5). A significant interaction effect between skill level and conditions [$F(2,52) = 3.23$, $p = .048$, $\eta^2_p = .11$] was also found. Follow up analysis revealed experienced golfers performance did not differ significantly across conditions [$F(2,24) = 1.52$, $p = .243$, $\eta^2_p = .11$]. However, novice golfers performance did differ significantly across conditions [$F(2,28) = 5.49$, $p = .017$, $\eta^2_p = .28$]. Pairwise comparisons revealed novices were significantly more accurate during the single task compared to both dual task conditions (audio $p = .011$, 95% CI = -21.13, -3.21, visual $p = .012$, 95% CI = -12.94, -1.93) (see figure 6.5)\textsuperscript{21}.

\textsuperscript{20} Although the QE-late duration was shorter during the dual-visual condition 13 participants (4 experienced, 9 novice) on 62 trials returned their gaze back to the ball prior to contact. Dual-visual putting performance of participants that returned their gaze to the ball was not significantly different to participants that did not ($t(26) = -.64; p = .531$).

\textsuperscript{21} 2.14\% of putts taken were successfully landed on the circular target. Novice 0.35\%, experienced 1.79 \%. Single condition 0.71\%, dual-audio 0.36 \%, dual-visual 1.07 \%. 

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Figure 6.5. Putting performance error (cm) of experienced and novice golfers during single, dual-audio and dual-visual conditions (mean ± s.e.m.).

Secondary task performance. ANOVA revealed no significant main effect for skill level, \([F(1,26) = .14, p = .714, \eta^2_p = .01, 95\% CI = -5.55, 3.86]\) or condition (dual-audio vs. dual-visual) \([F(1,26) = 1.33, p = .259, \eta^2_p = .05, 95\% CI = -.86, 3.07]\); and no interaction effect \([F(1,26) = .21, p = .652, \eta^2_p = .01]\) was found.

6.3.2.3 Attentional effort

ANOVA revealed no significant main effect for skill level \([F(1,26) = .00, p = .992, \eta^2_p = .00, 95\% CI = -15.93, 15.78]\). A significant main effect was found for condition \([F(2,52) = 47.04, p = .001, \eta^2_p = .64]\). Pairwise comparisons revealed that participants invested significantly less effort in the single task condition compared to both dual-audio \((p = .001, 95\% CI = -40.87, -21.28)\) and dual-visual \((p = .001, 95\% CI = -44.54, -26.31)\) conditions. No significant interaction effect was found \([F(2,52) = .28, p = .670, \eta^2_p = .01]\).
6.3.2.4 Cognitive anxiety

ANOVA revealed no significant main effect for skill level \( [F(1,26) = .12, p = .735, \eta^2_p = .01, 95\% CI = -1.5, 1.07] \). A significant main effect was found for condition \( [F(2,52) = 24.09, p = .001, \eta^2_p = .48] \). Pairwise comparisons revealed that participants were significantly less anxious in the single task condition compared to both dual-audio \( (p = .001, 95\% CI = -3.6, -1.68) \) and dual-visual \( (p = .001, 95\% CI = -3.61, -1.65) \) conditions (see figure 6.6). No significant interaction effect was found \( [F(2,52) = 1.45, p = .245, \eta^2_p = .05] \).

![Figure 6.6. Cognitive anxiety of experienced and novice golfers during single, dual-audio and dual-visual conditions (mean ± s.e.m.).](image)

6.3.3 Discussion

The overall aim of experiment 2 was to further investigate the attentional underpinnings of the QE duration using a dual-task paradigm to manipulate the attentional effort allocated to the response programming of a golf putt. This is the first study to have used a dual-task paradigm to investigate the QE’s
relationship with attentional effort. While much of the literature uses the QE as a measure of attention (e.g. Moore et al., 2012; Wilson et al., 2009), very few researchers have explicitly investigated the QE’s attentional effort underpinnings. We predicted that the response programming function of the QE would be disrupted during both of the dual-task conditions, reflected by less accurate performance for novice golfers. Consequently, if the measurable aspect of the QE (duration) is influenced by the attentional effort allocated to golf putting, the duration will decrease during dual-tasks, in line with the addition of a secondary task and consequential disruption of attentional effort and response programming.

The increased investment of reported mental effort and the similarity in secondary task performance for both dual-task conditions and skill levels provides a manipulation check that all participants engaged with both dual-tasks.

**6.3.3.1 The Quiet Eye**

The QE duration of both novice and experienced golfers was influenced during the dual-visual condition only; the QE duration was significantly shorter compared to both dual-audio and control conditions. Furthermore, the analysis of QE proportions revealed that the late QE duration was responsible for the reduced overall QE duration; the early QE duration remained consistent across conditions. The reduced late QE duration for the dual-visual condition demonstrates that QE does not reflect overall load on the cognitive system created by the dual-task but seems to correspond with the online disruption of a golfer’s ability to apply attentional effort to the response programming of putting. However, the maintenance of the QE during the dual-audio condition, coupled with no other changes in reported effort and anxiety measures, indicates that
despite the same reductions in attentional effort for both dual-task conditions, the changes in QE during the dual-visual condition reflect its sensitivity to the overt movement in the location of visual attention, rather than the amount of attentional effort allocated to putting. Participants used overt eye movements towards the presented number in their periphery, rather than using covert attention. The QE duration therefore seems to be a measure of overt attention (gaze) and not the covert allocation of resources and effort. As such, attentional focus (gaze) and attentional effort were dissociated during the QE in the dual-audio condition, with the overt duration measure of QE not reflecting changes in attentional effort and impaired response programming of the putting task. While defined as the QE in this study, the maintained final fixation in the dual-audio condition seems to be merely a steady gaze, rather than a real QE duration during which functional response programming occurs.

### 6.3.3.2 Performance and the Quiet eye

In line with previous research (Beilock et al., 2002), putting performance was significantly less accurate during both dual-task conditions, compared to the control condition (single task), but only for novice golfers. Therefore, the online disruption of the ability to apply attentional effort during the QE, caused by both secondary tasks, adversely affected novice putting performance. While inferior putting performance corresponds with reduced QE duration during the dual-visual condition, such inferior performance for the dual-audio condition corresponded with maintained QE durations. However, as discussed above, the final fixation in the dual-audio condition appears to be merely a steady gaze and, as others have shown, steady gaze does not always demonstrate disruptions in response programming and consequential effects on performance (Vine et al., 2015).
In contrast, the same online disruption to the ability to apply attentional effort to the primary task did not influence experienced golfers’ putting performance, demonstrating that they can maintain their putting performance with less online response programming resources. Furthermore, the reduced late QE duration did not influence performance during the dual-visual condition. The maintenance of performance can be explained by the suggested automaticity of expert performance and the reduced need for attentional resources online (Fitts & Posner, 1967; Beilock et al., 2002), but also by the investment of resources into response programming prior to a putt (Cooke et al., 2014; Babiloni et al., 2008). In line with performance, the early QE duration remained consistent across all conditions and, therefore, allowed adequate pre-programming, aiding performance. However, this proposal is not upheld by novice golfers, whose performance suffered despite maintaining their early QE duration. Novice golfers’ durations were significantly lower than experienced golfers and, therefore, it seems that only early QE durations above a certain threshold provide enough pre-programming to enable maintained performance.

Nonetheless, such findings contradict previous research that has found that disruptions in online control and late QE negatively affect expert performance (Vine et al., 2013; Vine et al., 2015). However, the critical difference between these findings is that performance differences found by Vine et al. were on the basis of ‘all or none’ in terms of visual information and online control. Although it is difficult to establish the exact allocation of attentional resources, online control was still possible in the dual-task conditions and was sufficient to maintain performance.
6.3.3.3 Conclusions

This is the first study to have examined QE’s attentional effort underpinnings using a dual-task design that disrupted participants’ ability to apply attentional effort to task processing. Results confirm that QE is a measure of overt attention (gaze). However, this gaze measure does not tell us everything, particularly regarding changes in attentional resources that are allocated covertly and the subsequent effects on performance. Despite the dissociation between gaze and attentional effort, experienced golfers’ performance indicates a lack of dependence on attentional resources presented online, and highlights the importance of movement programming prior to putting, as reflected by the maintenance of early QE duration. While this research tackles previous QE-attention assumptions, QE’s relationship with attentional effort is still unclear.

6.4 General discussion

The current study provides a novel and warranted examination of the QE duration and the influence of the quantity of attentional resources that are allocated to a task. Experiment 1 results indicate that the early QE duration is sensitive to the motivated activation of attentional effort to achieve a more difficult goal. Experiment 2 results demonstrate the overt measures of the QE duration can be dissociated from the covert allocation of attentional effort. Together, the findings demonstrate the intricacy of QE’s relationship with attentional effort.

Attentional effort was manipulated in both experiments. However, the QE’s response was not consistent. It seems the differences between the findings may be a result of the manipulations. The manipulation of goal motivation (experiment 1) was a motivated allocation to either increase or decrease attentional effort to putting, whereas experiment 2 was not a
motivated withdrawal of effort from putting. Due to golfers completing the primary and secondary tasks simultaneously, attention was actively allocated to the secondary task rather than actively withdrawn from putting. Therefore, reductions in attentional effort allocated to putting were inadvertent. As such, it seems QE did not mirror the reductions in attentional effort that were allocated to putting during experiment 2 but was instead maintained in line with goal directed visual behaviour, whether that was maintaining the QE (seen in dual-audio condition) or gaining task relevant information (seen in dual-visual condition). The findings therefore indicate that the QE is influenced by the active/motivated allocation of attentional effort but it is not sensitive enough (at least with current measures) to reveal movements in the locus of attentional effort and does not activate shifts in gaze (covert attention). While the gaze-attention dissociation is not a novel finding, this study has highlighted the difficulty in assessing the quality and functionality of a QE using current measures.

Furthermore, the findings hold theoretical importance as they demonstrate that increases in QE are not exclusively task dependent. It seems that, while the effect of increased motivation on the QE was small (only the early QE), such increases are strategic. The findings coincide with theories of motivation, which advocate that humans evaluate the likely value and cost of exerting effort (see MIT; Wright, 1996; Richter, 2013). Additionally, the findings may provide potential explanations for previously unresolved findings. For instance, longer QE durations relating to worse performance (e.g. chapter 4; Moore et al., 2012) could be as a result of disrupted attentional effort that is not reflected in the QE duration. Furthermore, our findings suggest that longer QE durations for experienced golfers may be a result of elevated motivation,
providing a potential explanation for why experts are found to have longer QE durations than novices. This notion coincides with QE training research, which indicates that possessing a superior gaze strategy (longer QE) equips performers with greater resources to perform the task, resulting in the adoption of a more challenged state to approach the task (Moore et al., 2013). Moreover, performance under assessment will hold more value for experts than for novices, who have little personal investment in terms of handicap, reputation, etc. This elevated motivation is suggested to stimulate goal-directed behaviour, directing attentional focus and greater attentional resources to the task (Sarter et al., 2006; Moore et al., 2012). Consequently, motivation could explain why experienced golfers possess longer QE durations in both studies.

Such motivated responses indicate that experienced golfers do not strive for efficient response programming (Cooke et al., 2014; Babiloni et al., 2008). While this seem to be the case for the pre-programming of movements, reflected by changes in the early QE duration (experiment 1), experienced golfers demonstrate efficiency during the late QE, maintaining performance with reduced online attentional resources (experiment 2). Such differences in processing may explain the efficiency paradox (Mann et al., 2016) between the contradicting findings surrounding expertise, processing efficiency, and what the QE duration represents.

6.4.1.1 Limitations and future research

While goal difficulty elicited changes in QE, we acknowledge the potential for fluctuations of effort within a condition, the opportunity for individual interpretation of the goals and the potential influence of self-set goals that was not accounted for. Furthermore, while experiment 1 demonstrates that QE responds to changes in effort on the basis of motivation derived from goal
difficulty and chances of success, Sarrazin, Roberts, Cury, Biddle and Famose (2002) highlights that effort is also influenced by an individual’s achievement goal (Nicholls, 1984). Sarrazin et al. reveal that individuals who adopt a task (mastery) orientation exert more effort than those that adopt an ego (performance) orientation. Future research may wish to further test QE’s sensitivity to effort by examining QE’s response to effort that is influenced by different achievement goals. In experiment 2, only the influence of disrupting attentional effort online, during the late QE proportion, was examined and not during early QE. Disrupting the ability to apply attentional effort during early and late QE would provide a more holistic view of QE’s relationship with attentional effort. Moreover, future research should create additional dual-task conditions. For instance, having an additional secondary visual task that requires no eye movements to establish whether eye movements or disrupted task processing effect the QE. More accurate QE measures are also needed to identify and differentiate final fixations that are functional, rather than merely steady gaze, which at present is difficult. Across both experiments, the assessment of objective measures of attentional effort (independent of the QE duration) would also aid the understanding of QE’s relationship with attentional effort.

6.4.1.2 Conclusions

This study extends knowledge surrounding the function of the QE, tackling prominent QE-attention assumptions within the literature. Findings highlight the sensitivity of the QE to psychological factors (motivation) and provide support for previous research that has assumed QE reflects a measure of overt attentional control. However, the dissociation between QE duration and attentional effort highlights the caution that should be taken when interpreting and drawing conclusions from gaze duration with regard to the QE’s function.
Our findings can hopefully encourage future investigation into the function of the QE duration and its relationship with attention.
Chapter 7: General discussion
7.1 Summary of Key Findings

While the literature often refers to the QE as a characteristic of superior performance, the functional mechanisms that underpin the QE are not well understood. Many researchers advocate the need to better identify and understand the mechanisms that underlie the QE (Williams, 2016; Gonzalez et al., 2015). The purpose of this thesis was to examine the function of the QE duration, what it represents and how it exerts an influence by exploring its attentional underpinnings and the prominent cognitive mechanism of response programming. Overall I aimed to aid understanding of the QE by exploring what the duration of QE can actually tell us about its function.

Study 1 (chapter 4) predicted that, if the QE reflects the response programming function, increasing the complexity of movement parameters should increase the QE duration. The manipulation of different parameters of golf putting and the examination of different response programming functions (pre-programming vs online control) during the QE enabled me to build on previous research and explore the QE’s response to specific iterations of increased task demands. (Experienced) golfers revealed longer QE durations for more complex iterations of the task and, furthermore, more sensitive analyses of the QE proportions suggest that the early QE duration (prior to movement initiation) is closely related to force production and impact quality. Results indicate that the increased difficulty provoked an increase in pre-programming, to accommodate the increased task demands, as reflected by the early QE duration. The design meant that it was not possible to meaningfully assess the QE-performance relationship, which was a key aim of study 2 (chapter 5).
Study 2 (chapter 5) moved on to examine the influence of trial-to-trial dependence on the functionality of the QE duration. It was predicted that errors in performance would elicit increases in the QE duration of subsequent trials, reflecting a compensatory adjustment in processing to recover performance. Interestingly, there was no difference in QE between randomly chosen hits and misses. However, QE durations were significantly longer on hits directly following a miss, but significantly shorter on misses following a miss. The findings highlight the important role of QE in recovering from an error and improving performance, further supporting the response programming function of the QE. Findings also highlight the potential for a link between QE and the allocation of attentional resources to the task (effort).

Study 3 (chapter 6) experiment 1 explores QE’s relationship with attentional effort further by examining the influence of attentional effort that is activated by motivation rather than putting demands. It was predicted that QE would increase in line with increased motivation to achieve a specified goal. Results revealed that experienced golfers increased their early QE duration from easy to moderate goal difficulty conditions only, suggesting that QE is not purely determined by the demands of the task but that golfers have the ability to apply attentional effort strategically, supporting the influence of psychological factors on the QE duration.

With results across the studies indicating that QE is influenced by attentional effort, experiment 2 tested this using a dual-task paradigm. It was predicted that if the duration aspect of the QE reflects the attentional effort allocated to golf putting, the duration would decrease in line with the addition of a secondary task and consequently disruption in attentional effort and response programming. Results confirm that QE reflects an overt measure of attention yet
is not sensitive enough (at least with current measures) to reveal the covert division of attentional effort. Furthermore, key differences were found between experienced and novice golfers’ performance, highlighting a lack of dependence on attentional resources presented online for experienced golfers.

In total, the four studies examined varying contingencies and their influence on the QE duration. Together, a number of key findings emerge from the studies; figure 7.1 provides a simplified graphical representation of these key findings. Firstly, the findings have demonstrated that QE is influenced by attentional effort, whether that is activated by task demand or motivational contingencies (putt difficulty, error recovery, goals). As previous QE research has focused on the influence of the structural requirements of a task, neglecting the element of intention, this finding is important, demonstrating that QE is a strategic gaze behaviour. However, the relationship between attentional effort and QE is not clear-cut and involves several caveats, as shown by the dashed lines in figure 7.1. As such, the second key finding is that QE is only influenced by the active allocation of attentional effort - when changes in attentional effort are not self-driven (e.g. by the use of secondary tasks). Finally, while this thesis supports the established finding that QE is an overt gaze measure, responding to the overt movements in the location of visual attention, it also provides long overdue confirmation that QE is not sensitive to covert changes in attentional effort and, therefore, is not a covert measure of attention. This finding, in particular, has significant implications that are discussed below.
Figure 7.1. A diagram of the contingencies that influence and do not influence the QE duration through attentional effort during golf putting.

7.2 Discussion of findings and their implications

7.2.1 Response programming function of the QE

The findings in these studies contribute significantly to our knowledge surrounding the QE’s mechanisms and function. The most prominent explanation of the QE is the response programming function, postulating that QE provides a sufficient period for the effective parameterisation of the subsequent movement (Williams et al., 2002). It is during this period when sensory information is synthesised with the mechanisms necessary to both plan (pre-programme) and control (online) the appropriate motor response.

The findings from study 1 and 2 support the response programming function of the QE. When the difficulty of the putting task was increased in study 1, the QE duration also increased to accommodate the processing demands. Furthermore, the QE duration in study 2 was found to increase for hits directly following a miss, in line with compensatory adjustments in processing needed to correct errors (Botvinick et al., 2001). Consistent with previous examinations of the response programming function (Williams et al. 2002; Klostermann et al. 2013; Horn et al. 2012), such findings indicate that QE is accommodating the
response programming requirements imposed by the tasks. Interestingly, it seems that in the studies in which a change in programming was required (study 1-task demands and study 2-error recovery) the early QE proportion is found to increase for experts, demonstrating that programming requirements are placed prior to putting. Together the findings indicate that the primary value of a longer QE duration is the pre-programming function (as proposed by Vickers, 1996). Recent research has focused on the importance of late QE durations for controlling movements online (Vine et al., 2013; Vine et al., 2015) however, these findings refute this idea. It is possible that the mechanisms causing changes in QE in studies 1 and 2 are different to the mechanisms that cause changes to QE in this previous research from Vine and colleagues, which focused on manipulating state anxiety. For instance, Vine et al. (2013, 2015) suggested that anxiety made it more difficult to maintain goal-directed focus (based on the prediction of Eysenck et al.’s (2007) Attentional Control Theory) and that this control was most likely to break down late in the swing, as target related disruptions became most salient. In contrast, during studies 1 and 2 where tasks require a change in programming demands, a pre-programming function is used, reflected by increases in the early QE duration.

Nonetheless, study 2 reveals the late QE was shorter for randomly selected missed compared to hit putts. While this would indicate that the late QE is important for performance, such analysis is missing and not accounting for the functional variability and dependency of performance on previous trials. When this functional variability was examined, the response reprogramming suggested to occur during the early QE duration, aids error recovery.

However, study 3 (exp. 2) reveals that the QE duration does not consistently reflect (in terms of duration) the response programming allocated to
putting. The QE duration was reduced during the dual-visual condition but was maintained in line with baseline during the dual-audio condition, despite the disruptions to response programming (as indexed by subsequent performance disruption for novice golfers). Although reductions in QE during the dual-visual condition result in less response programming, our findings question the reliability of a maintained QE duration to reflect the internal workings of movement programming. QE research often assumes that ‘looking’ equals ‘seeing’. In other words, the point of gaze reflects what is being perceived and attended to. This is a big and, in some cases, flawed assumption considering that looking does not always reflect seeing, as highlighted in this thesis.

Study 3 (exp. 2) demonstrates that, although performers can be looking at the same location (the ball) from one condition to the next, if the path of response programming is blocked by a concurrent task then this fixation does not reflect a QE. The italics reflect the fact that, while this fixation is QE by definition (e.g. location and duration), it is not the QE by function, requiring the conversion of parameters into movement planning and control. This function is often assumed when interpreting a QE duration. However, these findings reveal this might not always be the case. Furthermore, the findings also highlight the issue with the current QE definition not being able to distinguish between the quality of a fixation, specifically the difference between steady gaze and a real QE duration during which functional response programming occurs. However, the key implication for performers is that they should try and ensure that internal monologues do not create a dual-task condition that reduces the availability of resources to the programming enabled by the QE.

The QE seems to be sensitive to the increase in response programming requirements but it should also be functional (Williams et al., 2002). While study
2 demonstrates QE’s functionality, increasing for successful putts, it is not surprising that there was no relationship between QE and performance in study 1, given that performance is more affected by the actual task difficulty rather than the effort to overcome the difficulty. Simply put, if you make a task more difficult, performance is going to decline. Furthermore, it is not possible to unpick this QE-performance relationship because of the opposing influences that longer QE durations and increased task demands have on performance. Study 2 demonstrates that when the confound (task difficulty) associated with trying to make sense of the QE-performance relationship is removed we see that a longer QE is functional, even under increased processing demands (error recovery). However, the tension surrounding the functional benefit of QE under difficult conditions remains. Further research may wish to explore this tension by increasing the task difficulty incrementally over a number of trials. One might expect to find an inverted U point where increases in QE fail to overcome the demands of the task. This may provide a potential way to tease apart the issue concerning the relationship between QE, task demands and superior performance.

Furthermore, the contrast in the QE-performance relationship findings between studies 1 and 2 supports Vickers’ (2016) view that only 100% successful and unsuccessful performance should be used to examine QE’s relationship with performance. The combining of all performance error is suggested to not provide a “true measure of performance accuracy” (Vickers, 2016; p. 12) and, therefore, the chances of seeing a relationship between QE and performance error are reduced (Vickers, 2016). However, performance outcomes do not always reflect the quality of performance. For instance, well executed putts could result in a miss whereas a poorly executed putt could
result in a hit (Mann, 2007). In addition, when examining unsuccessful outcomes, it is unclear whether a performer’s error was a mere fraction or several meters. Furthermore, if there is a strong link between QE and performance, the QE should differentiate performance on a continuous rather than dichotomous level (Williams, 2016). While I believe that radial error was an appropriate measure of performance, particularly when examining differences in response programming, more research is needed to establish the extent to which QE is able to predict levels of performance accuracy.

The findings from study 3 (exp. 2) also reveal some interesting findings in terms of QE’s functionality. For instance, experts were able to maintain performance during the dual-visual condition despite a reduced QE duration, specifically the late QE duration associated with online control. While performance can be explained by the investment of resources into response programming prior to a putt, reflected by the increase in early QE (cf. Cooke et al., 2014; Bablioni et al., 2008), such findings contradict previous research that has found disruptions to late QE and online control negatively affect expert performance (Vine et al., 2013; 2015). These contradictory findings are discussed in more detail in the sections below.

Together, the findings support that QE is sensitive to increases in response programming demands and the early pre-programming proportion of the QE supports this function. However, future research is needed to examine QE’s ability to predict performance on a continuous level.

7.2.2 QE’s relationship with attentional effort and motivation

In line with studies 1 and 2, study 3 (exp. 1) reveals that experienced golfers increase their early QE duration in pursuit of task attainment. However, this increase is despite no imposed changes to the response programming
requirements. The variation in QE seems to occur in line with increased motivation that stems from a change in goal difficulty (easy to moderate goals). The QE responds to manipulations of putt difficulty and motivation, both of which influence attentional effort (Kahneman, 1973; Sarter et al., 2006) yet differ in terms of prospective response programming requirements, demonstrating that QE is influenced by attentional effort. Specifically, I believe that the results indicate QE is influenced by a motivated strategy that is not dependent on task requirements.

As postulated by MIT (Wright, 1996; Richter, 2013), motivation and consequently effort can increase proportionally with the perceived task demands, but the two can also dissociate. While the early QE in study 3 (exp. 1) increased in spite of no additional task programming requirements, it also did not directly follow the goal requirements. The early QE increased from easy to moderate goals with no further increases for the hardest goal, specifically demonstrating the independence of QE from the difficulty of the putting task. Furthermore, although the QE duration demonstrated an error recovery function in study 2, increasing for hits that followed a miss, the QE did not increase for consecutive missed putts. While this is of contrast to the CMH (Botvinick et al., 2001) such findings support the functional relevance of the QE. If golfers increased their QE, putts were re-parameterised in accordance with the error, resulting in successful performance. For trials were golfers didn't increase their QE, putts were missed again.

It would seem that the differences following a missed putt and reason for golfers not lengthening their QE duration might lie in the motivation to recover performance or the ability to maintain attentional effort (inhibit distraction). As discussed in study 2, the attenuated QE on the consecutive miss occurrences
may reflect participants' withdrawal of effort from immediate task goals, in line with the predictions of the MIT (Wright, 1996; Richter, 2013), or a disruption of attentional effort, with anxiety from the miss inducing attentional biases towards the error as a threatening cue.

Although the latter suggestion is in keeping with the QE anxiety literature, it is not fully supported by the findings in study 3 (exp. 2), which demonstrate that disruptions in attentional resources to another task/cue do not influence the QE (dual-audio condition). Nonetheless, such differences could reflect the contrasting effects of self-induced dual-task (negative monologues) versus experimentally induced dual-task (arithmetic). In study 1, it would seem that effort and task demands are increasing proportionally and demands have not reached the threshold where effort (reflected by the QE) has been withdrawn.

Together, the results from studies 1, 2 and 3 (exp. 1) indicate that the allocation of attentional effort influences the QE duration, enabling a period of response programming. Despite this, study 3 (exp. 2) reveals that QE’s relationship with attentional effort is complex. While the findings above indicate that the QE is sensitive to increases in the application of attentional effort, the QE did not respond to certain changes of attentional effort in study 3 (exp. 2). During the visual dual-task condition, where the secondary task created an overt change in attentional effort, the QE was found to reduce. In contrast, during the audio dual-task condition, where the secondary task created a covert, non-visual change in attentional effort requiring no change in gaze, the QE duration was unaffected. As such, it would seem that the QE duration has limited discriminatory power to reflect all covert changes in attentional resource allocation.
However, anxiety, an internal state, does impact the QE duration and the quality/effectiveness of QE’s function (response programming) (e.g. Behan & Wilson, 2008; Nibbeling et al., 2012). Furthermore, the findings from this thesis also show that changes in attentional effort that were not a result of changes in the visual location (task demands, error recovery, motivation) did influence the QE duration and its function. While all instances (i.e. lower motivation and audio dual-task) changed attentional effort, manipulations of goal motivation, error recovery and task demands were motivated applications to either increase or decrease attentional effort to putting, whereas study 3 (exp. 2) was not a motivated withdrawal of effort from putting. Due to golfers completing primary and secondary tasks simultaneously, attention was actively allocated to the secondary task rather than actively withdrawn from putting. Therefore, reductions in attentional effort allocated to putting were inadvertent and not self-driven. The findings therefore indicate that the QE is influenced by the active/motivated allocation of attentional effort but is not sensitive enough (at least with current measures) to reveal covert changes in processing occurring during its duration.

Such findings demonstrate that under the current measurement and non-experimental settings, it would be difficult to assess if such changes had occurred. It seems that there is a risk that QE research will become too assured of the association between gaze and attention and consequently of what the current measures of QE reflect. One way to assess the functionality of a QE duration is to examine neurological activity (discussed in more detail in section 7.4), which is able to reveal covert changes in processing (Ring et al., 2015) and therefore could aid the differentiation between steady gaze and real QE durations.
Overall, the finding that active/motivated allocation of attentional effort influences the QE would seem to be applicable to other research. For instance, Vickers and Williams (2007) found that, under the highest workloads in a biathlon task when maximal effort was being expended, the QE duration was at its longest, indicating that the QE was increased through the exertion of effort. Furthermore, research examining QE and anxiety provides further discussion surrounding my assertion that active/motivated allocation of attentional effort influences the QE.

Although anxiety is found to disrupt attentional resources allocation (Eysenck et al., 2007), it is also found to stimulate attentional effort as an active coping strategy used to compensate for the detrimental effects that anxiety can have (Wilson et al., 2007). Yet the QE is often found to reduce under anxiety (Behan & Wilson, 2008; Nibbeling et al., 2012) which does not coincide with the findings of this thesis that attentional effort influences the QE. However, research has shown that QE does not always decrease under anxiety; in some cases the QE can be maintained (Moore et al., 2012; Vine & Wilson, 2011; Vickers & Williams, 2007) as shown in study 3 (exp. 1). As such, QE’s sensitivity to attentional effort that is shown in this thesis, provides a potential explanation for why QE is sometimes maintained under anxiety. Furthermore, Mann et al. (2016) suggest that QE “may in fact represent the time needed to accommodate the detrimental effects of anxiety/arousal on the recruitment of task specific resources” (p. 3). However, further research is needed to examine whether QE’s sensitivity to anxiety is purely dependent on the allocation of attentional effort.

While the findings in this thesis indicate that QE is only influenced by the active/motivated allocation of attentional effort, previous research indicates that
QE does respond to seeming inadvertent (non-motivated) changes in attentional effort. QE is reduced under anxiety that is suggested to create dual-tasking where attentional resources are inadvertently withdrawn from the task at hand by worrisome thoughts (Wilson, 2012; Ring et al., 2015). Nevertheless, it is possible that QE’s sensitivity to anxiety is not purely a result of covert disruptions in attentional resources through dual-tasking. Rather the maintenance of QE during similar dual-tasking (dual-audio condition) would indicate that under anxiety QE may be responding to overt disruptions in attention allocation towards task-irrelevant stimuli, activated by bottom-up stimuli-driven attentional control. For instance, it is suggested that when anxious the hole becomes salient in putting and therefore attention is directed towards it early (Vine et al., 2013). While this stimulus is still relevant to the task the movement of gaze towards to hole means the QE is cut short and critical information for putting execution is lost. Although it is not clear exactly what information is gathered performance often suffers without it (Vine et al., 2013).

Nonetheless, the finding that QE duration is influenced by the motivated allocation of attentional effort has implications for other research in the field. Similarly to MIT, by evaluating the demands of the current task and the possession of necessary resources or skill, the biopsychosocial model of challenge and threat (BPSM, Blascovich, 2008) suggests performers either adopt a challenge (approach motivation) or threat (avoidance motivation) state depending on the demand-resource balance. When a challenge state is adopted, yielding approach motivation, the QE duration is found to increase due to a challenge state encouraging effective focus of attention (Moore, Vine, Wilson & Freeman, 2012; Moore, Vine, Freeman & Wilson, 2013; Vine et al., 2013). However, due to the similarity in evaluations of task demands and ability
for both the BPSM and MIT, together with the similarity in QE’s responses to challenge and motivation, it is possible that attentional effort may be the mechanism underlying a challenge state. Future research may wish to examine challenge and threat states, the application of attentional effort and the QE together to explore the possibility of attentional effort being the mechanism underlying motivational states.

Furthermore, motivation could also explain previous findings that have been unable to demonstrate increased QE duration with increased task complexity and processing requirements (Wilson & Pearcy, 2009; van Lier et al., 2008). The consistency of the QE duration across increased complexity conditions that is shown in the studies of Wilson and Pearcy (2009) and van Lier et al. (2008) may have been strategic and intentional to avoid wasting effort. Accordingly, research that uses task complexity to assess the response programming function of QE needs to consider the influence of motivation and not just the processing requirements.

Together, this thesis demonstrates that QE’s relationship with attentional effort is not straightforward. While the results indicate that the QE is influenced by the motivated allocation of attentional effort, the QE is not influenced by covert changes in attentional effort. Such findings support the QE as a measure of overt attention control yet question the current sensitivity of QE measures to be able to reveal changes in covert attentional effort.

7.2.3 QE’s relationship with expertise

In common with Vickers (1992) and much of the literature (Lebeau et al., 2016), the QE has proved to reflect a characteristic of expertise. Experienced golfers had significantly longer QE durations than novice golfers across all the relevant studies. It seems that, with experience and through training, experts learn to
strategically direct their gaze control system to maximise relevant information acquisition (via the QE) and support subsequent motor response planning (Wilson et al., 2015). However, this interpretation, like many other similar interpretations of longer QE for experienced performers, is based on the assumption that we know what a longer QE represents. The ability to reduce the allocation of attentional effort and response programming to the task, yet maintain the QE (dual-audio condition), demonstrates that at present it is not possible to identify instances when the predominant interpretation of a longer QE duration for experts is incorrect.

Furthermore, researchers have interpreted a single and longer fixation as efficient (Mann et al., 2007). However, considering that a longer QE is suggested to reflect an increase in attentional resources and response programming, it seems that experts do not strive for efficient task processing but rather err on the side of caution when deciding what is needed to be accurate. This is particularly evident for the early pre-programming proportion of the QE, which is found to increase or be maintained for experts in all studies in this thesis. The suggested increase in task-relevant resource allocation prior to putting is supported by the EEG findings of Cooke et al. (2014) and Bablioni et al. (2008) who indicate that expertise – at least in self-paced tasks – invest more, not less, programming resources (in motor areas of the brain) in the final seconds prior to putting. Specifically, the pattern of high-alpha power activation in Cooke et al.’s study indicates that, upon addressing the ball, experts expend fewer motor resources. Yet the clear reduction in high-alpha power in the final seconds preceding and during the movement reflects experts’ greater mobilisation of programming resources.
Interestingly, study 3 (exp. 2) indicates the efficiency of expert performance. In line with expertise literature that suggests experts require minimal energy expenditure and more efficient brain processes that elicit reduced cortical activity (Haier et al., 1988; Beilock et al., 2002), experts were able to maintain putting accuracy under dual-task conditions. This demonstrates their reduced requirements for online attentional resources compared to novice golfers. Nonetheless, such findings contradict previous research that has found disruptions in online control and late QE negatively affect expert performance (Vine et al., 2015). However, the critical difference between these findings is that performance differences found by Vine et al. were on the basis of an ‘all or none’ approach in terms of visual information and online control. Whereas, in study 3 (exp. 2), although it is difficult to establish the exact allocation of attentional resources, online control was still possible, just to a lesser degree, indicating that ‘less’ is still sufficient. Nonetheless, the QE durations in the dual-audio condition did not reflect this suggested efficiency of performance; the late QE duration did not respond to the reduction in resources allocated to response programming. Although late QE did reduce under dual-visual conditions, the contrast in findings to the dual-audio condition demonstrates that this was not an efficiency response.

Such discrepancy between QE durations and performance efficiency highlights what has recently been termed the efficiency paradox (Mann et al., 2016), which describes the contradictory nature of what a longer QE represents and the suggested neural efficiency of experts. Mann et al. summarises the paradox by posing this rhetorical question, “If efficiency, strictly speaking, enables experts to perform greater, more detailed work in relation to the total energy expended, how then does the QE represent and/or enable efficiency?”
Although a longer QE promotes inertia of the eyeball movement, it is also suggested to reflect greater response programming. However, considering the results from study 3 (exp. 2), two potential factors emerge as explanations for the QE’s efficiency paradox. Firstly, experts’ performance does not seem to be entirely efficient, with the early QE duration being maintained in line with performance, supporting the investment of resources into response programming prior to a putt (Cooke et al., 2014; Bablioni et al., 2008; also see Gallicchio et al., 2017). Second, QE did not respond to the reduction in resources allocated to response programming. As such, without examination of planning and execution efficiency coupled with the assumption that QE reflects processing it is not surprising that a paradox arises.

However, the question still remains why late QE is maintained when experts are able to maintain performance with less of its suggested online control function. I speculate that, due to the internally paced nature of putting and lack of temporal demands, gaze could be maintained on the basis of trial duration as there is no need to move the locus of gaze unless attention is taken away before putt offset, as shown by the dual-visual condition. Nonetheless, it seems that while study 3 demonstrates that experts are able to perform efficiently, it is not something they strive for. Overall, much more research is needed to understand and explain the efficiency paradox, particularly the examination of QE proportions and the response programming functions. Neurological research in golf has primarily examined the pre-programming of movement rather than online control (Mann et al., 2011). Therefore, the examination of QE proportions and temporally matched measures of neural activation relating to movement planning and execution could enable greater insight into performance efficiency and QE durations.
7.3 Practical implications

The findings from study 2 highlight methodological implications for QE research. Typically, when examining performance outcome differences in the QE, participants perform a certain number of successful and unsuccessful trials that are averaged to gain a representation of QE during different outcomes. However, study 2 reveals that this trial selection strategy has the potential to miss significant QE duration differences by assuming trial independence. When the QE duration was examined on a trial-to-trial basis, significant differences were found within and between outcomes. Furthermore, although Vickers (2016) has indicated that studies examining hit vs. miss differences in the QE selected unsuccessful trials that occur either before or after the successful trial, studies including Mann et al. (2011) do not state how putts were selected. As such, this could explain why QE differences are not consistently found.

Consequently, the functional relevance and dependency of trials shown in the findings of study 2 should influence the methods adopted by future research, specifically the trials that are selected to examine the QE during different outcomes.

There are also some applied implications of this thesis. Study 2 highlights the potential role of the QE in aiding performance recovery. Within the actual game of golf the process of error recovery is highly relevant. The findings from study 2 demonstrate that golfers should increase their QE duration following a miss, allowing more time to adjust response programming in line with the error, to ensure that they don’t compound their error and miss again. However, it is unclear whether such effects are applicable to consecutive putts of different lengths in a round of golf, for instance a birdie putt followed by a subsequent putt for par, or for putts with similar parameters on different holes.
Further research could explore the potential influence of QE under different instances of error recovery.

Another applied implication can also be drawn from study 2 and study 1. The QE’s response to more difficult and unsuccessful putts requiring more response programming, demonstrates that golfers should increase their QE for more difficult putts to allow more time for programming. The sensitivity of the early QE to the manipulations of difficulty indicates that golfers should specifically focus on increasing their early QE duration, allowing more pre-programming. By dividing the QE into the early and late QE proportions, as shown throughout the thesis, golf coaches could, with the use of an eye-tracker, provide detailed feedback on which QE proportion is lacking and examine the effect of instruction. While the findings indicate the importance of the early QE proportion on successful putts, successful performance was characterised by the contribution of both proportions in study 2 (under different analysis). However, the findings in this thesis (particularly study 3) also highlight the caution that should be taken when implementing QE training; in some instances, the use of QE as a training tool may not be able to identify any issues with the allocation of covert attention that may explain unsuccessful performance. As such, an additional implication is that novice performers in particular should be advised to try and keep a quiet mind in order to not create a self-generated dual-task condition which can negatively affect performance, even if gaze is kept steady (Wilson et al., 2015). The assessment of brain activity using measures of EEG is able to demonstrate what I am referring to by a quiet mind. A recent EEG study in golf putting by Ring et al. (2015) revealed that brain activity differed under high, compared to low, performance pressure. Under high pressure, a state that is suggested to induce dual-tasking by the
processing of worrisome thoughts (Wilson, 2012), high-alpha power was found to increase. In contrast, under low pressure, high-alpha power was reduced, highlighting the notion of a quiet mind. Yet this notion may seem somewhat counterintuitive given that high-alpha power has an inverse relationship with cortical activity associated with motor programming (Pfurtscheller, 1992). As such, the increases in high-alpha under pressure are suggested to reflect the deviation of resources away from the motor programming.

Furthermore, Ring et al. (2015) also demonstrated that, by using neurofeedback, it is possible to train brain activity, specifically the suppression of theta and high-alpha power. While such training did not aid performance of recreational golfers, such neurological activity is associated with successful putting performance (Cooke et al., 2014; 2015; Babiloni et al., 2008). Therefore, maintaining optimal brain activity, and not dual-tasking (increasing high-alpha) is important. Nonetheless, as highlighted by Ring et al. (2015), it may be the method used to elicit the neurological activity (i.e. the task/tasks) that is critical rather than the activity itself.

Moreover, the fact that QE follows the objective MIT path of effort allocation in study 3 (exp. 1) also has applied implications. It demonstrates that QE is sensitive to psychological factors relating to the perceived chances of success. As such, coaches need to consider the strategic nature of QE by focusing on ensuring golfers perceive putts as a challenge, aiding the optimal allocation of attentional effort and QE, not just the feeling of effort. This seems particularly important during difficult tasks where the chances of success may be reduced. Such implications are supported by studies that have demonstrated that the QE duration is longer when challenge states are adopted (Moore et al., 2012).
7.4 Research limitations and future research

The major limitation of this thesis was that no objective measures of attentional effort or cognitive processing were used to support the interpretation of the QE duration findings. Although the QE findings in study 3 (exp. 1) follow the predicted fluctuations of attentional effort proposed by the MIT (Wright, 1996; Richter, 2013), an objective measure could aid the understanding of QE’s relationship with attentional effort. Future research that wishes to replicate or improve these studies should aim to use an independent measure of attentional effort.

Furthermore, there are limitations in chapter 6, in that the self-report measures of mental effort and anxiety were not measured at the same level of temporal sensitivity as the QE duration and performance measures. QE and performance were measured for each trial whereas self-report measures were only measured at the conclusion of each condition. Particularly during study 3 (exp. 1), measurement after each trial could have enabled us to examine any fluctuations in subjective effort in accordance with the remaining opportunity for goal attainment. For instance, there may have been differences in subjective effort depending on whether or not the goal was still attainable within the number of putts remaining. This would have provided a better representation of the conditions’ subjective effort.

In addition, across the studies presented in this thesis, the number of trials selected for analysis varies. Although the number of trials selected for analysis in each study has a valid rational - including learning effects, availability of specific outcomes and numbers that are in keeping with similar research examining the QE in golf - the impact of varying trial numbers on the
efficacy of the findings relating to QE and performance warrants further investigation.

Overall, the contradicting, and sometimes confusing, findings in this thesis demonstrate that greater precision in our ability to assess the QE is needed in future research. I have identified key areas that I believe need addressing. Firstly, to overcome the limitation above and provide an additional measure to assess the quality of QE (rather than relying on a duration measure) future research needs to gain measures of the QE’s underpinning – attentional effort and, consequently, response programming.

Physiological measures that have been used to assess attentional effort and cognitive processing in sport include heart rate variability (HRV) (Harris et al., 2017), pupillometry (Moran et al., 2016) and neurological activation (Mann et al., 2011). Whilst HRV and pupillometry are frequently used as measures of mental effort they are also sensitive to generic stress, arousal and light (for pupil dilation) (Beatty, 1982; Berntson, et al., 1997), therefore isolating responses to effort even in a controlled laboratory environment is challenging. Furthermore, as demonstrated by Moran et al. (2016) reliably and consistently capturing the pupil data using an eye tracker is also challenging. Moran et al. excluded four out of fifteen participants on the basis of pupil data no reaching the ‘good trial’ criteria denoting that dilation information should be present for at least 75% of the trial duration (Hochmann & Papeo, 2014). Although heart rate variability and pupillometry are more convenient measures for data collection, neurological activation, such as EEG, enables great reliability and time locked precision compared to MRI, which is too slow to provide temporal accuracy with movements.
Moreover, not only could EEG measures enable the assessment of QE quality it could also ease the tension reflected in the proposed efficiency paradox (Mann et al., 2016). Although Mann et al. (2011) has previously examined the QE alongside ERP measures, to the best of my knowledge both have not been examined together since. Furthermore, Mann et al. focused on the neurological preparation of movements, neglecting the possibility of response programming online during the late proportion of QE. As discussed above in section 7.2.3, the examination of neurological activation relating to response programming during both proportions of the QE may explain the contradicting findings surrounding expertise, processing efficiency, and what the QE duration represents.

In terms of examining neurological indicators of attentional resource allocation during the QE, Cooke et al. (2015) provides evidence that high-alpha power (11-13 Hz) is a marker of resource allocation for motor programming. In addition, Ring et al. (2015) indicates that high-alpha power is sensitive to the diversion of attentional resources. As such, examining high-alpha power during the QE would seem an appropriate neurological measure to examine the quality of the QE and the QE proportions.

Future research may also wish to examine theta power (4-7 Hz) activation during the QE, a wave form that is associated with tasks requiring greater goal-directed control and focused attention (Cavanagh & Frank, 2014). However, there is not always a clear consensus of what activation means. For instance, Cooke et al. (2014) interpreted a decrease in theta power for experts as an increase in focused attention (Bakhshayesh, Hansch, Wyschkon, Rezai, & Esser, 2011) in line with high-alpha activation, whereas Baumeister et al. (2008) interpreted an increase in theta power for experts as an increase in
focused attention (Smith, McEvoy, & Gevins, 1999). As such, specific activation patterns during the QE would be open to interpretation.

Second, the findings in this thesis question whether the current definition has enough discriminatory power to reflect all changes in attentional effort and response programming, and the extent to which it can predict performance. At present, the QE is defined as gaze movement within 1° of a visual angle on a target, for a minimum of 100ms. However, gaze is rarely still and fixational eye movements, including microsaccades, are not accounted for in the current definition of QE (see Gonzalez et al., 2015). Microsaccades are found to inhibit perceptual fading (Martinez-Conde et al., 2004) but can also be suppressed during high precision tasks (Winterson & Collewijn, 1976), indicating that they may be influenced by attention allocation (Gowen, Abadi, Poliakov, Hansen, & Miall, 2007). While measurement of such fine-grained eye movements during the QE is required to provide greater insights into its functional role, QE’s definition, and therefore parameters, is constrained by the measurement systems used to assess the phenomenon (e.g. the ASL mobile eye system). As such, advances in mobile eye tracking measurement are required to enable greater sensitivity in both measurement and definition of the QE. Alternatively, future research could explore the use of Electro-OculoGraphy (EOG) previously used by Mann et al. (2011). This eye-tracking technique records eye movements at a higher frequency, aiding the detection of subtle eye movements. Furthermore, in comparison to video based recordings, EOG removes some of the subjectivity in data coding.

Third, I believe future research needs to consider the precision and reliability of QE analysis. Together with analysis software (QE solutions in the case of this thesis) researchers use skill specific coding parameters to analyse
gaze data. The specified definition of a fixation (e.g. minimum duration, degrees of a visual angle) enables the coding of a fixation’s onset and offset, with the analysis software determining the presence of a QE duration relative to the critical movement. Although tracking eye movements is objective and the coding parameters are consistent for a given skill, the process of coding is subjective. While inter- or intra-rater reliability analysis can detect variability in coding, the second rater is typically from within the same institution and agreement is high. Future research may wish to investigate the consistency of coding between researchers in the field of QE. While differences in coding may be slight, overall such differences could change levels of significance and how findings are interpreted.

In addition to improving the precision of assessing the QE, there are other areas that require further investigation. For instance, further research is needed to fully understand the applied implications of study 2. While the findings indicate that increasing the QE following a miss aids performance recovery, at present the error recovery function is only applicable for repetitions of the same putt. It is unclear whether such effects are applicable to consecutive putts in a round of golf that are of different lengths, or for putts with similar parameters, on different holes. Future research may wish to examine whether error recovery is present when the putt following a miss is a different distance (shorter or longer), when the need to recover performance is still present but the response programming requirements have changed. Such investigation may provide a more ecologically valid representation of putting performance and the function of the QE.

Furthermore, while study 3 (exp. 2) provides an indication of the limitations in the QE’s sensitivity, further research is needed to clarify exactly what the QE
is, or is not, responding to. A follow up study could entail creating additional dual-task conditions. The current dual-visual condition encourages participants to shift their gaze towards the projected number. While the consistency of the QE during the dual-audio condition indicates that the reduced QE during the dual-visual condition was due to the shift in gaze, a secondary visual task that does not require eye movements would confirm this assertion. The projected number for multiplication could be projected on and surrounding the ball, for instance. Furthermore, additional conditions are needed to investigate whether the distraction of a secondary task, or its additional task processing, is influencing the QE. Such investigation could be undertaken by golfers performing a dual-task condition that does not require them to provide an answer to the multiplication sum. As such, the presentation of numbers would be purely a visual or audio distraction. Moreover, study 3 only examined the influence of disrupting attentional effort online during the late QE proportion. Disrupting the ability to apply attentional effort during early and late QE would provide a more holistic view of QE’s relationship with attentional effort.

7.5 Final Conclusions

This thesis answers the calls for further investigation of QE’s underlying mechanisms. The series of studies tackles some of the prominent difficult questions surrounding the QE and, while making significant contributions to the QE literature, the findings reveal that many unanswered questions remain. The overriding finding of this research was that, although QE was sensitive to response programming requirements (e.g. putting difficulty; error recovery), the motivated allocation of attentional effort, which enables response programming, is suggested to be the key influencing factors on the QE duration. However, drawing tight conclusions in terms of what QE represents and how it exerts an
influence is difficult. Chapter 6 demonstrates that QE does not always reflect its suggested response programming function and, while findings support the QE as a measure of overt attention, the current measures of QE are not sensitive enough to reflect covert changes in attentional effort. This has implications for how gaze durations can be interpreted and highlight the need for further research to provide clarity and greater understanding surrounding the QE’s function and relationship with performance and expertise.

Overall, I believe that in order for the field to progress, research has to become more precise. Ultimately, if we keep measuring the QE in the same way we will keep getting the same variable, inconclusive results. Future research requires the use of more advanced and accurate eye tracking technology, better QE definitions, more extensive examination of neural correlates and improved consistency of QE analysis.
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doi:10.1080/1750984X.2012.723728


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Appendices
Appendix 1. Informed consent form

SPORT AND HEALTH SCIENCES

College of Life and Environmental Sciences

INFORMED CONSENT

I have read and understood the Information Sheet concerning the study, and all my questions have been answered satisfactory. I understand that I am free to request further information at any stage.

I understand that:

1. My participation in the study is entirely voluntary

2. I am free to withdraw from the project at any time without any disadvantage

3. The data will be destroyed at the conclusion of the project, but any raw data on which the study depend on will be retained in secure storage

4. In the case of publication of collected data my anonymity will be persevered
I give informed consent to participate in this study.

.................................................................

..............................

(Signature)

(Date)

This project has been reviewed and approved by the Ethics Committee of the

School of Sport and Health Science
Appendix 2. Mental effort rating scale

(RSME; Zijlstra, 1993)

Rating Scale Mental Effort

Please indicate, by marking the vertical axis below, how much effort it took for you to complete the task you've just finished.
Appendix 3. The mental Readiness Form

(MRF-3; Krane, 1994)

The 3 questions below are designed to assess your performance state. Please indicate one number on each scale that you feel most closely how you feel RIGHT NOW.

My thoughts are:

- 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10 / 11 /

  CALM WORRIED

My body feels:

- 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10 / 11 /

  RELAXED TENSE

I am feeling:

- 1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10 / 11 /

  CONFIDENT SCARED
Thank you for showing an interest in this study. Please read this information sheet carefully before deciding whether or not to participate.

**What is the aim of the study?**

The purpose of the study is to examine the utilisation of visual information in different conditions of varying difficulty. Visual control is an important feature that characterises highly skilled and accurate performances in putting. The aim of the study is to discover if different task demands effect visual control and putting performance.

**What is involved in the study?**

If you agree to participate you will be asked to attend a single testing session which should last less than 45 minutes. Participants will be required to wear an eye-tracker and must be able to putt without glasses. During testing, you will
undertake in excess of 90 putts. On completion you will be given the opportunity to discuss your performance with the experimenter.

**What types of participants are needed?**

We require experienced golf participants that are in good health and free from any sports or other injuries, which might make it difficult for you to carry out the golf putting. Participants are not required to bring their own putter.

If you decide to participate, we thank you in advance for the time and effort you have decided to devote of our investigation. If you decide not to take part, there will be no disadvantage to you of any kind and we thank you for considering our request.
What is the aim of the study?

The aim of the study is to examine the utilisation and focus of visual attention in highly skilled golfers during a putting task. Optimal visual attention is an important feature that characterise highly skilled and accurate putting performance.

What is involved in the study?

If you agree to participate you will be asked to attend a single testing session which should last approximately 30 minutes. Participants will be required to wear an eye-tracker. During testing, you will undertake approximately 20 putts on a flat putting surface from 10ft. On completion, there will be the opportunity for performance analysis.

Participants

We require highly skilled (single figure handicap) golf participants that are able to putt without glasses. Participants are not required to bring their own putter.
If you decide to participate, we thank you in advance for the time and effort you have decided to devote to our investigation. Participation in the study is entirely voluntary and you are free to withdraw from the project at any time without any disadvantage.

For more information please contact: Rosanna Walters-Symons – Mob: 07976454361, Email: rw321@exeter.ac.uk

SPORT AND HEALTH SCIENCES

College of Life and Environmental Sciences

Mental effort, Goal attainment and Visual Control in Golf Putting

Information sheet for participants

What is the aim of these studies?

The aim of the studies is to examine putting performance in different conditions and understand what factors create good and bad performance through participants wearing some measurement equipment and answering questions.

What is involved in the studies?

If you agree to participate you will be asked to attend a single testing session where you will take part in two studies lasting approximately 60 minutes in total. Participants will be required to wear an eye-tracker. During testing, you will undertake approximately 60 putts on a flat putting surface from 10ft or 5ft. On completion, there will be the opportunity for performance analysis.

Participants

We require highly skilled (single figure handicap) and novice (no experience) golf participants that are able to putt right handed and without glasses or contact lenses. Participants are not required to bring their own putter.
If you decide to participate, we thank you in advance for the time and effort you have decided to devote to our investigation. Participation in the study is entirely voluntary and you are free to withdraw from the project at any time without any disadvantage.

For more information please contact: Rosanna Walters-Symons – Mob: 07976454361, Email: rw321@exeter.ac.uk

University of Exeter

Richard’s Building, St Luke’s Campus, Heavitree Road, Exeter, EX1 2LU, UK
## Appendix 7. Number of trials selected, Mean and Standard Deviation per participant.

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Appendix 8. Selected and presented numbers for the secondary arithmetic task (study 3 – exp. 2)

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