# Manuscript Details


| | |
|---|---|
| **Manuscript number** | HMS_2019_678_R2 |
| **Title** | Pupillometry: an examination of the allocation of attention in the planning and motor performance of a golf putt. A preliminary investigation. |
| **Article type** | Registered Report Stage 2: Full Article |



**Abstract**

The present study assessed the potential value of using pupillometry to explore skill level differences in the allocation of attention during planning and performance of a golf putt across three putting conditions of varying complexity. Although numerous studies have reported on skill level differences in performers' visual search behaviours, performance accuracy and quiet eye duration (QE) across a range of performance settings, few have provided an objective measure of the allocation of attention during task performance. Fourteen participants were assigned to two groups [low handicap (LHG) and high handicap (HHG)] completing ten putts in three conditions; right to left (RL), left to right (LR) and straight (ST) from 1.75m while wearing a mobile eye tracker. Skill based differences in the allocation of attention during green exploration and skill execution were observed. Pupil constriction observed for both groups during the QE period provides evidence of increased workload directly related to the increased motor task precision required in the physical performance of the putt. LHG had significantly more fixations of longer duration than their HHG counterparts. Distinct differences were also evident between skill levels in relation to number of fixations, fixation duration and QE duration on each putting condition. The significantly longer QE duration and larger pupil constrictions exhibited by skilled performers offer evidence of a distinctive concentration of cognitive activity characterised by highly automated processes.



| | |
|---|---|
| **Keywords** | pupillometry, cognitive effort, visual perception, eye-tracking |



| | |
|---|---|
| **Corresponding Author** | Evelyn Carnegie |
| **Corresponding Author's Institution** | Edge Hill University |
| **Order of Authors** | Evelyn Carnegie, David Marchant, Sam Towers, Paul Ellison |
| **Suggested reviewers** | Mark Campbell, Aidan Moran |


## Submission Files Included in this PDF

**File Name [File Type]**

HMS Response for Reviewers Final D2.docx [Response to Reviewers]

Abstract.docx [Abstract]

G4 Manuscript File -R3.docx [Manuscript File]

Figure 1.docx [Figure]

Figure 2.docx [Figure]

Table 1.docx [Table]

CRediT author statement.docx [Author Statement]

Professor Mark Williams
Editor in Chief,
Human Movement Science

Dear Professor Williams

Attached is a copy of the manuscript Ref: HMS_2019_678_R1 which is now titled "*Beyond visual fixations and gaze behaviour. Using pupillometry to examine the mechanisms in the planning and motor performance of a golf putt*". This title has been revised from the original title "Pupillometry: an examination of the allocation of attention in the planning and motor performance of a golf putt. A preliminary investigation." in accordance with suggestions made by the reviewers. This is a second revision of the manuscript that has adhered to minor revisions suggested by the reviewers.

Once again, my co-authors and I would like to thank yourself and the reviewers for your professional handling of our manuscript and, for deeming the paper acceptable for publication once suitable minor revisions have been addressed. We feel the review process has added much value to the paper and have sought to respond positively to the reviewer's comments throughout. Once again to facilitate your evaluation of the second revision of the manuscript we have also directed you to the exact place in the manuscript where the revision can be located. We have also highlighted additions and changes to the manuscript in red text in the new main document.

Finally, thank you once again for this opportunity. If you require any further information, please let us know. We look forward to hearing from you.

Yours sincerely

Dr Evelyn Carnegie

## Human Movement Science

| | Reviewer 1 Comments: | Response: | Location |
|---|---|---|---|
| | **Specific Comments** | | New Line after changes |
| 1 | Precision and complexity.<br><br>My previous comment did not question the need for precision in golf putting. It questioned the fact that requirements on precision were not manipulated despite that the model presented in the Introduction is based on the manipulation of both complexity and precision. The need to manipulate both complexity and precision to evaluate this model should be addressed in the limitations and future directions section. | *Thank you, we have now acknowledged the need for future research to consider manipulation of both complexity and precision to provide a more comprehensive examination of the allocation of attention during motor performance.* | 669-671 |
| 2 | Inhibition.<br><br>I do not see how these findings support the inhibition hypothesis. The authors stated that longer QE duration and larger pupil constrictions "(...) offer evidence of this distinctive concentration of cognitive activity at the point immediately prior to skill execution (...)" (L658-659). First, why would pupil constriction reflect greater inhibition and not any other cognitive process that has nothing to do with inhibition? | *Reflecting further on the question of inhibition we agree with the observation made and have removed reference to pupil constrictions* (L658-659). *This sentence has been amended to read 'The significantly longer QE duration exhibited by the LHG during the QE period in this study offers additional evidence of this distinctive concentration of cognitive activity at the point immediately prior to skill execution characterised by highly automated processes'.* | 656-659 |
| | Second, the authors have misinterpreted their QE measure as reflecting only the period prior to skill execution. However, as they have also acknowledged in their response letter, their measure of QE mixes the phases before and after movement execution. | *Apologies for not rectifying this oversight in our resubmission. Whilst we did provide clarification in our previous response that the QE measure used in this study related to total QE duration and not different phases of movement, we neglected to adjust our description in the text. This has now been rectified.*<br><br>*Sentence has been amended to read: 'The QE for golf putting was* | 325-326 |

| | | | |
|---|---|---|---|
| | | *defined by Vickers (2007) as the final fixation toward the ball'.* | |
| | **Reviewer 2 Comments:** | **Response:** | |
| | **Specific Comments** | | |
| 1 | I like the new title too and think this works much better for the manuscript. | *Thanks for confirming that the proposed title better reflected the nature of the work. The paper title has now been amended to:*<br><br>*'Beyond visual fixations and gaze behaviour. Using pupillometry to examine the mechanisms in the planning and motor performance of a golf putt'* | 1-2 |

**Abstract**

The present study assessed the potential value of using pupillometry to explore skill level differences in the allocation of attention during planning and performance of a golf putt across three putting conditions of varying complexity. Although numerous studies have reported on skill level differences in performers' visual search behaviours, performance accuracy and quiet eye duration (QE) across a range of performance settings, few have provided an objective measure of the allocation of attention during task performance. Fourteen participants were assigned to two groups [low handicap (LHG) and high handicap (HHG)] completing ten putts in three conditions; right to left (RL), left to right (LR) and straight (ST) from 1.75m while wearing a mobile eye tracker. Skill based differences in the allocation of attention during green exploration and skill execution were observed. Pupil constriction observed for both groups during the QE period provides evidence of increased workload directly related to the increased motor task precision required in the physical performance of the putt. LHG had significantly more fixations of longer duration than their HHG counterparts. Distinct differences were also evident between skill levels in relation to number of fixations, fixation duration and QE duration on each putting condition. The significantly longer QE duration and larger pupil constrictions exhibited by skilled performers offer evidence of a distinctive concentration of cognitive activity characterised by highly automated processes.

**Key Words:** pupillometry, cognitive effort, visual perception, eye-tracking

# Beyond visual fixations and gaze behaviour. Using pupillometry to examine the mechanisms in the planning and motor performance of a golf putt.

**Abstract**

The present study assessed the potential value of using pupillometry to explore skill level differences in the allocation of attention during planning and performance of a golf putt across three putting conditions of varying complexity. Although numerous studies have reported on skill level differences in performers' visual search behaviours, performance accuracy and quiet eye duration (QE) across a range of performance settings, few have provided an objective measure of the allocation of attention during task performance. Fourteen participants were assigned to two groups [low handicap (LHG) and high handicap (HHG)] completing ten putts in three conditions; right to left (RL), left to right (LR) and straight (ST) from 1.75m while wearing a mobile eye tracker. Skill based differences in the allocation of attention during green exploration and skill execution were observed. Pupil constriction observed for both groups during the QE period provides evidence of increased workload directly related to the increased motor task precision required in the physical performance of the putt. LHG had significantly more fixations of longer duration than their HHG counterparts. Distinct differences were also evident between skill levels in relation to number of fixations, fixation duration and QE duration on each putting condition. The significantly longer QE duration and larger pupil constrictions exhibited by skilled performers offer evidence of a distinctive concentration of cognitive activity characterised by highly automated processes.

**Key Words:** pupillometry, cognitive effort, visual perception, eye-tracking

## Introduction

Perception action research in the sport domain has seen an increased focus on empirical research related to gaining an in-depth understanding of visual search strategies and processes employed by performers across a range of sports performance contexts utilising varied eye tracking systems. Sports related research employing eye tracking technology dates back more than forty years to research on gaze behaviour in basketball by Bard and Fluery (1976). Since this early work, an extensive body of research exists exploring expert-novice differences in varying aspects of gaze behaviour during performance. More specifically, expert-novice differences in the allocation of attention during performance of a range of motor control tasks has received much attention (see Discombe & Cotterill, 2015 for a review). With specific reference to the task of golf putting, the early work by Vickers (1992) demonstrated that low-handicap golfers were found to display a visual search strategy which allocated a larger proportion of fixations to the ball and target which were of longer duration than those allocated to the club and surface, in contrast with the high-handicap performers.

Subsequent research has typically supported the general consensus that expert performers employ different visual search strategies than their novice counterparts. Higher skill level performers have displayed visual search behaviour that involved fewer fixations of longer duration compared to less skilled performers in task specific self-paced aiming tasks such as basketball free throw and pistol shooting (Vickers, 1996b; Lee, Kim, & Park, 2009) and video-based anticipation tasks in soccer, volleyball, and golf putting (Canal-Bruland, Lotz, Hagemann, Schorer & Strauss, 2011; Piras, Pierantozzi, & Squtrito, 2014; Campbell & Moran, 2014).

The differences observed in perceptual-cognitive skills measured by analysis of visual search strategies are considered to provide an index of performers allocation of attention during task performance, (Mann, Williams, Ward & Janelle, 2007). More specifically, the underlying assumption of researchers has been that fixations of longer duration are viewed as indicative of the amount of information that is being extracted and the number and placement of those fixations indicative of the principle information sources informing the decision-making process, (Mann, et al., 2007). Using a simulated green reading task, Campbell & Moran (2014) concluded that in contrast to novice performers, skilled performers had fewer fixations in three of the six viewing positions, and fixation duration for two of the six viewing positions increased among the skilled group. The authors interpreted these findings as evidence that 'expert golfers display distinctive periods of visual cognitive activity while inspecting aspects of the golf putt', p 370. They also considered this finding as providing further evidence in support of Vickers (1992) conclusion that more highly skilled golfers employed a search strategy which involved fewer gaze combinations to specified areas of interest in the task environment in combination with longer fixation durations than their less skilled counter parts on a golf putting task. Such findings, the authors conclude, offer further evidence of an economy of visual search patterns displayed by expert performers when planning movements.

In contrast, however, experts were found to have more fixations of shorter duration than novices in tasks involving reading of medical images and assessment of video-based simulations of soccer game situations (Litchfield, Ball, Donovan, Manning & Crawford, 2008 and Roca, Ford, McRobert, & Williams, 2013). These contrasting findings may in part, as suggested by Mann et al. (2007), be explained by the differing nature of the type of task involved, the research paradigm utilised, the method of stimulus presentation, and a reliance on a different perception-action coupling, as a result of task simulation, rather than physical performance.

When task complexity was increased within offensive simulations in soccer play, Vaeyens, Lenoir, Williams, Mazyn, & Philippaerts (2007a, 2007b) found that in more complex sets, players were found to employ a higher number of fixations of shorter duration. Similarly, Roca et al. (2013) found that skilled soccer players employed different visual search strategies dependent upon task constraints. Skilled players had more fixations of shorter duration toward more locations in the visual display on the far compared to the near viewing condition. Less skilled players tended to spend longer periods of time focusing on player in possession or ball flight in both viewing conditions.

Attempts to understand further the gaze behaviour aspects of task performance, particularly in relation to motor preparation, have focused on the period defined by Vickers (1996a) as *Quiet Eye* (QE). This is defined as the final fixation that is located on a specific target or object within 3° of visual angle for at least 100ms before movement initiation (Vickers 1996a). The QE period has been accepted as the time-period when task-relevant cues are processed helping to refine and guide motor response execution, (Vickers, 1996b). Extensive research has focused on this concept leading to QE emerging as a key predictor of skilled performance in targeting and interceptive tasks, (Walter-Symons, Wilson & Vine 2017). Research has shown experts to have longer QE durations than novice performers across a variety of tasks such as shooting (Janelle, et al. 2000; Causer, Bennett, Holmes, Janelle & Williams, 2010), darts (Rienhoff, et al. 2013), billiards (Williams, Singer & Frehlich, 2002), table tennis (Rodrigues, Vickers & Williams, 2002) and football (Piras & Vickers, 2011).

However, whilst this growing research base appears to offer consistency of research findings, there is a paucity of research to explain the underlying cognitive mechanisms of QE as highlighted by Gonzalez et al. (2015). As emphasised by Frank

& Schack (2016), to date the theoretical explanations proposed to describe the mechanisms of QE can be categorised as either cognitive or ecological approaches. Within the cognitive domain, aligned to Vickers (1996a) location-suppression hypothesis, the programming hypothesis considers QE as the period of time for the programming and fine tuning of a response (Vickers, 2009). Supporting this hypothesis, Williams et al. (2002) found increases in QE duration in line with increases in task complexity with longer QE durations observed on successful as opposed to unsuccessful shots irrespective of the performers skill level.

Adopting an ecological approach Oudejans, van de Langenber & Hutter, (2002), suggested the possibility of continued detection of visual information throughout the final stages of movement execution countering the suppression aspect of the location-suppression hypothesis. Using a temporal occlusion paradigm, Oudejans et al found that basketball shooting percentage with late-vision shooting was similar to shooting percentages when full vision was available. This, they suggest, implies that the QE period might not be critical when movements are controlled using the continuous detection and use of visual information during the final phase of task execution. Similarly, Causer, Hayes, Hooper & Bennett (2017) found that on a golf putting task the period defined as 'pre-programming duration' (starting at QE onset and ending at backswing initiation) was significantly longer during the occlusion condition whereas the components defined as 'dwell duration' (starting at the point of contract of the putter on the ball and ending with gaze deviation of 1°) and 'on-line duration' (starting at the initiation of the backswing and ending when the putter contacted the ball or gaze deviated by 1°) were significantly longer during the full vision condition. They concluded that whilst pre-programming increased when vision was occluded this was not sufficient to compensate for the need for online visual control which they state as critical to performance.

Addressing specifically the question of the underlying cognitive mechanisms of QE, Moran et al. (2016) employed the use of pupillometry as a means of providing an objective measure of the role of attentional effort in QE. This study used 11 show jumping athletes categorised by three skill levels, expert, intermediate and novice. Study findings indicated that pupil dilation increased during QE, however, inconsistencies were noted in relation to skill level differences. The authors highlighted the small n value in each skill category (n = 4 in novice and intermediate groups and n = 3 in expert group) as contributing to the observed pupillary differences between expert and novice performers.

Whilst some degree of caution should be applied to the application of finding from the above study, the use of pupillometry in studies of this nature is worthy of further consideration. The validity of pupillometry as an accurate measure of increases in cognitive effort (mental activity), has been long established (Hess & Polt, 1964; Kahneman & Beatty, 1966). Pupillometry has been found to be an objective measure of the online allocation of attention during performance and thus, as a mechanism by which cognitive processing can be better understood (Laeng, Sirois & Gredeäck, 2012; Alnæs, et al. 2014; Eckstein, Guerra-Carrilo, Miller Singley & Bunge, 2017). The changes in pupil diameter are considered to provide an objective measure of the processing demands of a cognitive task. There currently remains a lack of consensus in regarding the direction of pupillary change reflecting these increased processing demands. For example increased pupil dilation has been shown to reflect increased processing demands (Alnæs et al, 2014; Moran et al, 2016). Changes in pupil diameter during physical performance on a power grip task were shown to track the invested level of effort regardless of whether that effort was physical or mental. (Zénon, Sidibé & Olivier, 2014). This, the authors conclude, supports the use of pupillometry as valid measure of effort across a range of tasks.

In contrast, Fletcher, Neal and Yeo (2017) indicated that decreases in pupil dilation (constriction), particularly in tasks of motor precision, should be interpreted as indicative of increases rather than decreases in workload. Using a Fitts' Law movement task, which enabled motor response precision to be manipulated in low-precision, medium-precision, and high-precision conditions, changes in pupil diameter were assessed. The study found that 'increased task precision appeared to cause a decrease in pupil diameter in the period between response planning and response execution of a discrete movement task', p 314. As such, pupil diameter characteristics may respond differently depending upon the cognitive and motor characteristics of a task. Following this line of reasoning it would, therefore, be reasonable to assume that on tasks, such as golf putting, requiring a high level of motor precision, pupil dilation during QE would decrease in accordance with the degree of precision required for task completion. Such characteristics are predicted to be evident in highly skilled (automated) athletes performing accuracy tasks such as golf putting, target shooting darts and archery.

To date, research aimed at understanding the cognitive processes underpinning skilled motor performance, has tended to focus on either visual search behaviour as assessed through analysis of visual fixations, duration and location of fixations or the concept defined by Vickers (1996a) as QE. As highlighted by Campbell & Moran (2014), future research should seek to combine these analyses in an effort to provide a more detailed assessment of a complete perception-action cycle. In an effort to better understand the underpinning mechanisms of QE, Campbell et al. (2019) used task-evoked pupillary response measurement to assess cognitive load during QE on a golf putting task. The study did not find any differences between the low handicap group (LHG) and high handicap group (HHG) in relation to cognitive effort, pupillary dilation and QE durations with increased task difficulty (putt distances 1.83m and 3.66m). The authors did however, acknowledge the potential lack of distinction in task difficulty as an area for consideration in future studies. Nonetheless, the increased pupillary dilation (from baseline) noted on both putting distances was concluded to provide evidence of the cognitive demands of the task and the allocation of cognitive effect during performance preparation and execution, regardless of performer's skill level.

Whilst acknowledging the contrasting interpretations of pupil dilation vs. pupil constriction as an indication of processing demands, as highlighted above, the present study sought to assess the potential value of using pupillometry to explore skill level differences in planning, visual perception and execution of a golf putting task. Across varying putting conditions, and different from typical laboratory putting tasks, participants were challenged in terms of putting angle and force selection by 'single break' or 'double break' green environments. Specifically, the study aimed to add further to existing literature by using task-evoked pupillary response measures to investigate the interaction between visual search behaviour as a measure of the decision-making process, QE as an indicator of motor preparation, performance outcome and cognitive effort required during skill exploration and execution. This approach aims to provide a richer understanding of cognitive load during performance and task execution. The combining of these standard indices of visual search behaviour within a single study offers a preliminary insight into the potential links between previously reported gaze behaviours during planning and task execution phases of a self-paced motor task. To date research has tended to focus on specific phases rather than employ a whole process approach. This study provides an initial insight into the interplay of previously reported findings relating to visual search patterns, QE and cognitive demands (assessed using pupillometry) on a golf putting task.

In keeping with current literature, this study employed an *in situ* design which is considered to more clearly demonstrate the impact of skill level in perceptual performance (Mann, et al. 2007). Based on previous research, the following hypothesis were formed: *Hypothesis 1*: skilled golfers (LHG) would display a significantly greater level of performance accuracy on each of the three putt conditions. *Hypothesis 2*: LHG would display fewer fixations of longer duration (as per Vickers, 1996b; Lee, Kim, & Park, 2009; Canal-Bruland, Lotz, Hagemann, Schorer & Strauss, 2011; Piras, Pierantozzi, & Squtrito, 2014; Campbell & Moran, 2014), most notably on putting conditions of increased complexity. *Hypothesis 3*: LHG would display significantly different patterns of gaze behaviour (areas of interest viewed) compared to novice performers across the varying putting conditions (Vickers, 1992; Campbell and Moran, 2014). *Hypothesis 4:* more difficult putts [Left to Right (LR) and Right to Left (RL)] would require more cognitive effort as evidenced through changes in pupil diameter during both the QE period and throughout skill execution (Alnæs et al, 2014; Moran et al, 2016). *Hypothesis 5*: LHG would have significantly longer QE duration on each putt condition (Janelle, et al. 2000; Causer, Bennett, Holmes, Janelle & Williams, 2010; Rienhoff, et al. 2013; Williams, Singer & Frehlich, 2002; Rodrigues, Vickers & Williams, 2002; Piras & Vickers, 2011).

## Method

### *Participants*

Fourteen participants (11 males and 3 females) of two different golf ability levels volunteered to take part in the study. Adopting similar procedures to Campbell et al. (2018) participants were assigned to either the low handicap group (LHG) (n=7, mean age 26.3 yr, SD 9.9) with a single figure handicap ranging from +1 to 9 (mean =5.57, SD = 2.64) or a high handicap group (HHG) (n=7, mean age 27.4 yr, SD 10.1) with a handicap of 10+ (mean = 17.29, SD = 3.86). Power analysis using G*Power (3.1.9.4) (Faul, Erdfelder, Lang & Buchner, 2007) indicated that based on a small to moderate effect size of $\eta_p^2 = 0.31$ (based on data from Campbell et al., 2019 given the similarity of task and performance setting) fourteen participants was considered sufficient to achieve power of 0.8 in an F test, given α 0.05. This sample size is also in keeping with sample sizes generally found in pupillometry based studies of between 10 to 22 participants as reported by O'Shea & Moran (2018). The partial eta squared values generated for between group differences were used to generate effect size f values to subsequently calculate statistical power. This power analysis identified that the sample size (n = 14) was sufficient for this study. Participants were provided with written information about the study and all provided written informed consent. Experimental procedures were approved by a university ethics committee. On completion of the putting task participants were fully briefed on the purpose of the study.

**The Putting Task**

Artificial putting greens (birdieball, UK) were used to create three different putting conditions via the placement of 'wedges' under sections of each putting mat to create varying slope conditions (right to left (RL), left to right (LR) and straight (ST). The RL and LR putts added an element of 'break' to the putt, as a consequence of the added slope, which increased task complexity through the requirements for the golfer to make a judgement on the 'pace' of the putt to ensure the ball followed the chosen putt line and the 'abstract and ill-defined' nature of the target given the added dimension of 'break', (Wilson & Moran, 2009). For right handed golfers, McLean (2013) postulates that the most difficult putt is one breaking left to right. The selected putts therefore, provide varying degrees of complexity with the ST putt the easiest and the LR putt the hardest. Participants putted regular-sized (4.27 cm diameter) white golf balls from 1.75 m to a regulation hole (10.8 cm diameter) using their own golf putter. Participants were instructed to follow their normal putting routine in reading the green, lining up and taking their putt. For consistency gaze analysis for each putt began a consistent five seconds prior to the backswing and ended when the ball left the club face. No time limits were placed on the participants in performing the task. Similar to the simulated task used by Campbell & Moran (2014), participants had to make a perceptual judgement as to how the varying slope conditions would affect the line of travel of the ball towards to hole. However, unlike the simulated task used in the Campbell & Moran study, participants in this study, having engaged in the green-reading task, lined up and physically engaged in striking the putt towards the target hole.

### ***Measures***

#### *Performance Outcome*

For each participant, the performance outcome of each putt was recorded using a simple success (holed putt), miss (putt not holed) coding system. This system was chosen to reflect the accuracy of golf scoring whereby performance is assessed on total number of shots taken from tee to holed putt. The use of a scoring system of 1 for a holed putt and 0 for a missed putt is consistent with that used by Campbell et al. (2019).

#### *Visual Search Behaviour*

The Tobii Glasses 2™ mobile eye tracking system was used to measure and record gaze behaviour at sampling rate of 50Hz. This binocular tracking system captures gaze location, using corneal reflection and dark pupil techniques utilising near-infrared illumination to generate reflection patterns on the cornea and pupil. The scene camera captures the participant's view of the environment (with a field of view 82 deg. horizontal/48 deg. vertical) and images of the eyes and corneal reflection patterns are captured via a series of eye tracking sensors in each lens. These captured images are used to identify participants point of gaze within the recorded scene image. The wearable head unit is connected to a small recording unit, using a HDMI cable, which stores captured data on an SD card for processing at a later stage using Tobii Pro Lab Analyser™ software. The recording unit is controlled remotely via a tablet running Tobii Glasses Controller™ software.

Tobii Pro Lab Analyser™ software (v1.86) was used to identify participants' visual search behaviour identified through point of gaze throughout performance and task execution phases of the putting tasks. The software enables captured data to be analysed producing a series of metrics for further analysis. Following analysis of all participants trials, individual participant output reports were created with this data prepared for further analysis.

Measures of search behaviour were examined, namely, the mean number of fixations per trial, the mean duration of each fixation (in milliseconds), the mean number of fixations to a specified area of interest (AOI) and the mean duration of fixations to each AOI (in milliseconds). The specified AOI were ball, hole, centre portion of green, right side of green and left side of green.

*Quiet Eye Duration*

The QE for golf putting was defined by Vickers (2007) as the final fixation toward the ball. Using the parameters defined by Vickers, (2007) and Wilson, Vine & Wood (2009), QE onset was recorded as the commencement of the final fixation before initiation of the backswing with QE offset recorded when gaze deviated from the ball by more than 1° visual angle for more than 100 ms (Vine, Lee, Wlaters-Symons & Wilson, 2015). Videos captured using the Tobii Glasses Controller™ software were analysed using the Tobii Pro Lab Analyser™ software (v1.86) using the timeline tools feature to identify and define QE onset and QE offset, as defined above, for each participant trial. This data was then exported to Excel to enable the calculation of QE duration.

*Pupil Dilation*

Mean pupil diameter (mm) was calculated using the pupil dilation scores from participants left and right eye for each fixation and QE period on each performance trial for each of the three putting conditions. In line with the procedures adopted by Hochmann & Papeo (2014) and Moran et al. (2016), trials where pupil dilation data was available for a minimum of 75% of total trial duration were included in data analysis. Where these conditions where not meet two participants were excluded from the study (one HHG and one LHG). For trials retained for further analysis, missing data were replaced using the linear interpolation process reported by Porter et al. (2007) and also utilised by Campbell et al (2016). This process uses valid pupil diameter scores on either side, filling the gap with composite scores. This process was used to replace less than 3% of the total data set. Adopting a similar approach to Campbell et al. (2019) mean pupil diameter during initial calibration served as baseline pupil diameter. To account for individual differences in absolute pupil diameter between participants, percentage change score from baseline was used to control for this variability (Moran et al., 2016; Mathot et al., 2018). Therefore, changes in pupil diameter, including those during QE, are reported relative to baseline pupil diameter (Moran et al. 2016).

***Procedure***

Participants attended a single testing session and after reviewing written information about the study, each provided written informed consent. A Tobii Glasses 2™ mobile eye tracking system was fitted on the participant and an initial calibration using the Tobii calibration card (1-point system) was conducted. Final calibration was conducted using a nine-point calibration system which involved participants directing gaze to each of the nine points within the scene prior to beginning the familiarisation phase. Eye tracking calibration was performed prior to each putting condition and repeated as necessary. Prior to performance for each putt condition participants completed 10 familiarisation putts. Participants then completed 10 putts towards the target hole for each putting condition, right to left (RL), left to right (LR) and straight (ST), in a random order, with a 1-minute rest between trial blocks. To control for unwanted pupil dilation effects the ambient light in the room was kept constant throughout all testing procedures and carefully monitored using a Lux light meter (CEM DT-1300, Shenzhen, China). Following completion of the task, participants were thanked for their time, debriefed on the purpose of the study and offered an opportunity to discuss their performance with the experimenter.

***Data Analysis***

The six dependent variables of outcome accuracy, number of fixations, fixation duration, QE duration, changes in mean pupil diameter from baseline throughout performance and changes in mean pupil diameter from baseline during the QE period were analysed separately using 2 x 3 mixed-model ANOVA. Participant skill level (LHG, HHG) was the between-participant factor and putting slope condition (RL, ST, LR) were the within-participant factors.

Separate three-way mixed ANOVA was used to investigate the effects of skill level (LHG, HHG), putting slope condition (RL, ST, LR) and AOI location (Ball, Hole, Centre, Right, Left) on AOI fixation count and percentage viewing time to each AOI location. Skill level (LHG, HHG) was the between-participant factor and putting slope condition (RL, ST, LR) and fixation location (ball, hole, centre, right, left) as within-participant factors. For any repeated measures ANOVA, violations of the sphericity assumption were corrected using Greenhouse-Geisser procedures. Effect sizes were reported as partial eta squared ($\eta_p^2$). Significant main and interaction effects were followed up using Bonferroni corrected pairwise comparisons and Tukey's HSD post hoc tests, the alpha level was set at $p < .05$.

**Results**

***Performance Outcome***

Using a 2 (participant skill level) x 3 (putting condition) mixed-model ANOVA there was no significant skill level X condition interaction for performance outcome, $F^{(1, 24)} = 2.323$, $p = 0.143$, $\eta_p^2 = .162$. There was a significant main effect of skill level for performance outcome which showed HHG (mean and SD) were poorer performers compared to LHG (mean and SD), $F\,(^{1,\,12}) = 9.749$, $p = 0.009$, $\eta_p^2 = .448$. The means of 'performance outcome' scores for RL, ST and LR were (*M* = 43.57, *SE* = 7.24, *M* = 44.57, *SE* = 6.57 and M = 29.55, *SE* = 9.03) for LHG and (*M* = 4.28, *SE* = 7.24, *M* = 27.14, *SE* = 6.57 and *M* = 20, *SE* = 9.03) for HHG, respectively. Performance outcome for the RL putting condition was associated with a mean score 11.93 (95% CI, 1.55 to

22.1) points lower than outcome for the ST putting condition, a statistically significant difference, $p = .05$.

### *Visual Search Behaviour*

### *Fixation Count*

ANOVA revealed a significant interaction between putting condition and skill level on fixation count, $F(^{2, 266}) = 5.770$, $p = 0.01$, $\eta_p^2 = .043$. There was a statistically significant difference in fixation count between skill levels on the RL putting condition $F(^{1, 133}) = 13.347$, $p = 0.001$, $\eta_p^2 = .090$ and LR putting condition $F(^{1, 133}) = 33.734$, $p = 0.001$, $\eta_p^2 = .150$, (Figure 1). There was no statistically significant difference in fixation count between skill levels on the ST putting condition $F(^{1, 133}) = 0.779$, $p = .379$, $\eta_p^2 = 0.006$. There was no statistically significant effect of putting condition on fixation count for the HHG $F(^{1, 133}) = 0.850$, $p = .430$, $\eta_p^2 = .012$. There was a statistically significant effect of putting condition on fixation count for the LHG $F(^{1, 133}) = 0.850$, $p$  0.001, $\eta_p^2 = .160$. LHG had significantly more fixations for the RL ($M$ = 19.212, SD 0.730) and LR ($M$ = 19.303, SE 0.779) than the ST putting condition ($M$ = 15.864, SE 0.854). *Figure 1 near here*

### *Fixation Duration*

ANOVA revealed a significant interaction between putting condition and skill level on fixation duration, $F(^{2, 266}) = 11.968$, $p = 0.001$, $\eta_p^2 = .083$. There was a statistically significant difference in fixation duration between skill levels on the RL putting condition $F(^{1, 133}) = 48.215$, $p$  0.001, $\eta_p^2 = .263$, on the ST putting condition $F(^{1, 133}) = 65.319$, $p = 0.001$, $\eta_p^2 = .323$ and on the LR putting condition, $F(^{1, 133}) = 18.278$, $p = 0.001$, $\eta_p^2 = .120$, (Figure 1). There was no statistically significant effect of putting condition on fixation duration for the HHG $F(^{1, 133}) = 1.145$, $p = 0.315$, $\eta_p^2 = .017$. There was a statistically significant effect of putting condition on fixation duration for the LHG $F(^{1, 133}) = 12.248$, $p = 0.001$, $\eta_p^2 = .159$. LHG had significantly shorter fixation durations for the RL (*M* = 457.983, SE 17.359) and LR (*M* = 444.251, SE 22.036) than the ST putting condition (*M* = 562.209, SE 29.115).

***Fixation Count to AOI***

ANOVA revealed a statistically significant three-way interaction between putting condition, skill level and fixation count to AOI, $F(^{8, 1064}) = 3.635$, $p = 0.001$, $\eta_p^2$ = .0.27, (Table 1). There was a statistically significant simple two-way interaction between putting condition and fixation count to AOI for both HHG, $F(^{8, 544}) = 58.282$, $p = 0.001$, $\eta_p^2 = .462$ and LHG, $F(^{8, 520}) = 66.516$, $p = 0.001$, ηp 2 = .506. There was a statistically significant simple main effect of condition for both HHG, $F(^{4, 272}) = 45.578$, $p = 0.001$ and LHG $F(^{4, 268}) = 65.331$, $p = 0.001$ on fixation count on the RL putting condition. Data are mean ± standard deviation unless otherwise stated. For each skill level all simple pairwise comparisons were run between different putting slope conditions and fixation locations (ball, hole, centre, right, left). For both HHG and LHG the greatest number of fixations on each putting slope condition was on the ball. For HHG performers there was a statistically significant mean difference between number of fixations on the ball and number of fixations on hole, centre, right and left AOI, between the hole and the right and left AOI, between the centre and right and left AOI and between the right and left AOI across all three putting slope conditions $p$ = 0.001. For LHG there was a statistically significant mean difference between number of fixations on the ball and number of fixations on hole, centre, right and left AOI, between the hole and the right and left AOI and between the centre and left AOI across all three putting slope conditions, $p$ = 0.001. *Table 1 near here*

***Percentage Viewing Time to AOI***

ANOVA revealed a statistically significant three-way interaction between putting condition, skill level and percentage viewing time on fixation location, $F(^{8, 96}) =$ 2.582, $p$ = 0.013, partial $\eta_p{}^2$ = .177. There was a statistically significant simple two-way interaction between putting condition and fixation location for both HHG, $F(^{8, 48}) =$ 5.001, $p$ = 0.001, $\eta_p{}^2$ = .455 and LHG, $F(^{8, 48})$ = 3.951, $p$ = 0.001, $\eta_p{}^2$ = .397. There was a statistically significant simple main effect of condition for both HHG, $F(^{2, 12}) =$ 23.724, $p$ = 0.001 and LHG $F(^{2, 12})$ = 8.198, $p$ = 0.006 on percentage viewing time to the left of the green. For HHG the percentage time fixated on the left portion of the green was 25.05 ± 5.48 on LR putting slope condition, 6.70 ± 5.87 on the RL putting slope condition and 14.30 ± 5.14 on the ST putting condition. There was a statistically significant mean difference between the LR and RL putting conditions of 18.35 (95% CI, 9.24 to 27.46) ms, $p$ = 0.002 and the LR and ST putting conditions of 10.74 (95% CI, 2.30 to 19.19) ms, $p$ = 0.017, but not between the RL and ST putting conditions, 7.61 (95% CI, 1.23 to 16.44) ms, $p$ = 0.090. For LHG the percentage time fixated on the left portion of the green was 16.13 ± 5.40 on LR putting slope condition, 5.99 ± 6.85 on the RL putting slope condition and 6.65 ± 3.51 on the ST putting condition. There was a statistically significant mean difference between the LR and ST putting conditions of 9.48 (95% CI, 2.52 to 16.45) ms, $p$ = 0.013, but not between the RL and ST putting conditions, 0.65 (95% CI, 9.48 to 10.97) ms, $p$ = 0.095 or the RL and LR putting conditions, 10.14 (95% CI, 0.02 to 10.14) ms, $p$ = 0.05. All other simple main effect of condition and percentage viewing time to specified fixation locations were not significant, $p = 0.05$.

### *QE Duration*

The interaction effect between skill level and QE Duration was not statistically significant, $F\,(^{2,\,248}) = 1.783$, $p = 0.174$, $\eta_p^2 = .014$, (Figure 2). The main effect of putting condition showed a statistically significant difference in QE duration, $F(^{2,\,248}) = 7.853$, $p = 0.001$, $\eta_p^2 = .060$ between putting conditions. QE durations on the RL ($M$ = 2135.472, SE 80.194) were significantly longer than on the ST ($M$ = 1832.156, SE 63.025) and the LR condition ($M$ = 2022.539, SE 81.784). The main effect of skill level showed a statistically significant difference in QE duration, $F(^{1,\,124}) = 17.288$, $p = 0.001$, $\eta_p^2 = .122$. LHG revealed significantly longer QE durations ($M$ = 2249.717, SE 83.977) than HHG ($M$ = 1743.728, SE 88.075). *Figure 2 near here*

### *Change in Pupil Dilation*

There was no statistically significant interaction between skill level and putting condition on changes in mean pupil dilation from baseline, $F(^{2,\,266}) = 0.285$, $p = 0.752$, $\eta_p^2 = .002$. ANOVA revealed that the main effect of skill level showed a statistically significant difference in the percentage change in mean pupil diameter from baseline, $F(^{1,\,133}) = 5.653$, $p = 0.019$, $\eta_p^2 = 0.041$ between LHG and HHG. Data are mean ± standard error, unless otherwise stated. The marginal means for changes in pupil diameter from baseline were -2.548 ± 0.484 for LHG and -4.160 ± 0.474 for HHG, a statistically significant mean difference of 1.611 (95% CI, 0.271 to 2.952), $p = 0.019$, (Figure 2).

***Change Pupil Dilation during QE***

There was no statistically significant interaction between skill level and putting condition on changes in mean pupil dilation from baseline during the QE period, $F(^{2, 248}) = 2.470$, $p = 0.094$, $\eta_p^2 = .020$. The main effect of putting condition was not statistically significant, $F(^{2, 248}) = 1.595$, $p = 0.205$, $\eta_p^2 = .013$. Similarly the main effect of skill level was not statistically significant, $F(^{1, 124}) = 1.258$, $p = 0.264$, partial $\eta^2 = .010$, (Figure 2).

## Discussion

Adopting a novel approach, this study combined standard indices of visual search behaviour, namely, number and duration of visual fixations with assessment of QE, cognitive effort throughout skill execution as assessed using pupillometry and location of visual fixations and performance outcome. Using pupillometry the broad aim of the study was to assess the potential value of this measure to better understand the interaction between each of these variables and their relationship with skilled performance and task complexity in an effort to provide a richer understanding of cognitive load during performance and task execution. Results demonstrated differences in cognitive processes, as evidenced by differences in the number of fixations, fixation duration, QE duration and pupillary constrictions as a function of skill level and task complexity.

Based on the research findings outlined previously we predicted that skilled performers (LHG) would display a significantly greater level of performance accuracy across the three putting conditions which would be underpinned with significantly fewer visual fixations of longer duration, significantly longer QE duration and significantly different patterns of gaze behaviour compared to less skilled performers (HHG) across the three putt conditions. Differences in cognitive effort, as assessed via changes in pupillary dilations, between putt conditions were also predicted for both groups. A significant main effect of skill level on performance accuracy confirmed that LHG had significantly greater performance accuracy than HHG on the RL slope condition. Although not found to be statistically significant the LHG also had a greater number of successful putts on the ST and LR putting conditions. Hypothesis 1 was not supported. It should be noted, however, that whilst not statistically significant the LHG were consistently more accurate than the HHG across all putting conditions.

For the cognitive aspects of the task as assessed by visual search behaviour there was a significant interaction between skill level and putting condition and number and duration of visual fixations. LHG displayed significantly more fixations on both the RL and LR conditions which were significantly shorter in duration to those of HHG rejecting Hypothesis 2. These findings are contrary to those of Campbell and Moran (2014) who found that lesser skilled performers had more fixations of shorter duration than the more skilled performers on their simulated golf putting task. Similarly, higher skill level performers were found to display visual search behaviour that involved fewer fixations of longer duration compared to less skilled performers in sports such as soccer, volleyball, (Vickers, 1996; Lee et al., 2009).

Studies by Piras et al., (2014) and Canal-Bruland et al., (2011) employed the use of simulated activities having participants view video-clips of the sport skill (basketball and shooting respectively) rather than undertake physical performance of the task. This approach may have impacted on visual search rates of performers who were placed in passive situations of viewing video simulations rather than physically conducting movement within a more natural dynamic sporting environment. Whilst previous literature does not present an agreed position on expectations in this area, the findings of this study support those of Litchfield et al. (2008) and Roca et al. (2013) who reported experts to have more fixations of shorter duration than novices when identifying novel task-relevant information. Similarly, the observed increased number of fixations of shorter duration when task complexity was increased offers further support to the findings of Vaeyens et al. (2007a, 2007b). The conflicting findings between studies employing in situ versus simulated tasks needs to be acknowledged when attempting to interpret study findings.

The initial analysis of general visual search behaviour in this study offers preliminary evidence of the adoption of different visual search behaviours by skilled performers dependent on their perception of task complexity, in this case the need to explore more fully the green to identify the correct putting line on the RL and LR putting conditions. Such findings might be considered to offer preliminary support for Williams and Burwitz (1993) suggestion that expert performers seek the areas of the display which offer the most information to assist in extraction of task-relevant cues. Considered alongside Mann et al's observation that the nature by which testing is conducted has been shown to impact on fixation durations the findings of this study suggest a need for future research to examine further visual search behaviour using an in-situ approach to better understand the decision-making processes at play during complex task performance.

Further exploration of visual search behaviours through analysis of data relating to fixation count and percentage viewing time of these fixations to specified areas of interest on the green, again provided some contrasting findings to those of Campbell and Moran (2014). Of notable interest is that both groups dedicated the greatest number of fixations and percentage viewing time on the ball followed by focus on the hole in each putting condition. These findings revealed statistically significant differences in the number of fixations to specified AOI for both groups on each of the putting conditions. Furthermore, significant differences in the percentage viewing time to specified AOI were identified for HHG on the LR compared to RL and ST putting slope conditions and for LHG on the LR compared to ST putting condition. In each of these cases the differences were associated with the percentage time focused on the left portion of the green.

In relation to these conditions for both groups the pattern of visual search behaviour remained consistent between the RL and ST putting conditions with the most notable differences evident between skill levels on the LR putting condition with an increased percentage viewing time to the left portion of the green. However, on the LR putting condition there was a significant increase in the number and duration of fixations to the left portion of the green for both groups. In contrast, whilst there was some increase in focus towards the right portion of the green on the RL condition these increases were not found to be significant. Taken together these findings are considered to offer further support that there are distinct differences in visual search strategies between golfers' dependent upon skill level supporting Hypothesis 3. HHG typically spend less time focused on the ball and instead focus more on each of the other AOI compared to LHG. We consider these findings to suggest that LHG are more efficient in their analysis of the putt, that is, LHG are quicker to extract task relevant cues from AOI enabling more time for movement programming as confirmed by their significantly longer QE durations (Williams, 2002).

We also explored changes in pupillometry as a mechanism to gauge the on-line allocation of attention during green exploration and skill execution. (Laeng et al. 2012; Alnæs et al. 2014; Eckstein et al. 2017). Given the complexity of this measure and the task in general, analysis focused firstly on skill level differences from baseline, in pupil diameter throughout the completion of the golf putting task as an initial indication of shifts in cognitive effort throughout performance. Results indicated that LHG displayed a significantly lower percentage change in pupil dilation than the HHG during task performance. These findings suggest that the LHG demonstrated greater efficiency in the allocation of cognitive effort during task performance which is interpreted as further indication of their greater control in allocating cognitive resources to task relevant information. For both groups, the percentage change from baseline indicated a reduction in pupil diameter i.e. pupil constriction rather than increased dilation, for each putting condition. These results are seen as offering further support to the suggestion of Fletcher, Neal & Yeo (2017), that in motor tasks of increased precision demands, pupil constriction rather than dilation may be observed and should '*be interpreted as indicating an increase, rather than a decrease, in workload'* p.314.

Following this line of enquiry further, analysis of percentage changes in pupil diameter from baseline during the period defined by Vickers (1992a) as QE, showed no significant skill level differences across each of the putting conditions. However, whilst both groups were found to have pupil constriction during the QE period, LHG displayed more consistent percentage changes in mean pupil diameter from baseline compared to HHG. These findings are at odds with those of Moran et al (2016) who concluded that longer QE periods were associated with increases in pupil dilation which they interpreted as providing evidence of attentional effort during the QE period. Such contrasting findings are perhaps not surprising given, as previously noted, the differing nature of the task, simulated vs. performance. Results of this study are however, in line with those of Fletcher et al (2017) which concluded that decreases in pupil diameter should be interpreted as an indication of increases rather than decreases in workload particularly in tasks with increased motor task precision and high levels of automaticity.

Whilst these findings support hypothesis 4, they also add further to the debate on the precise interpretation of pupil dilation vs pupil constriction in different performance contexts and as such offer a line of enquiry worthy of further exploration.

When coupled with data relating to QE durations which showed experts to have significantly longer QE durations on each putting condition (supporting Hypothesis 5), our findings add further to the early suggestions by Vickers (1996), that the QE period represents a time period when task-relevant cues are processed and motor plans are coordinated for successful completion. Offering a cognitive theoretical explanation for this, Vickers (2009), suggested that the longer QE duration of expert groups reflected the time required to cognitively process visual information picked up '*in order for the complex neural systems underlying control of the limbs to be assembled and activated'*, p283. The longer QE durations displayed by both groups on the RL and LR putting conditions support Williams et al (2002) finding that QE duration increased in line with increases in task complexity. Findings of this study also indicate that pupil constriction demonstrates other dynamic processes during this perceptual phase of action preparation.

As reported by Laeng, Sirois & Gredeäck (2012) pupillometry has been used within psychology research for more than 50 years and can be used to provide '*clues about the real-time structuring of cognitive processing*' p 24. Although statistical significance was not observed in relation to changes in pupil dilation during the QE period, we consider the greater pupil constriction of the skilled performers, observed in this study during the QE period, as indicative of the use of more automated motor processes. This may reflect the suppression of irrelevant neural activity thereby reflecting reduced cognitive load during this period, Fletcher et al. (2017). Indeed, as an indicator of global neural activation, Just, Carpenter & Miyake, (2003) and Fletcher et al. (2017) suggest a reduction in pupil diameter in motor preparation may well reflect the neural and neuromuscular quieting associated with expert motor preference of precision tasks (e.g., Vine et al., 2011, Cooke, et al., 2014).

Such findings are considered to offer further support for the *inhibition hypothesis* proposed by Klostermann, Kredel and Hossner (2014), which suggests that the longer QE durations reflect '*the need for inhibiting alternative movement variants so that only the optimal variant gets parameterized (in movement preparation as well as during movement execution)*', p 398. The significantly longer QE duration exhibited by the LHG during the QE period in this study offers additional evidence of this distinctive concentration of cognitive activity at the point immediately prior to skill execution characterised by highly automated processes. This is in keeping with Vickers' (2009) proposal that the longer QE duration of experts is indicative of the time required to programme and fine tune a movement before execution.

Whilst the present study reports skill levels differences in the allocation of cognitive effort during task performance it fails to provide a specific analysis of when shifts in cognitive effort happen throughout the performance. Future studies should look to overcome this limitation by assessing pupillary changes for each fixation in a time ordered manner to gain an in-depth insight into the mechanisms underpinning the control of visual information in the planning, visual perception and execution of movement. Furthermore, future studies should also give greater consideration to the manipulation of task complexity and precision to enable more comprehensive examination of the allocation of attention during task performance.

In conclusion, the present study provides evidence of skill level variances in the adoption of different visual search behaviours dependent on visual perception of task complexity, resulting in skilled performers having more fixations of shorter duration, differences in fixation count and percentage viewing time to specified AOI and significantly longer QE durations than their less skilled counterparts. In contrast to the findings of Moran et al (2016), who concluded that increased pupil dilation during the QE period provided evidence of attentional effort, the findings of this study, suggest that the observed pupil constriction of both skill level groups during the QE period provides evidence of increased cognitive effort directly related to the increased motor task precision required in the physical performance of this putting task. The greater level of consistency displayed by skilled performers across putting conditions is considered to be representative of increased automaticity of motor processes. Further research is required to develop a greater understanding of the underlying mechanisms of visual perception throughout task performance. Such an insight can be provided through analysis of pupillometry changes throughout task performance which would help provide a greater level of understanding of visual cognitive activity which could be used for performance enhancement through more focused and informative instruction. Whilst attempts were made within this study to mimic the unevenness of the putting green, future research should also consider the use of natural outdoor settings to improve further the ecological validity and transferability of research findings to performance settings.

**References**

Alnæs, D., Sneve, M.H., Espeseth, T., Endestad, T., van de Pavert, S.H.P., and Laeng, B. (2014). Pupil size signals mental effort deployed during multiple object tracking and predicts brain activity in the dorsal attention network and locus coeruleus. *Journal of Vision, 14,* (4), 1-20.

Bard, C., and Fleury, M. (1976). Analysis of visual search activity during sport problem situations. *Journal of Human Movement Studies 3*, 214–222.

Campbell, M.J. and Moran, A. (2014). There is more to green reading than meets the eye! Exploring the gaze behaviours of expert golfers on a virtual golf putting task. *Cognitive Processes*, *15*, 363-372.

Campbell, M.J., Moran, A.P., Bargary, N., Surmon, S., Bressan, L. and Kenny, I.C. (2019). Pupillometry during golf putting: A new window on the cognitive mechanisms underlying quiet eye. *Sport, Exercise, and Performance Psychology. 8*(1), 53-62. doi: 10.1037/spy0000148

Cañal-Bruland, R., Lotz, S., Hagemann, N., Schorer, J., and Strauss, B. (2011). Visual span and change detection in soccer: an expertise study. *Journal of Cognitive Psychology*, *23*, 302–310.

Causer, J., Bennett, S.J., Holmes, P.S., Janelle, C.M. and Williams, A.M., (2010). Quiet eye duration and gun motion in elite shotgun shooting. *Medicine and Science in Sports and Exercise, 42*(8):1599–1608.

Causer J, Hayes SJ, Hooper JM, Bennett SJ (2016) Quiet eye facilitates sensorimotor preprogramming and online control of precision aiming in golf putting. *Cognitive Process*. doi:10.1007/s10339-016-0783-4

Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., McIntyre, D. and Ring. C. (2014). Preparation for action: psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology, 51*(4). 374-384.

Discombe, R. M., & Cotterill, S. T. (2015). Eye tracking in sport: A guide for new and aspiring researchers. *Sport & Exercise Psychology Review, 11,* 49–58.

Eckstein, M.K., Guerra-Carrilo, B., Miller Singley, A.T., and Bunge, S.A., (2017). Beyond eye gaze: What else can eyetracking reveal about cognition and cognitive development? *Developmental Cognitive Neuroscience*, *25*, 69-91.

Faul, F., Erdfelder, E., Lang, A.G., and Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behaviour, and biomedical sciences. *Behavior Research Methods, 39*(2), 175-191

Fletcher, K., Neal, A., and Yeo, G. (2017). The effect of motor task precision on pupil diameter. *Applied Ergonomics*, *65*, 309-315.

Frank, C., and Schack, T. (2016). In my mind's (quiet) eye: a perceptual-cognitive approach to the Quiet Eye – comment on Vickers. *Current Issues in Sport Science,1:107.* doi: 10.15203/CISS_2016.107

Gonzalez, C. C., Causer, J., Miall, R. C., Grey, M. J., Humphreys, G., and Williams, A. M. (2015). Identifying the causal mechanisms of the quiet eye. *European Journal of Sport Science*, *17*, 74-84.

Hess, E.H., and Polt, J.M. (1964). Pupil size in relation to mental activity during simple problem-solving. *Science, 143,* 1190-1192

Hochmann, J.R. and Papeo, L. (2014). The invariance problem in infancy: A pupillometry study. *Psychological Science*, *25*, 2038-2046.

Janelle, C.M., Hillman, C.H., Apparies, R.J., Murray, N.P., Meili, L., Fallon, E.A. and Hatefield, B.D., (2000). Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport & Exercise Psychology, 22,* 167-182.

Just, M.A., Carpenter, P.A., and Miyake A. (2003). Neuroindices of cognitive workload: Neuroimaging, pupillometric and event-related potential studies of brain work. *Theoretical Issues Ergonomics Science, 4*, 56-88.

Kahnemann, D., and Beatty, J. (1966). Pupil diameter and load on memory. *Science, 154,* 1583-1585

Klostermann, A., Kredel, R., and Hossner, E. J. (2014). On the interaction of attentional focus and gaze: The quiet eye inhibits focus-related performance decrements. *Journal of Sport & Exercise Psychology*, *36*, 392– 400.

Laeng, B., Sirois, S., and Gredebäck, G. (2012). Pupillometry: A window to the preconscious? *Perspectives on Psychological Science*, *7*, 18–27.

Lee, S.-M., Kim, S., and Park, S. H. (2009). Self-paced sport events under temporal constraints: visual search, quiet eye, expertise and constrained performance time in far aiming tasks. *International Journal of Applied Sports Science, 21*, 146–161.

Litchfield, D., Ball, L. J., Donovan, T., Manning, D.J., Crawford, T. (2008) Learning from others: effects of viewing another person's eye movements while searching for chest nodules. In B. Sahiner, & D.J. Manning (Eds.), *SPIE (2008). Proceedings of Medical imaging 2008: image perception, observer performance, and technology assessment*, (Vol 6917. pp. 691715–691719).

Mann, D. T., Williams, A. M., Ward, P. and Janelle, C. M., (2007). Perceptual-Cognitive Expertise in Sport: A Meta-Analysis, *Journal of Sport & Exercise Psychology*, *29*(4), 457-478.

McLean, J. (2013, August 12). Why you never make this putt. *Golf Digest.* Retrieved from http://www.golfdigest.com

Moran, A., Quinn, A., Campbell, M., Rooney, B., Brady, N., and Burke, C. (2016). Using pupillometry to evaluate attentional effort in quiet eye: A preliminary investigation. *Sport, Exercise, and Performance Psychology*, *5*(4), 365-376.

O'Shea, H. and Moran, A. (2018). To go or not to go? Pupillometry elucidates inhibitory mechanisms in motor imagery. *Journal of Cognitive Psychology, 30*(4), 466-483.

Oudejans, R. R. D., van de Langenberg, R. W., & Hutter, R. I. (2002). Aiming at a far target under different viewing conditions: Visual control in basketball jump shooting. *Human Movement Science*, *21*, 457–480.

Piras, A., Lobietti, R., and Squatrito, S. (2014). Response time, visual search strategy, and anticipatory skills in volleyball players. *Journal of Ophthalmology*, Article ID: 189268.

Piras, A., & Vickers, J. N. (2011). The effect of fixation transitions on quiet eye duration and performance in the soccer penalty kick: Instep versus inside kicks. *Cognitive Processing*, *12*(3), 245–255.

Porter, G., Troscianko, T., and Gilchrist, I. (2007). Effort during visual search and counting: Insights from pupillometry. *Quarterly Journal of Experimental Psychology, 60*(2), 211–229.

Rienhoff, R., Hopwood, M.J., Fischer, L., Strauss B., Baker, J. and Schorer, J. (2013). Transfer of motor and perceptual skills from basketball to darts. *Frontiers in Psychology, 4*: 593.

Roca, A., Ford, P.R., McRobert, A.P., and Williams, M. (2013). Perceptual-Cognitive skills and their interaction as a function of task constraints in soccer. *Journal of Sport & Exercise Psychology*, *35*, 144-155.

Rodrigues, S. T., Vickers, J. N., & Williams, A. M. (2002). Head, eye and arm coordination in table tennis. *Journal of Sports Sciences*, *20* (3), 187–200.

Vaeyens, R., Lenoir, M., Williams, A.M., Mazyn, L. and Philippaerts, R.M. (2007a). The effects of task constraints on visual search behaviour and decision-making skill in youth soccer players. *Journal of Sport & Exercise Psychology, 29*, 147-169.

Vaeyens, R., Lenoir, M., Williams, A.M., Mazyn, L. and Philippaerts, R.M. (2007b). Mechanisms underpinning successful decision making in skilled youth soccer players: An analysis of visual search behaviors. *Journal of Motor Behavior*, *39*, 395-408.

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

Vickers, J. (1996a). Visual control when aiming at a far target. *Journal of Experimental Psychology Human Perception Performance, 22*, 342-354.

Vickers, J. (1996b). Control of visual attention during the basketball free throw. *The American Journal of Sports Medicine, 24*(6), S93-S96.

Vickers, J. (2007). *Perception, cognition, and decision training: The quiet eye in action*. Champaign: Human Kinetics.

Vickers, J. (2009). Recent advances in coupling perception and action: The quiet eye as a bidirectional link between gase, focus of attention and action. In M. Raab, J. Johnson, & H. Heekeren (Eds.), *Mind and motion: The bidirectional link between thought and action* (pp 279-289). Amsterdam, the Netherlands: Elsevier.

Vine, S.J., Lee, D.H., Wlaters-Symons, R and Wilson, M.R. (2015). An occlusion paradigm to assess the importance of the timing of the quiet eye fixation. *European Journal of Sport Science*, *25*, 1-8.

Vine, S.J., Moore, L.J. and Wilson, M.R. (2011) Quiet eye training facilitates competitive putting performance in elite golfers. *Frontiers in Psychology, 2*: 8.

Vine, S. J., Moore, L. J., & Wilson, M. R. (2014). Quiet eye training: The acquisition, refinement and resilient performance of targeting skills. [Supplemental material 1]. *European Journal of Sport Science*, *14*, S235–S242.

Walters-Symons, R.M., Wilson, M.R. and Vine, S.J (2017). The quiet eye supports error recovery in golf putting. *Psychology of Sport and Exercise, 31*, 21-27.

Williams, A.M., and Burwitz, K. (1993). Advance cure utilization in soccer. In T. Reilly, J. Clarys, & A. Stibbe (eds). *Science and Football,* vol. III. London: E & F.N. Spon.

Williams, A., Singer, R. and Frehlich, S. (2002). Quiet eye duration, expertise, and task complexity in near and far aiming tasks. *Journal of Motor Behaviour*, *34*(2). 197-207.

Wilson, M.R. and Pearcy, C. (2009). Visuomotor control of straight and breaking golf putts. *Perceptual and Motor Skills, 109*, 555-562.

Wilson, M.R., Vine, S.J. and Wood, G. (2009). The influence of anxiety on visual attentional control in basketball free throw shooting. *Journal of Sport & Exercise Psychology, 31*(2). 152–168.

Zénon, A., Sidibé, M. and Olivier, E. (2014). Pupil size variations correlate with physical effort perception. *Frontiers in Behavioral Neuroscience, 8,* Article 28

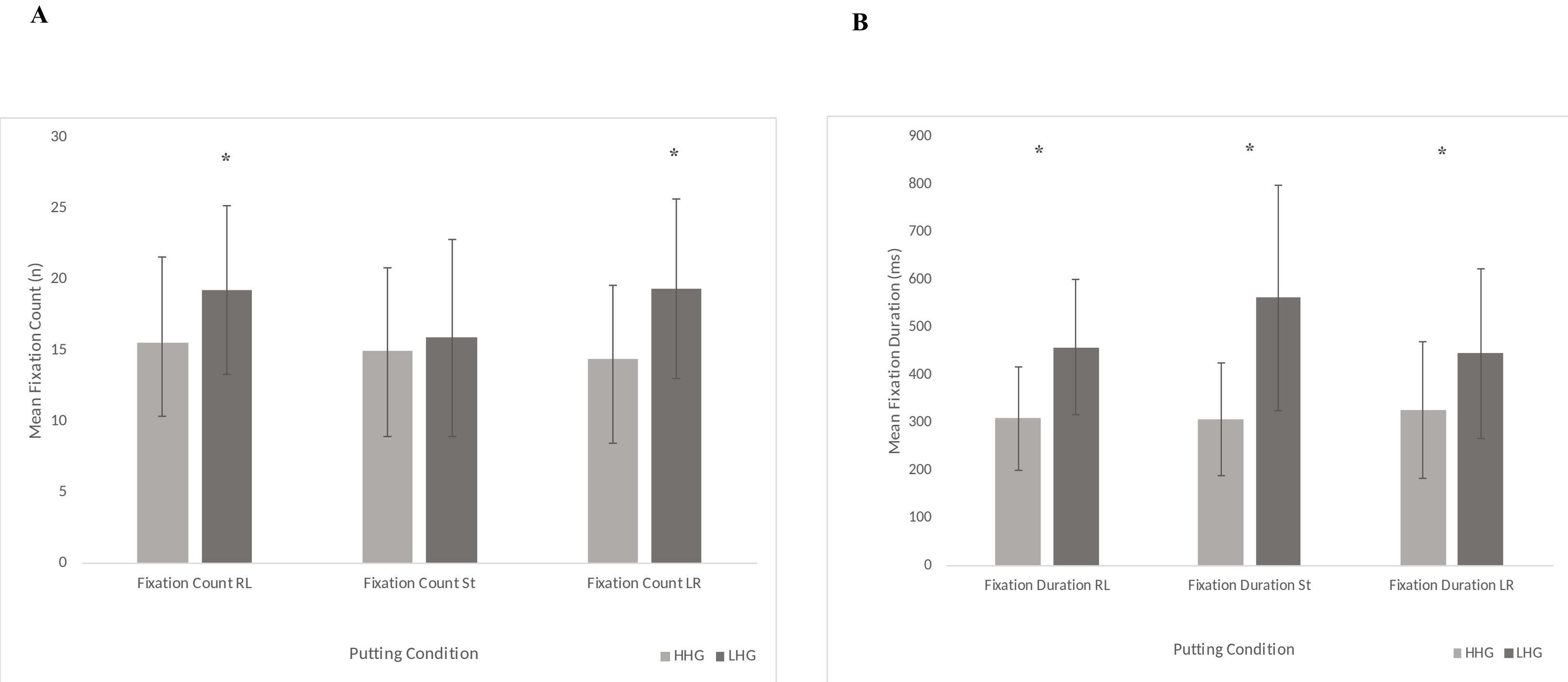
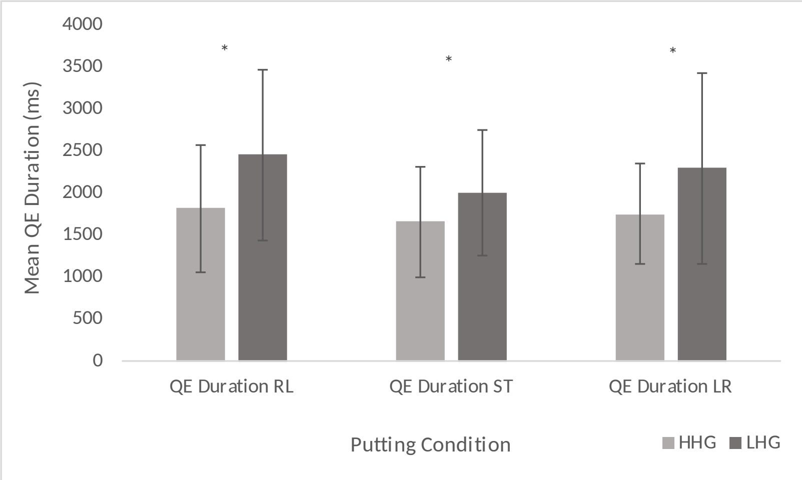
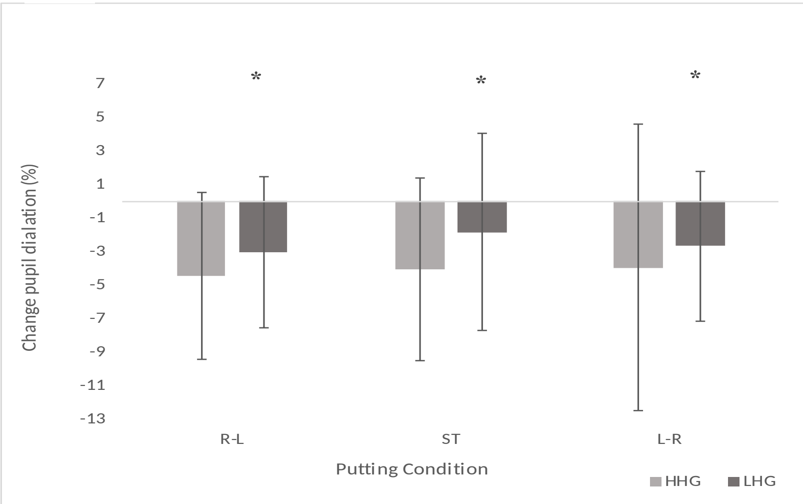



**Figure 1 (A)** Mean and SD fixation count. **(B)** Mean and SD fixation duration. *$p$ <0.05

**A**




**B**




**C**

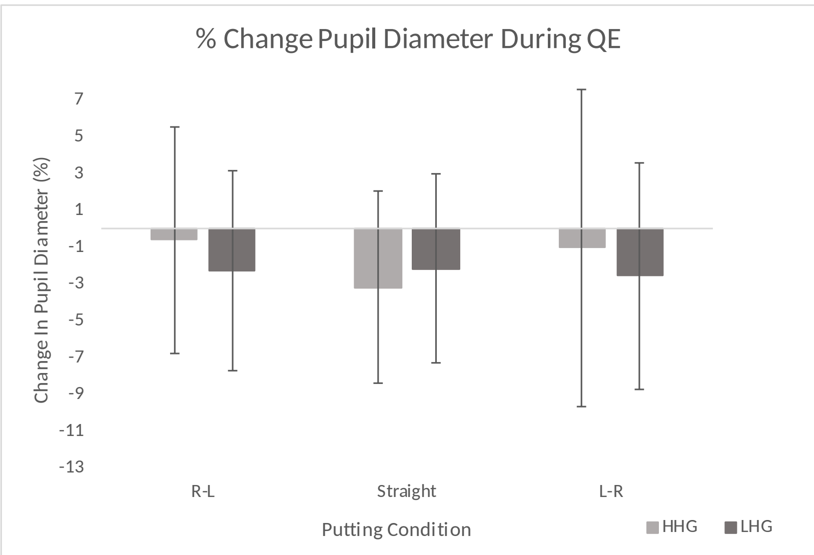



**Figure 2** **(A)** Mean and SD QE duration. **(B)** % Change in pupil dilation and SD. **(C)** % Change in pupil dilation during QE and SD. *$p < 0.05$

Table 1 Mean (SD) Number of Fixations to AOI across putting conditions

| **AOI Location** | **HHG** | | | **LHG** | | |
|---|---|---|---|---|---|---|
| | RL | St | LR | RL | St | LR |
| Ball | 6 (4.19) | 5.32 (3.61) | 5.33 (2.82) | 6.68 (2.95) | 6.27 (3.92) | 7.14 (3.46) |
| Hole | 2.92 (2.34) | 2.94 (1.96) | 1.74 (1.54) | 4.03 (3.01) | 2.97 (2.35) | 2.56 (2.25) |
| Centre | 2.96 (1.93) | 3.61 (2.97) | 1.33 (2.06) | 3.00 (2.43) | 2.79 (2.21) | 2.56 (2.39) |
| Right | 1.59 (1.96) | 0.51 (0.92) | 0.14 (0.43) | 1.38 (1.88) | 0.44 (0.91) | 0.32 (0.88) |
| Left | 0.57 (1.29) | 1.45 (1.68) | 4.38 (2.67) | 0.80 (1.23) | 0.98 (1.52) | 3.82 (2.98) |

CRediT author statement

**Evelyn Carnegie**: conceptualization, methodology, formal analysis, writing original draft, supervision; **David Marchant**, writing reviewing and Editing, formal analysis; **Sam Towers**, Investigation; **Paul Ellison**, conceptualization, writing reviewing and Editing, supervision