A critical analysis of the functional parameters of the quiet eye using immersive virtual reality

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Funding – DH was supported by a Royal Academy of Engineering UKIC Fellowship.

Acknowledgements – The authors would like to thank Connor Burns, Josh O'Hara, Megan Walters and Eden Theodore for help with data collection.

Conflict of interest – The authors declare no conflicts of interest.

Word count – 8436

Abstract

Directing ocular fixations towards a target assists the planning and control of visually-guided actions. In far aiming tasks, the quiet eye, an instance of pre-movement gaze anchoring, has been extensively studied as a key performance variable. However, theories of quiet eye are yet to establish the exact functional role of the location and duration of the fixation. The present work used immersive virtual reality to manipulate key parameters of the quiet eye – location (experiment 1) and duration (experiment 2) – to test competing theoretical predictions about their importance. Across two pre-registered experiments, novice participants (*n*=127) completed a series of golf putts while their eye movements, putting accuracy, and putting kinematics were recorded. In experiment 1, participants' pre-movement fixation was cued to locations on the ball, near the ball, and far from the ball. In experiment 2, long and short quiet eye durations were induced using auditory tones as cues to movement phases. Linear mixed effects models indicated that manipulations of location and duration had little effect on performance or movement kinematics. The findings suggest that, for novices, the spatial and temporal parameters of the final fixation may not be critical for movement pre-programming and may instead reflect attentional control or movement inhibition functions.

Keywords: QE; golf putting; gaze; attention; VR; aiming

Public Significance Statement

Although directing eye gaze on a target before initiating an action toward it appears fundamental to proper execution of the action, it is unclear exactly how eye movements guide aiming actions. This study demonstrates that, for far aiming tasks, variations in the timing and location of eye movements may be less important than previously thought.

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General Introduction

For visually-guided motor skills, the way in which visual attention is deployed, both during and prior to skill execution, is a key determinant of successful execution (Goodale, 2011; Land & Hayhoe, 2001; Mann et al., 2007; Neggers & Bekkering, 2002). With experience, and through training, experts in visually-guided skills learn to strategically direct their gaze control system to optimise efficient information acquisition and guide accurate goal-directed movement (Land, 2009). One particular visual behaviour – known as the quiet eye (QE; Vickers, 1996, 2007) – has been identified as an important determinant of movement quality and performance outcomes in target and aiming tasks (Lebeau et al., 2016; Rienhoff et al., 2016). The QE fixation is the final fixation made to the target location that is initiated prior to movement execution (Vickers, 1996a, 1996b). When throwing a ball, shooting a weapon or controlling a surgical instrument a long, stable fixation has been proposed as a critical period for planning and controlling the motor response (Gonzalez et al., 2017; Vickers, 1996a; Williams et al., 2002). Yet, despite numerous studies examining this phenomenon, the exact manner in which the QE fixation provides performance benefits remains unclear (Klostermann et al., 2016; Rienhoff et al., 2016; Wilson et al., 2016).

The QE fixation is characterised by two key dimensions, the *location* and the *duration* of the fixation[1]. Definitions of the QE differ slightly across studies but have generally specified that the critical fixation must be directed to the location of the target (within 1-3° of

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[1] The timing of the fixation in relation to movement phases is also relevant, but is less well understood and rather more task specific (Vickers, Causer, & Vanhooren, 2019).

visual angle) and last in excess of 100ms (long enough for visual information to be consciously processed) (Vickers, 1996a, 2007). The functionality of a long, stable fixation directed to the target is intuitively appealing, as co-alignment of visual and motor systems in space simplifies the computational problem of visually-guided movement (Land, 2009; Neggers & Bekkering, 2002).

There has, however, been limited experimental work that has addressed whether the exact location and duration of the fixation are determinants of performance outcome. Two of the most prominent theoretical accounts of QE make divergent predictions regarding the importance of the exact location and duration of the final fixation. The *response programming* explanation proposes that the QE fixation supports acquisition of visual information to process task parameters and prepare the upcoming movement (Gonzalez et al., 2017; Vickers, 1996a; Williams et al., 2002). Consequently, the exact location and duration are important for acquiring sufficient visual information from the most informative areas of the visual scene, at the right time.

By contrast, the *attentional control* explanation emphasises that the importance of the QE does not primarily lie in its information acquisition role. Instead the QE is thought to be reflective of a visuomotor system that is optimised toward current goals. Vine and Wilson (2011) equate longer QE fixations with governance by a top-down, goal-directed attentional system, and describe how longer fixations may help to suppress distractions from bottom-up, salience-driven interruptions (Corbetta & Shulman, 2002). However, under this account, it is not the fixation itself that is driving performance, but attentional processes more generally. Maintaining a still fixation on the ball during the putt may just help to avoid distraction while the motor response is being prepared and executed. While a longer QE might be an indicator of better attentional control, it is not the fixation *per se*, but rather the underlying attentional state, that is important for performance. Consequently, the exact location and duration are less important, provided the performer can maintain appropriate attentional control.

In a more general sense, the response programming explanation can be characterised as an '*outward-in*' explanation, in that the duration and location of the fixation are vital for ongoing visuomotor computations[2] and act as determinants of performance outcomes (Gonzalez et al., 2017; Vickers, 1996a; Walters-Symons et al., 2018; Williams et al., 2002). Meanwhile, the attentional control explanation can be characterised as predicting an '*inward-out*' role, where the QE is merely reflective of the cognitive processes (e.g. good attention control) that are the more direct determinants of performance. If the QE does indeed play a more inward out role, the focus on measuring the final fixation in QE research may actually be missing what really drives the effect (e.g. attentional control/investment more generally).

While the existence of the QE has been identified in upwards of 30 motor tasks (Vickers, 2016), it is important to consider how the nature of the task may moderate the importance of the timing and location parameters (Wilson et al., 2016). Those 30 tasks can be subdivided along one important dimension; whether they are *self-paced* or *externally-paced*. While, during self-paced tasks, a performer has time to pre-programme an action using a series of fixations across a preparation window (Button et al., 2011; Dicks et al., 2017; Vickers & Rodrigues, 2000), spatial and timing parameters may become more critical when actions are under temporal pressure (Miles et al., 2015; Wilson et al., 2016). In the current work we adopt the skill of golf putting, a self-paced task, in order to examine the functionality of the location and duration of the QE when there is ample pre-programming time and the fixation is not required to locate the target.

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[2] Or to facilitate more direct performer-environment relationships in the case of ecological accounts (Oudejans et al., 2005).

The present studies

Attempts at examining QE mechanisms have, to some extent, been hampered by the practicalities of manipulating the task environment. The use of immersive virtual reality may provide a new route for more precise experimental manipulations and improved study of visuomotor skills (Craig, 2013; Zaal & Bootsma, 2011). Previous QE studies have used semi-virtual tasks (e.g. targets on a screen; Klostermann et al., 2013; Klostermann & Hossner, 2018) and simulations (e.g. surgical and military simulators; Moore et al., 2014; Wilson et al., 2011), and the current approach builds on this work by adopting a fully immersive, high-fidelity virtual reality golf putting simulation (Harris et al., 2019). As all aspects of the virtual environment can be tracked, virtual reality also supports the automation of calculating QE duration (e.g. see Kredel et al., 2015), answering calls from some researchers to replace manual coding of gaze with algorithmic approaches (Klostermann et al., 2016). In two studies we aimed to use the experimental control afforded by virtual reality to examine the competing predictions of the response programming and attentional control explanations of QE (and, more broadly, the outward-in versus inward-out role for QE) by manipulating the spatial and temporal parameters of the final fixation.

Experiment 1 - Location

Models of visually-guided behaviour describe how the repositioning of visual attention precedes a motor action, with the eyes moving to fixate a target prior to acting upon it (Bekkering & Sailer, 2002; Land, 2009). It seems natural that in the golf putt, the ball (the initial target) and the hole (the final target) would then be targets for visual attention prior to the initiation of the swing (Vickers, 2007), with the final fixation on the ball to guide putter-ball contact. However, for self-paced tasks, like putting, the pre-shot fixation does not need to locate/monitor a moving target, and much of the necessary visual information can be collected during previews of the ball location during shot preparation (or available via proprioception in the case of body/putter location) (Button et al., 2011). Indeed, some studies have shown visual occlusion during the putt to induce only small reductions in putting accuracy (Aksamit & Husak, 1983; Vine et al., 2017; but see also Causer et al., 2017 who found larger disruptions as a result of occlusion during the putting action). Therefore, it is unclear how much additional information is acquired during an extended QE fixation, and whether a similar level of performance could be achieved by fixations to other locations.

A compelling finding by Mackenzie, Foley and Adamczyk (2011) has suggested that it may even be effective to attend to a location that is nowhere near the ball. Mackenzie and colleagues trained participants to focus on either the ball (the initial target) or the hole (the final target) during the putt. Attending to the hole (at a distance of either 1.22 or 4 meters) during the putting stroke had no detrimental effect on performance outcomes, no effect on measures of putter-ball contact quality, and even improved putting kinematics by reducing putter speed variability. Similarly, unpublished doctoral work by Lee (2015) details that training participants to attend to either the ball or hole during the putt resulted in no differences in putting outcomes or putting kinematics. These findings suggest that even without peripheral sight of the ball putting performance could be maintained. They are, however, still compatible with the response programming explanation, as fixations to the far target could still serve to support movement planning.

The variation in the way in which researchers have defined the spatial bounds of the QE, ranging between one (Vine & Wilson, 2010) and three degrees (Behan & Wilson, 2008) of visual angle, also suggests that the exact location may be incidental. QE fixations within 3 degrees of visual angle of the ball equate to ~8cm either side of the ball for an average height adult; a sizeable variation in location. The precision of current mobile eye tracking technology has also been a barrier to investigating the relative functional role of the specificity of the location and whether a 'quieter eye' that remains within one degree is better than a fixation within three degrees (Gallicchio, et al., 2017; Gallicchio & Ring, 2019).

In summary, it has not been conclusively shown that the exact location of the pre-shot fixation is a determinant of successful skill execution, yet it remains part of the accepted definition of the QE. Indeed, fixations to either the final target (the hole) or the initial target (the ball) appear to be effective. This is illustrated, in extremis, in a study by Aksamit and Husak (1983), who found that fixating the ball, the hole or even putting *while blindfolded* had no effect on radial errors. We aimed to not only further examine the role of fixating the hole, but also to explore the effect of viewing the ball with the parafovea, by directing fixations close to, but not directly on the ball. While the response programming explanation would suggest that fixation locations away from the target (near or far) would be detrimental, the attentional control explanation can account for no performance decrement. Based on the findings of Mackenzie, Foley and Adamczyk (2011) and Lee (2015) it was predicted that QE fixations to locations around the ball, or even to the hole, would have no detrimental effect on putting performance or putting kinematics.

Methods

Preregistration

The research question, hypotheses, sampling plan, methods, materials, and statistical analyses were all pre-registered on the Open Science Framework and can be accessed online (https://osf.io/35fgp/). Any additional analyses not present in the preregistration are specified as exploratory.

Design

A repeated measures design was used, with participants completing four location conditions in counterbalanced order based on a Latin squares design. The location conditions were: 1) on the ball; 2) above the ball; 3) behind the ball; and 4) on the hole. The primary outcome measure was putting accuracy (radial error in cm), and secondary measures were QE durations (in milliseconds) and putting kinematics (movement of the putter head in x, y and z planes).

Participants

Eighty (40 female) non-golfers, i.e. novices, were recruited via convenience sampling from the University undergraduate population. A novice population was chosen to enable sufficient statistical power and to avoid the confounding effects of disrupting the well-established putting routines of expert golfers with the experimental manipulations. Establishing participants as novice golfers was based on having no prior formal golf training or official handicap (as in Moore, Vine, Cooke, et al., 2012). Sample size estimation was calculated using the “SIMR” package for R (Green & MacLeod, 2016). A very small difference, a 10cm change in putting radial error, was selected as the smallest meaningful effect of interest. Monte Carlo simulations (n = 1000) of a series of linear mixed effects models with participant as a random factor (and $\beta = 10.0$) were run under scenarios of increasing sample size using SIMR to generate a power curve. Given 20 trials per participant, 95% power was reached for a sample size of 60 (the R code and the power curve for the analysis is available in the supplementary materials: https://osf.io/35fgp/). Additional participants were recruited to make the sample robust to any potential data loss. Participants were provided with details of the study and gave written informed consent on the day of the testing visit. Ethical approval was granted by the departmental Ethics Committee prior to data collection.

Task and Materials

VR golf putting

The VR golf putting simulation was developed using the gaming engine Unity 2019.2.12 (Unity technologies, CA) and C#. The simulation was displayed using the HTC-Vive (HTC, Taiwan), a 6-degrees of freedom, consumer-grade VR-system which allows a 360° environment and 110° field of view. The Vive headset includes a Tobii eye-tracker, which uses binocular eye tracking at 120Hz over the whole field of view to an accuracy of 0.5-1.1°. Gaze was calibrated in VR over 5 points prior to each block of putts. The Tobii system automatically detected when gaze was directed at the cued location. The accuracy was then further checked by the experimenter by asking the participant to fixate on the ball. Data was recorded for offline analysis. Graphics were generated on an HP EliteDesk PC running Windows 10, with an Intel i7 processor and Titan V graphics card (NVIDIA Corp., Santa Clara, CA). The VR putter was created and tracked by attaching a Vive sensor to the head of a real golf club. Participants putted from 10ft (3.05m) to a target the same size and shape (diameter 10.80cm) as a standard hole. Participants were instructed to land the ball as close as possible to the target, but the ball did not drop into the hole. Auditory feedback mimicking the sound of a club striking a ball was provided concurrent to the visual contact of the club head with the ball. The game also featured ambient environmental noise to simulate a real-world golf course and enhance immersion. We have previously demonstrated the construct validity of an earlier version of this task for simulating putting (see Harris et al., 2019 for more details of the simulation validation).

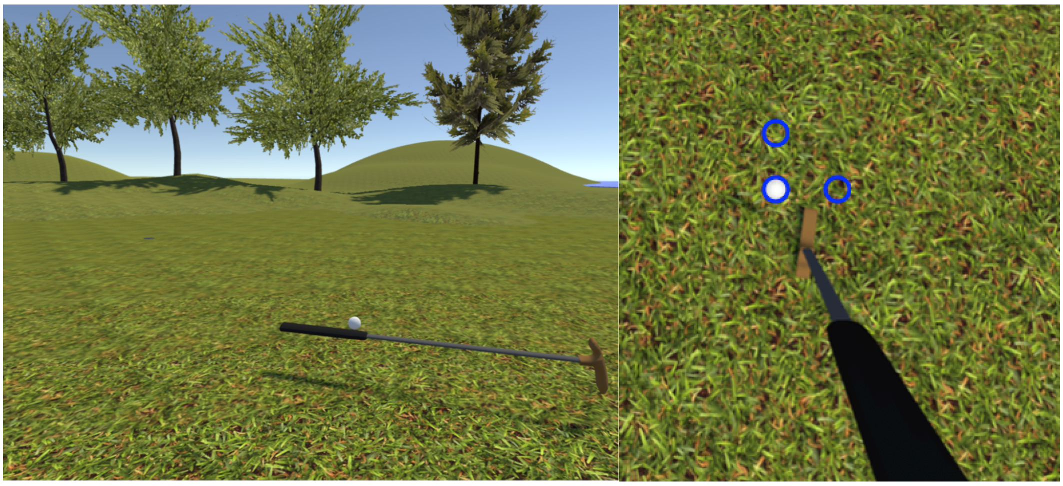

Figure 1. The golf putting task (left) and fixation locations on and around the ball (right)

Measures

Putting performance

As is typical of most recent quiet eye and targeting tasks (Causer et al., 2017; Horn & Marchetto, 2020; Razeghi et al., 2020; Walters-Symons et al., 2018), performance was assessed using a radial error measure. The distance of the ball from the hole (i.e. the two-dimensional Euclidean distance between the centre of the ball and the centre of the target; in cm) was automatically measured by the simulation. Performance was therefore assessed as a continuous measure of accuracy with putts landing on top of the hole assigned an error of zero.

Quiet eye period

The QE period was operationalised as the final fixation directed toward the ball, prior to the critical movement (Vickers, 2007). The critical movement in this case was defined as the initiation of the clubhead backswing, as in previous work in golf putting (Moore, Vine, Cooke, et al., 2012; Vine & Wilson, 2010). A fixation was defined as a gaze event maintained on an object within 1° of visual angle for a minimum of 100ms. The QE onset had to begin before movement initiation, but could continue right through the putting movement (e.g. as in Causer et al., 2017). QE offset occurred when gaze deviated from the target (ball or fixation marker) by more than 3° of visual angle, for longer than 100ms (Moore, Vine, Cooke, et al., 2012; Vickers, 2007). The absence of a QE fixation was scored as a zero.

An automated method of QE analysis (see Klostermann & Hossner, 2018 and Kredel et al., 2015 for similar approaches) was developed in MATLAB R2018a (Mathsworks, MA), which first identified fixations using a spatial dispersion algorithm using the EYEMMV toolbox for MATLAB (Krassanakis et al., 2014). Fixations parameters were set to a minimum duration criterion of 100ms and spatial dispersion of 1° (as recommended in Salvucci & Goldberg, 2000). Identification of the critical movement – the initiation of the club swing - was based on x-plane velocity of the Vive tracker, identified using peak detection in MATLAB. The final fixation initiated prior to this event, directed to the location of the target, was selected as the QE fixation (as in previous quiet eye work Causer et al., 2017; Vickers, 1996a). The location of gaze in the virtual environment could be determined at all times based on calculating a gaze vector from the known spatial orientation of the head and the gaze in head direction, which could be combined with the known position of all objects in the scene. The spatial locations of all objects were recorded on each frame of the simulation, so were timestamped and synchronised. All analysis code is available from the OSF: https://osf.io/35fgp/.

Putting kinematics

Two kinematic variables were calculated to index the quality of the putter swing/impact (Mackenzie et al., 2011; Mackenzie & Evans, 2010; Moore, Vine, Wilson, et al., 2012). Lower clubhead accelerations during the downswing have previously been linked to putting expertise and clubhead accelerations are frequently used as an indirect measure of motor control in putting studies (Cooke et al., 2012; Moore, Vine, Wilson, et al., 2012). Movement of the putter head in x, y, z planes (corresponding to the plane of the swing, the plane perpendicular to the swing, and up and down respectively) was recorded by the virtual environment. Kinematic data was de-noised using a five-point moving-average lowpass filter. Then, the velocity of the putter head at the moment of contact with the ball was calculated to index quality of impact, and mean accelerations during the swing were calculated for the x-axis (the plane of the downswing).

Procedure

Participants attended the lab for a single visit, which lasted approximately 30 minutes. First, participants had details of the experiment explained to them and they provided written informed consent. Next the experimenter checked that the participant had not experienced VR sickness before, and the participant was fitted with the VR headset. Participants completed 3 familiarisation putts followed by 20 test putts in each condition, in a counterbalanced order. In the ‘ball’ condition participants were instructed to look at the ball while they executed the putt. In the ‘above’, ‘behind’, and ‘hole’ conditions a blue circle was placed in the scene, which the participant was instructed to fix their gaze on whilst they executed the putt (Figure 1). They were told that they could look wherever they wanted whilst they were preparing, but that they must attend to the blue fixation point before and during the putt. To ensure the veracity of the manipulation, only pre-shot fixations directed to the instructed location were included in the analysis[3]. In the hole condition the fixation point

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[3] Of the potential 1600 trials, 25% (SD=3.3, min=0, max=16 per participant) were excluded from the hole condition, 27% (SD=3.7, min=0, max=13) from the behind condition, 24% (SD=3.2, min=0, max=12) in the

was placed on top of the hole. In the above and behind conditions the fixation point was located 2.5° of visual angle above and behind the ball respectively. This distance was chosen to make sure that the ball was clearly outside the foveal region but within the parafovea (Duchowski, 2017). The eye tracker was calibrated over 5 points in the visual scene prior to each block of putts. Participants were instructed to putt to the best of their ability and land the ball as close to the hole as possible. After completion of all conditions, participants were thanked for their participation and debriefed.

Data Analysis

Data analysis was performed in RStudio v1.0.143 (R Core Team, 2017). Data was first screened for outlying values more than 3 standard deviations from the mean (Tabachnick & Fidell, 1996), which were replaced with a Winsorized score by changing the outlying value to a value 1% larger (or smaller) than the next most extreme score. Error and QE data exhibited a positive skew and were transformed for analyses using a square root transform. A linear mixed effects model (LMM) was used to examine the effect of condition (ball, above, behind, hole) on the primary outcome variable, putting radial error, using the lme4 package for R (Bates et al., 2014). LMMs were also used to compare QE durations and putting kinematics (putter head velocity at contact, and x-plane accelerations). Most QE research has used averaged scores rather than examining individual trials, so the use of LMMs – which use trial level data – enables a more sensitive approach that more accurately models within-participant variance (Speelman & McGann, 2013). In order to determine the best fitting model, a maximal model was initially run, with random factors for participants and trial (Barr et al., 2013).

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ball condition and 28% (SD=3.9, min=0, max=15) in the above condition. In addition to trials where participants did not adhere to the instructions, these exclusions also reflect the removal of trials where there was eye tracking data loss or there was a difficulty with reliably identifying the initiation of the critical movement.

Principal Components Analysis was used to identify random factors that contributed to explaining additional variance to avoid overfitting, as described by Bates, Kliegl, Vasishth, and Baayen (2018). The best fitting model in each instance was chosen by simplifying the structure in line with the number of principal components. The Akaike information criterion was also used to compare subsequent models and check that the simplified model provided a better fit. While the experiment was powered to find even very small effects, Bayes Factors (using JZS priors) for LMMs were obtained using the BayesFactor package (Morey & Rouder, 2015) in order to provide more informative conclusions about null effects. We report BF, which represents the probability of the data under the alternative[4]. All analysis scripts and raw data are available from the Open Science Framework: https://osf.io/35fgp/.

Results

Performance

To examine the effect of location condition on putting performance a linear mixed effects model with a random factor for participant was run. The overall model had a total explanatory power (conditional R^2) of 13.67%, in which the fixed effects explain 0.18% of the variance (marginal R^2). The model's intercept is at 0.80 (SE = 0.018, 95% CI [0.76, 0.83]). Within this model the effect of condition was not significant, p=.08, $n_p^2 = .002$, BF = 0.005 (Figure 2). Even though the fixed effects explained little variance and the BF supported the null, as the main effect did approach significance, we ran pairwise tests (with Bonferroni-Holm correction) to check for group differences, but none were significant (ps>.37).

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[4] I.e. values greater than one (>1) indicate the alternative to be the more likely model, while values less than one (<1) indicate the null to be more likely.

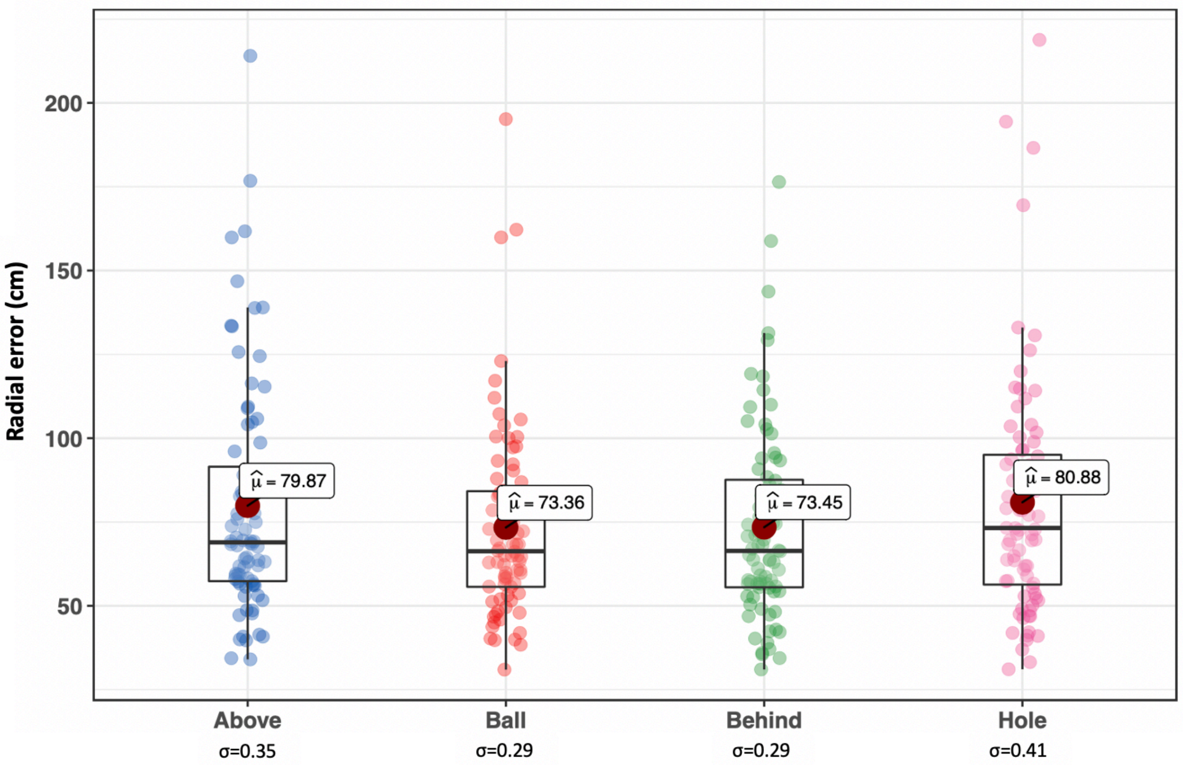

Figure 2. Box plot of putting accuracy across location conditions, displaying mean (labelled) median (black line), standard deviation (σ) and 95% CIs.

Quiet eye

To examine the effect of location condition on QE durations a linear mixed effects model with a random factor for participant was run. The overall model had a total R^2 of 28.56%, in which the fixed effects explain 2.54% of the variance. The model's intercept is at 21.44 (SE = 0.58, 95% CI [20.29, 22.58]). Within this model the effect of condition is significant, p<.001, n_p^2 = .034, BF= $5.9*10^{20}$. Pairwise comparisons with a Bonferroni-Holm correction indicated that QE durations in the ball and hole conditions were shorter than in the above and behind conditions (all *p*s<.001). There was no difference between above and behind (*p*=.07) and between ball and hole (*p*=.07), as is illustrated in Figure 3.

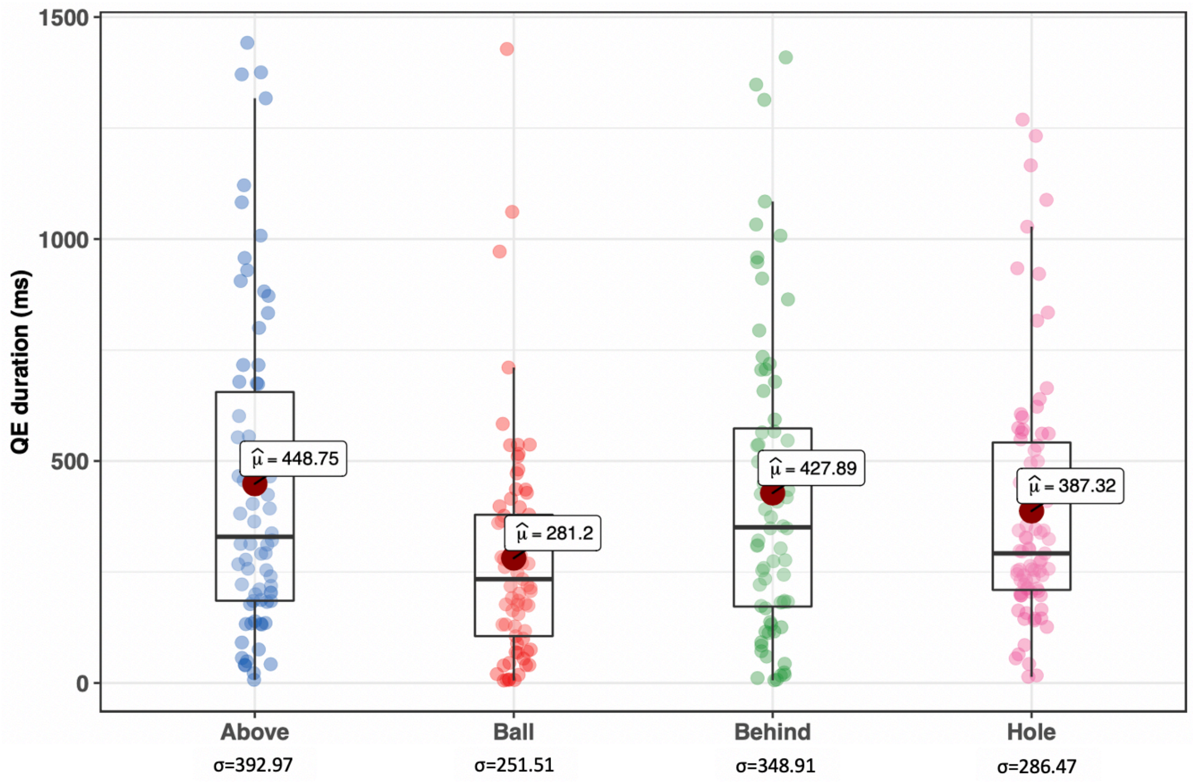

Figure 3. Box plot of QE durations across conditions, displaying mean (labelled) median (black line), standard deviation (σ) and 95% CIs.

To examine the effect of location condition on putter control, linear mixed effects models were run on putting kinematic variables (with participant as a random factor). The overall model predicting putter head velocity at contact had an R^2 of 37.16%, in which the fixed effects explain 0.40% of the variance. The model's intercept is at 4.05 (SE = 0.065, 95% CI [3.92, 4.18]). Within this model the effect of condition was significant but very small, $p < .001$, $n_p^2 = .006$, BF = 7.04 (see Figure 4). Pairwise comparisons with a Bonferroni-Holm correction indicated that putter head velocity for the hole condition was lower than for the above ($p = .006$) and ball ($p = .002$) conditions but was not significantly different from the behind condition ($p = .09$). There were no other differences between conditions (*p*s > .26).

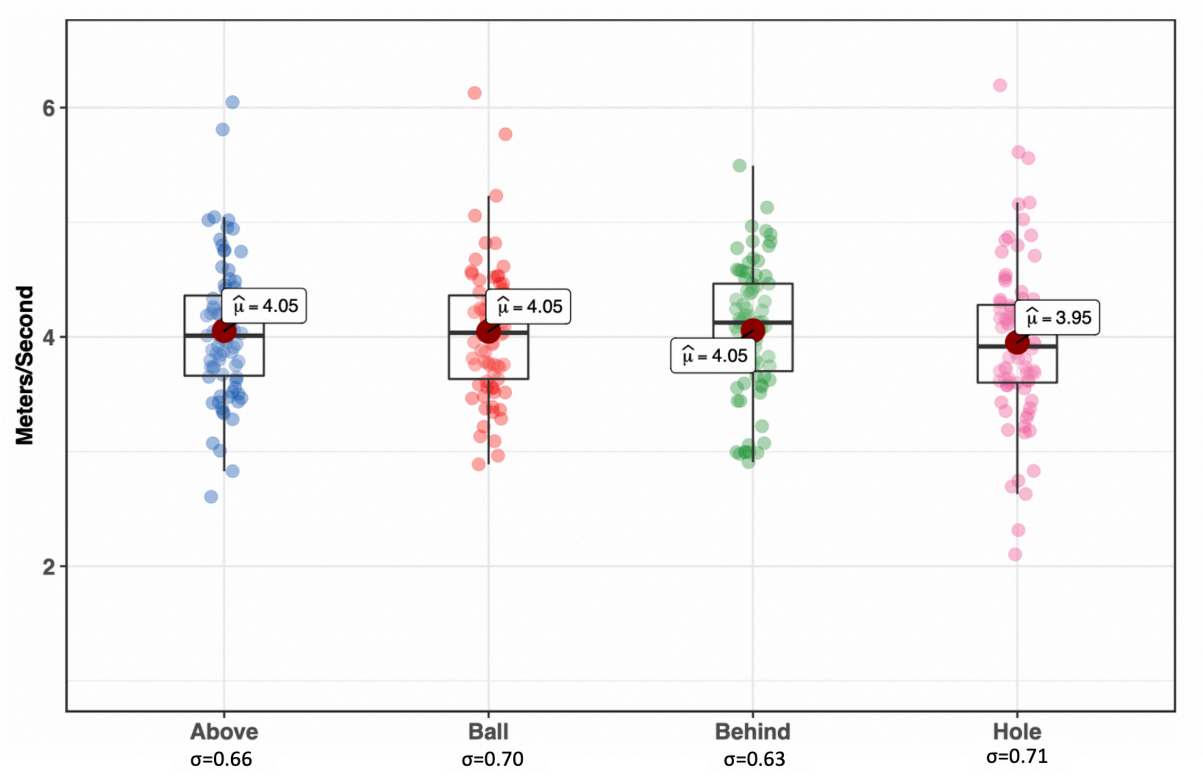

Figure 4. Box plot of putter velocity at contact across conditions, displaying mean (labelled), median (black line), standard deviation (σ) and 95% CIs.

The model predicting x-plane accelerations had an R^2 of 34.74%, in which the fixed effects explain 0.35% of the variance. The model's intercept is at 13.15 (SE = 0.38, 95% CI [12.40, 13.89]). Within this model the effect of condition is significant but very small, $p < .001$, $n_p^2 = .005$, BF = 0.09. Even though the effect was very small, paired contrasts were run to examine the significant effect. The comparisons indicated greater accelerations in the above ($p = .002$) and hole conditions ($p < .001$) compared to the behind condition. No other comparisons were significantly different (*ps* > .21).

Discussion

The aim of experiment 1 was to examine the importance of QE location in the performance of a simulated golf putting task, building on existing work using similar simulated tasks (Causer et al., 2017; Vickers, 1996a). While the QE is always defined as a fixation to the target, there has been little evidence to demonstrate that attending to the target actually confers a functional benefit over other locations. In line with our pre-registered hypothesis we found that the location of the pre-shot fixation had no effect on putting performance (supported by a Bayes Factor strongly favouring the null; BF = 0.005), suggesting that the exact location of the fixation was unimportant; a finding that poses a challenge for a response programming explanation for this task.

Analysis of QE durations suggested that participants made longer fixations when attending to the above and behind locations than on the ball or the hole (see Figure 3). The location manipulation may have induced participants to dissociate their overt attention from the location of the visual fixation, and consequently employed a longer QE to compensate. Similar effects have been observed previously when participants deliberately dissociated their gaze from their aiming intention during soccer penalties (Wood et al., 2017). Wood et al. suggest that when participants used a deceptive gaze strategy, longer QE durations were required to cope with the increased processing demands.

Analysis of putting kinematics indicated some differences in execution of the putting stroke (e.g. a reduction in putter head velocity at contact for the hole condition) but these changes were very small. Figure 4 also suggests slightly greater variability in contact velocity, possibly because participants had no visual feedback on putter head movement and had to rely on proprioception alone (Volcic & Domini, 2016).

Previous work (Mackenzie et al., 2011) has suggested that training participants to attend to the distant target, during aiming tasks that require contact between an instrument and an object (e.g. in golf putting), does not impair performance. Indeed, in the task of real-world golf putting, some professional golfers (e.g. Jordan Spieth) report using this strategy for short putts. Here we extend these findings to other locations, not directly on either the near or far target, to demonstrate that a QE close to the ball was as effective as on the ball. However, changes in QE duration might have compensated for the additional difficulty when not fixating the ball directly. We were also able to demonstrate this effect in a much larger sample than most previous work, and with the ability to ensure the veracity of the manipulation using eye tracking. Next we aimed to explore the importance of the other defining feature of the QE, its duration.

Experiment 2 - Duration

The rationale for the functional benefit of longer QE (up to a point; see Klostermann, et al., 2018) is based on the discovery of longer durations in experts versus novices and on successful versus unsuccessful trials (Vickers, 1996; 2007). A recent meta-analysis has supported the reliability of the expert/novice (~$\bar{d}$=1.04, 95% CI [0.04; 2.04]) and successful/unsuccessful (~$\bar{d}$=.58, 95% CI [-0.07; 1.23]) effects (Lebeau et al., 2016). While the response programming explanation suggests that an elongated fixation enables extended task parameterisation (e.g. force and direction), there has been limited direct manipulation of QE duration. Studies that have attempted to manipulate QE duration are somewhat limited by an accompanying uncertainty about target location. Klostermann et al. (2013, 2018) and Sun et al. (2016) have previously manipulated fixation duration by controlling target onset, finding shorter QE durations to be detrimental to performance when throwing a ball to a stationary or moving target. In these studies, QE onset was manipulated by delaying the appearance of the target relative to the instructed initiation of the throwing action. The studies of Klostermann et al. presented the target at one of four possible locations and Sun et al. occluded the early trajectory of a moving target. However, for these studies, participants in the short QE condition had less time to locate or monitor the position of the target and were uncertain about target location when planning the action. Klosterman et al. (2013) actually report that during pilot work the effect of the shorter QE manipulation on performance was absent when target location was predictable, and uncertainty about final location had to be added to elicit the effect. In a task when the target location is already known, such as golf putting, it is unclear whether shorter QE durations would still be detrimental.

Initial support for the idea that shorter QE durations may not be detrimental comes from doctoral dissertation data by Lee (2015), which revealed no effect of training long versus short QE durations in a putting task. Participants were trained over 2 days (420 trials) to adopt either a long (2500ms) or short (400ms) pre-shot fixation, yet there was no performance difference between the two groups at a retention or a pressure test. Both groups significantly improved their putting performance as a result of training, supporting the idea that the benefits of QE training may not be entirely due to longer pre-shot fixations. There are issues with this finding (it was likely underpowered, and the short QE group still maintained a QE of around 1000ms when unconstrained after training), but it provides an indication that when the location of the target is already known there may be little benefit to longer QE durations.

To further explore the importance of the QE duration we experimentally manipulated the duration of the early QE (before movement initiation) using auditory timing cues (as in Klosterman et al. 2018). We compared putting performance between conditions which allowed for short (400ms) and long (2500ms) pre shot QEs, with a free putting condition, in line with Lee (2015). If the QE plays an outward-in role in supporting motor programming (Mann et al., 2011) then longer QE durations should relate to better performance and shortened ones should be detrimental. However, based on an attentional control interpretation and Lee’s (2015) findings relating to QE training, we suggest that the exact duration of the fixation will not have a major effect on putting accuracy. Similarly, some researchers have suggested that the importance of the QE may lie in its timing, such that only a portion of the fixation is critical, but that longer fixations are maintained ‘just in case’ (Oudejans et al., 2002). Therefore, our pre-registered hypothesis was that there would be no difference in putting performance between long and short conditions, and that best performance would occur in the free putting condition.

Methods

Preregistration

The research question, hypotheses, sampling plan, methods, materials, and statistical analyses were again pre-registered on the Open Science Framework (https://osf.io/35fgp/).

Participants

Forty-seven novices (15 female) were again recruited from the University undergraduate population, but were an entirely different sample from experiment 1. Participants were provided with details of the study before attending testing and gave written informed consent on the day of the testing visit. Ethical approval was obtained from the departmental Ethics Committee prior to data collection. Sample size estimation was again calculated using the “SIMR” package (Green & MacLeod, 2016) based on a smallest meaningful effect of 10cm. Monte Carlo simulations (n = 1000) indicated that, given 20 trials per participant, power of >85% was reached for a sample size of 45 (the power curves are available in the supplementary materials: https://osf.io/35fgp/).

Design

A repeated measures design was used, with participants completing three putting conditions – 1) short QE, 2) long QE, 3) free putting – in a counterbalanced order using a Latin squares design. The primary outcome measure was putting accuracy (radial error in cm), and the secondary measures were putting kinematics (accelerations in the x-plane and velocity at contact). QE durations (in milliseconds) were also calculated as a manipulation check.

Task, Materials and Measures

The VR golf putting task and outcome measures were calculated as in Experiment 1.

Procedure

Participants attended testing on one occasion for approximately 30 minutes. After having the details of the study explained to them and providing informed consent, they completed the three putting conditions which consisted of 25 putts in each condition. The first five trials were for participants to learn the timing of the beeps and were discarded from the analysis. The participant heard beeps of three different sounds. The first sound indicated to look to the hole, the second indicated to look to the ball, and a final (different tone) sound provided the cue to initiate the putt (see Figure 5). Participants were cued to look from the ball to the hole twice over, before returning to the ball and initiating the putt. Adherence to the instructions was constantly monitored by the experimenter.

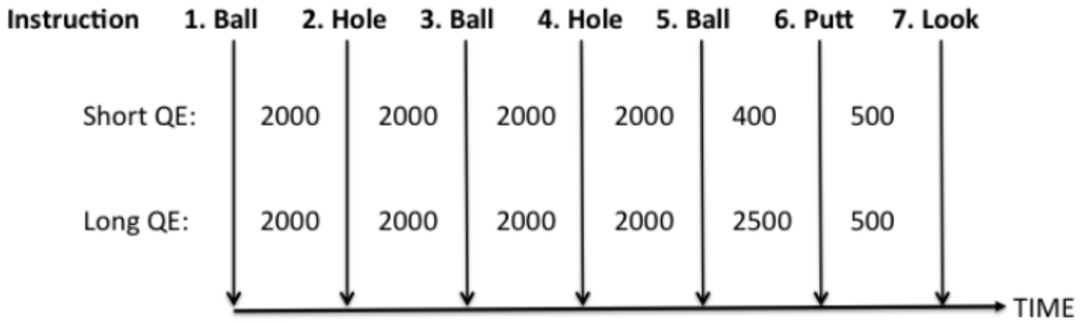

Figure 5. Illustration of auditory cues given to participants.

Data Analysis

Data analysis was conducted as in Experiment 1, using linear mixed effects models to examine the effect of putting conditions (short, long, free) on performance, QE duration and putting kinematics. Individuals trials were excluded from the baseline (151; 16%), long (87; 9%) and short (111; 11%) conditions when there was a loss of eye or head movement tracking, or when the critical movement could not be reliably identified. Error and QE data again showed positive skew and were square root transformed for analyses. All analysis scripts and raw data are available from https://osf.io/35fgp/.

Results

Quiet eye

To ensure the effectiveness of the QE manipulation an LMM was run on QE durations. The overall model predicting QE duration (with random slopes and intercept for participant) had a total explanatory power of 59.78%, in which the fixed effects explain 5.90% of the variance. The model's intercept is at 12.34 (SE = 1.32, 95% CI [9.70, 14.99]). Within this model the effect of condition is significant, $p < .001$, $n_p^2 = .018$, BF = $1.69*10^{25}$. As there was clear evidence for an effect of condition, for both frequentist and Bayesian models, pairwise comparisons with Bonferroni-Holm adjustment were run. The comparisons clearly indicated that the long condition produced longer QE fixations than the short ($p <$ .001) or free ($p <$ .001) conditions. There was no significant difference between the short and free conditions (p = .69). Consequently, the manipulation was successful at creating a clear difference between long (mean = 529.5ms, sd = 254.0) and short (mean = 261.6ms, sd = 245.2) conditions (see Figure 6).

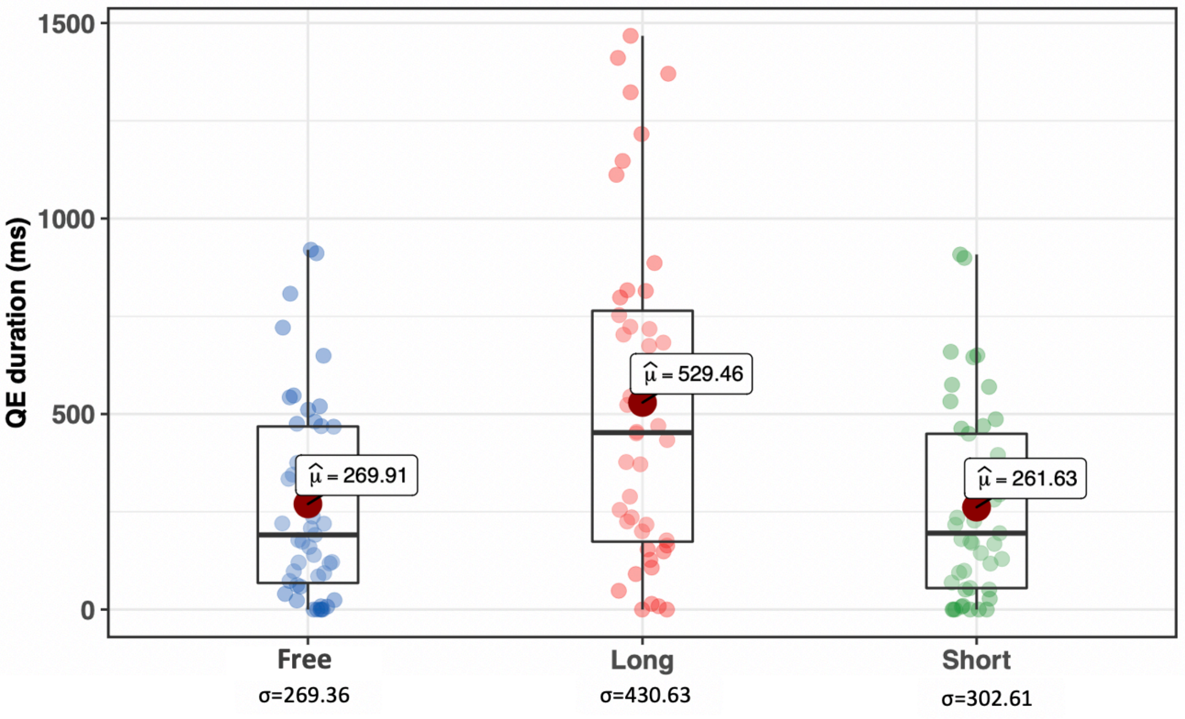

Figure 6. Box plot of participants mean QE durations (in milliseconds), displaying mean (labelled) median (black line), standard deviation (σ) and 95% CIs.

Performance

To examine the effect of duration condition on putting accuracy an LMM was run on radial error scores. The overall model predicting putting error (with random slopes and intercept for the factor participant) had a total explanatory power of 22.73%, in which the fixed effects explain just 0.68% of the variance. The model's intercept is at 0.85 (SE = 0.026, 95% CI [0.80, 0.90]). Within this model the effect of condition is marginally significant but very weak, $p = .04$, $n_p^2 = .004$, BF = 0.60 (see Figure 7). As the effect was very weak and the Bayes factor supported the null, no further tests were run.

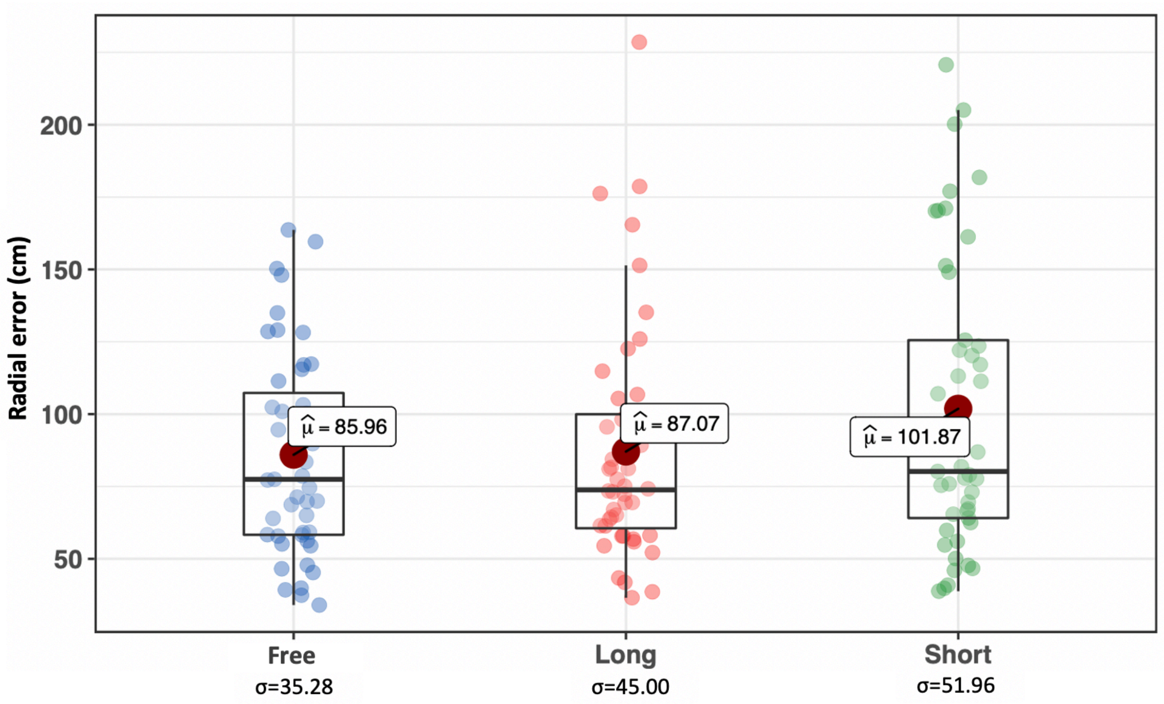

Figure 7. Box plot of participants mean radial errors (in cm), displaying mean (labelled) median (black line), standard deviation (σ) and 95% CIs.

Putting kinematics

To examine the effect of duration condition on putter control an LMM was run on putting kinematics (with random slopes and intercept for the factor participant). The overall model predicting velocity at contact had a total R^2 of 60.56%, in which the fixed effects explain 0.63% of the variance. The model's intercept is at 4.17 (SE = 0.12, 95% CI [3.93, 4.42]). Within this model the effect of condition is not significant and very weak, $p = .09$, $n_p^2 = .003$, BF = 0.03.

The overall model predicting x-plane accelerations had an R^2 of 49.35%, in which the fixed effects explain 2.35% of the variance. The model's intercept is at 13.18 (SE = 0.55, 95% CI [12.09, 14.31]). Within this model the effect of conditions was significant but weak, $p = .009$, $n_p^2 = .006$, BF = $1.64*10^6$. Pairwise comparisons indicated that putter accelerations in the downswing were marginally greater in the short compared to the long fixation condition ($p = .04$), but there were no differences between long and baseline ($p = .52$) and short and baseline ($p = .16$).

Discussion

In the QE literature, longer fixations are consistently linked with improved performance outcomes (Klostermann et al., 2018; Lebeau et al., 2016), but it remains to be established whether the duration is driving performance effects or is merely reflective of internal processes such as good attentional control. By manipulating the duration of the fixation, we aimed to determine whether the fixation itself is the functional element of the QE, or if attentional processes more generally (which can dissociate from gaze) may be more important. The findings here were in line with our pre-registered hypothesis, that there would be no performance differences when participants were manipulated into either a long or short QE. Despite the effect of condition on radial error being marginally significant, the effect was very small (0.4% of the variance) and the Bayes Factor supported the null over the alternative (BF = 0.60). Therefore, these results are at odds with the findings of Klostermann et al. (2018) Sun et al. (2016) who both found that manipulations to shorten the quiet eye disrupted performance. As discussed previously, this discrepancy may well be a result of the predictability of target location. In contrast to our prediction, participants did not perform any better in the free putting condition, but this may actually support the success of the manipulation, in that the instructions for creating a long or short QE were not in any way disruptive to normal performance.

Analysis of putting kinematics did suggest some small changes as a result of the manipulation. There were no changes in putter head velocity at contact, but compared to the long condition, the short condition induced larger accelerations in the plane of the downswing. Previous work has generally identified lower accelerations during the downswing as a feature of expertise (Cooke et al., 2012; Moore, Vine, Wilson, et al., 2012), so there may have been some slight disruption to the swing in the short condition. However, these were small effects so we should be wary of overinterpretation.

While the LMM indicated that the QE manipulation was successful in creating significant differences between the long and short conditions it should be noted that the durations in the long condition (mean = 529.5ms) might still not be considered ‘optimal’ in the context of those typically taught during QE training (Moore, Vine, Cooke, et al., 2012; Vine & Wilson, 2011). Hence it is possible that the QE was not sufficiently extended as to observe an improvement in performance. However, the differences in analysis method should also be borne in mind. The algorithmic approach used here may be responsible for the shorter durations when compared to manual coding studies; an issue we return to in the general discussion. Still, regardless of the analysis method we would have expected to see some performance differences between long and short groups given an increase in QE duration of more than 200%. The present finding that manipulation of the duration had no effect on putting accuracy certainly raises questions about the functional mechanism of the QE, and the response programming explanation.

General Discussion

In the present study we used innovative manipulations made possible by virtual reality, to address a core theoretical assumption of QE theory. Specifically, we aimed to establish whether the exact location and duration of the QE fixation are determinants of performance outcomes, as suggested by outward-in accounts, such as response programming. While much existing work has correlated QE with performance, we adopted experimental manipulations of the spatial and temporal parameters of the fixation to shed light on the exact functional mechanisms by which the QE informs goal-directed actions.

Experiment 1 illustrated that performance can be maintained even when the pre-shot fixation is directed to a range of locations. Experiment 2 found that inducing long or short QEs had no effect on performance and minimal effects on control of the putter. While fixations on the ball (Experiment 1) and longer final fixations (Experiment 2) were descriptively better, in line with the initial predictions of Vickers (1992, 1996a), the effects were sufficiently small that they were not statistically meaningful. These results effectively suggest that controlling the two defining features of the QE actually had little impact on skill execution. When considered together, the results do raise questions about the exact functional role of the QE. The present findings suggest that, for a self-paced task at least, a long fixation on the target is not necessary and any stable QE might provide the necessary quiet period of motor preparation for fine tuning the timing and coordination of the shot. In the golf putting task much of the visual information required to plan the movement can be processed during the entire ‘visual routine’ (Ballard & Hayhoe, 2009) of preparing for the putt, making the final fixation less important.

Evidently the current results pose a challenge for a response programming explanation of the QE in self-paced tasks. If variations in location and duration have little effect on performance, then it is unlikely that the primary function of the QE fixation is for gathering information to pre-programme the putt. Electroencephalogram (EEG) measurement has previously linked the QE period with an event-related potential (ERP) over the motor cortex believed to indicate movement preparation (i.e. the Bereitschaftspotential; Mann et al., 2011). However increased alpha power in visual cortex during the QE fixation has also been observed in EEG recordings (Gallicchio & Ring, 2019), which suggests reduced or inhibited visual processing. Taken together these findings suggest that while motor preparation may be occurring during the QE, it is not the primary function of the QE to collect visual information to enable that programming.

Two other explanations of QE are, however, consistent with the present findings. Firstly, an attentional control explanation would suggest that the primary importance of the QE is not for gathering visual information, but that a longer fixation on the target is reflective of the wider attentional state of the performer (and may help to maintain that state). From this perspective, the manipulations used here would have little impact on performance, provided the performer maintained a goal-directed focus of attention. Indeed, this is what was observed, manipulations of the parameters of the QE did not affect performance, indicating that they were not a functional element of the QE in this task. The extent to which our manipulations served to dissociate overt and covert attention (e.g. attending the ball as well as the cued location) is unknown, but explicit manipulations of covert attention while performers maintain stable overt visual attention could serve to test the attentional control explanation and determine whether allocation of (covert) attention is more important than overt gaze.

Secondly, the inhibition hypothesis of Klosterman and colleagues proposes that the QE duration serves to inhibit the preparation of non-optimal task solutions in favour of the optimal movement variant (Klostermann et al., 2014). The inhibition hypothesis is proposed to explain the ‘efficiency paradox’ whereby experts display longer QEs, despite expertise being associated with economisation of behaviour and automatization of control. Klosterman et al. suggest that experts have a much greater movement repertoire, and hence more sub-optimal movement variants requiring inhibition. Consequently, the location of the fixation would have little impact on performance and a short QE might fulfil the inhibition needs of novices; particularly as ‘short’ QE durations were similar to unconstrained QE here (i.e., free putting condition). A replication of the present work with expert performers could serve as a test of the inhibition hypothesis, as experimental shortening of the QE should be much more detrimental in experts.

Limitations

In defence of the response programming explanation, it could be argued that the use of novices in the present study – in contrast to those of Sun et al. (2016) and Klosterman et al. (2013)[5] – limits the conclusions that can be drawn about QE functionality, as manipulations of QE parameters might have a reduced impact in a novice population. For instance, it is reasonable to assume that the motor programme (e.g. Schmidt, 1975), or ability to generate accurate motor predictions from inverse models (e.g. Wolpert & Flanagan, 2001), is not well developed in novices. Hence if the benefit of the QE fixation lies in supporting fine tuning of motor commands, variations in location and duration of the QE may have more limited effects in novices who do not have a well-developed motor programme to adjust. Further, it may be the case that a certain amount of experience is needed to extract and make use of the relevant pre-shot visual information (as is the case in many areas of visual expertise; Brams

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[5] Both studies used throwing tasks which are less complex than a golf putt and participants (primarily sports science students) would likely be relatively proficient at this skill.

et al., 2019), such that, again, novices may be less affected by the exact location and duration of the QE. Early QE studies examined successful and unsuccessful execution in more skilled populations with a focus on optimal performance, where the effects of the QE may be the clearest (Vickers, 1992, 1996a). However, if QE is truly an important perception-action variable that supports information processing, movement preprograming, and coalignment of attentional and motor systems (Vickers, 2007) – as opposed to just being an irregularity of high-level performers – then similar effects should also be observable across skill levels. The possibility that the QE has slightly different functions, or just varying degrees of importance, in experts and novices means that it is crucial to extend these findings to more experienced performers in future work.

As discussed at the outset, these findings may only be relevant for self-paced aiming tasks, as externally-paced interceptive tasks do not permit a series of fixations during the pre-shot preparation time, and hence may place greater importance on the duration and location of the final fixation. The divergence from the findings of Klosterman et al. (2013; 2018) and Sun et al. (2016) in experiment 2 highlights that specific aspects of the task, like predictability of target location, might also modulate the duration effect. As Wilson et al. (2016) point out, the functional role of the QE may vary considerably across tasks, particularly as a function of the pre-programming time available (Horn & Marchetto, 2020). Therefore, it is necessary for future work to replicate the present findings but also to extend them to more complex aiming tasks with temporal constraints and more varied task demands. For similar reasons, it may be instructive to examine temporal and spatial manipulations of the portion of QE that occurs during the putt (‘online QE’), which may have elevated importance in self-paced tasks.

While we see this as a strength of the study, rather than a limitation, it is fair for us to highlight the manner in which QE was calculated in the present work, which differs from much of the literature to date (but see Klosterman & Hossner, 2018 for a similar algorithmic approach). Here we applied a stricter criterion for identifying the QE. The most common method of calculating the QE 'fixation' has been through manual coding, where the experimenter decides if the gaze cursor in the eye tracking video remains on the target during the critical period and then records the onset and offset. However, what is recorded is not really a 'fixation' in the truest sense; it is gaze directed to a particular location. Here we used an algorithmic approach that determined the occurrence of true fixations, based on spatial dispersion of consecutive points of gaze (Krassanakis et al., 2014). The durations of the QE detailed in Experiment 2 would be considered relatively short in the context of previous work, and short of the 'ideal' duration. However, this is likely to be a result of the stricter criteria that were used based on identifying a true fixation (e.g. as in Gallicchio et al., 2017; Klosterman & Hossner, 2018).

Conclusions

The current experiments have sought to extend enquiry into the proposed causal role of the QE in supporting performance in the far aiming task of golf putting. We conducted a critical analysis of fundamental tenets of QE theory, finding that the spatial and temporal parameters of the fixation may be less important than previously thought; results which favour attentional control and inhibition accounts over response programming in self-paced tasks. A core finding of this work is that it is possible to manipulate gaze without affecting performance, which suggests that the core functional benefit of the QE may be dissociable from overt gaze (i.e. an inward-out role). Perhaps close enough (experiment 1) and long enough (experiment 2) is good enough.

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