European Journal of Sport Science

ISSN: 1746-1391 (Print) 1536-7290 (Online) Journal homepage: http://www.tandfonline.com/loi/tejs20

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To cite this article: Daniel T. Bishop, Neil Addington & Giorgia D'Innocenzo (2017) Using visual guidance to retrain an experienced golfer's gaze: A case study, European Journal of Sport Science, 17:2, 160-167, DOI: 10.1080/17461391.2016.1216169

To link to this article: https://doi.org/10.1080/17461391.2016.1216169

Published online: 10 Aug 2016.

European Journal of Sport Science, 2017
Vol. 17, No. 2, 160–167, http://dx.doi.org/10.1080/17461391.2016.1216169

ORIGINAL ARTICLE

Using visual guidance to retrain an experienced golfer's gaze: A case study

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Abstract
Eye movements are essential for both predictive and reactive control of complex motor skills such as the golf swing. We examined the use of a visually guided learning protocol to retrain an experienced golfer's point-of-gaze immediately prior to execution of the full golf swing; his swing, and his gaze behaviour, had become established over more than a decade of practice and competition. Performance and eye movement data were obtained, from baseline, through intervention, to retention, for a total of 159 shots struck at a target 200 yards away. Results show that, at baseline, not only was the golfer's point-of-gaze not at the intended/predicted location, at the top-rear of the ball, but there was also high trial-to-trial variability. A bespoke visual guidance protocol improved his gaze behaviour considerably, in terms of accuracy and consistency – and this was reflected in accuracy and consistency of his shots. Implications of oculomotor interventions for the relearning of established motor skills are discussed.

Keywords: *Eye movements, golf, learning, oculomotor, sport*

Our eye movements typically occur in a top-down/goal-driven manner (Chen & Zelinsky, 2006), that is, we look where our current task requires us to. Accordingly, eye movements are highly predictive: not only do they precede action during complex motor tasks (Hayhoe, McKinney, Chajka, & Pelz, 2012; Sailer, Flanagan, & Johansson, 2005), but also when observing the actions of others (Flanagan & Johansson, 2003). Indeed, there is convincing evidence to date that gaze is tightly coupled to overt movements. In naturalistic tasks, gaze is typically directed to regions which are important for the task at hand; fixations are temporally bound to the evolution of the task and irrelevant areas are rarely fixated (Hayhoe & Ballard, 2005). For example, in a landmark study, Land and McLeod (2000) recorded the eye movements of three cricket batsmen, of varying skill level, as they faced deliveries from a bowling machine. Despite obvious skill differences, each of the batsmen made a predictive saccade to the anticipated bounce point of the ball; such anticipatory gaze behaviour has since been demonstrated in squash (Hayhoe et al., 2012).

Exogenous direction of learners' eye movements, that is, "gaze training", has been successfully applied to an array of contexts, including surgery (Vine, Masters, McGrath, Bright, & Wilson, 2012) and golf putting (Vine, Moore, & Wilson, 2014); and it can bring about subtle improvements in both kinematics and performance (Causer, Holmes, & Williams, 2011; Moore, Vine, Cooke, Ring, & Wilson, 2012; Moore, Vine, Smith, Smith, & Wilson, 2014). In the case of golf putting, *inter alia*, one particularly effective gaze strategy is the phenomenon known as the Quiet Eye (QE), defined as the "final fixation or tracking gaze located on a specific location or object in the visuomotor workspace for a minimum of 100 ms" (Vickers, 2007, p. 11). QE performance benefits demonstrated in the laboratory have also successfully transferred to naturalistic

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settings, even when the intervention is introduced only briefly (Vine, Moore, & Wilson, 2011).

Given the apparent trainability of gaze (Vine et al., 2012), plus the close coupling of eye and limb movements during skilled execution of complex visuomotor tasks (Hayhoe et al., 2012; Sailer et al., 2005), the question arises as to whether skilled performance of an extensively practised but highly complex skill may be improved by retraining similarly ingrained gaze behaviour. The present study addresses this question, using the full golf swing to do so.

In order to strike a golf ball 200 yards or more, a golfer must accurately direct a club head measuring approximately 12 × 7 cm, which can be travelling at speeds in excess of 100 miles per hour, in an arc that begins behind their head, to a ball measuring approximately 4 cm in diameter. Moreover, kinematics of the club head, such as its centredness relative to the ball, are the primary determinant of ball flight characteristics (Sweeney, Mills, Alderson, & Elliott, 2013). This renders the full swing a highly unique coordinative gaze-mediated aiming task like no other; one for which the location of the club–ball collision must be predicted to an extraordinarily high degree of precision. Although golf putting research has shown that appropriate point-of-gaze on the rear of the ball may be optimal for performance (i.e. Vickers, 2011), there are no such data for the full golf swing. Hence, our primary aims were to explore the relationship, if any, between an experienced golfer's gaze behaviour during preparation for the swing and the ensuing distribution of the ball around the target; and to use these data to retrain his point-of-gaze, in an attempt to improve his performance. Given the importance of club head centredness for correct ball flight (Sweeney et al., 2013) and the efficacy of gaze training for subtle improvements in kinematics (e.g. QE; Causer et al., 2011; Moore et al., 2012), we hypothesised that, for a skilled golfer performing a target-aiming golf task, (a) greater dispersion of final fixation locations prior to backswing initiation would be associated with greater dispersion of the balls from the target and (b) a gaze retraining intervention comparable to those used in QE protocols, designed to focus gaze appropriately (i.e. in a more centred location on the ball, relative to the intended line of travel) would mitigate ball dispersion.

Methods

Design and participant

The intervention comprised an A-B-A (pre-treatment/baseline, intervention, post-treatment) design, with a delayed retention test, one-week post-intervention. The participant was a 22-year-old male student who had been playing golf for 14 years, representing both his university and county in national competitions. His handicap of four rendered him eligible to be classified as an experienced golfer (Vickers, 2007).

Apparatus and materials

Golf task. At all phases, the participant was positioned in the same bay at a public golf driving range. Each ball (One-piece Full Distance, Rangeball UK Ltd.) was struck using a 5-iron club (Mizuno MP64, Mizuno Corporation, UK) from its resting position on a synthetic grass mat, towards an upright metal flag (hereafter the *target*) at a distance of 200 yards from the centre of the mat, onto a turf-covered fairway. Figure 1(a) depicts the setup.

Eye tracking. Point-of-gaze was constantly monitored using Applied Science Laboratories (ASL) Mobile Eye-XG Eye Tracking Glasses, recording monocularly at 60 Hz. Real-time data transferred wirelessly to a laptop computer, for online viewing and storage.

Ball distribution data. The researcher recorded the estimated final ball location using a 10 × 10 handheld grid that depicted a 50 yards × 50 yards region of the fairway with the target at its centre. The precision of this grid was facilitated by various landmarks (e.g. other flags, bunkers) with known distances, longitudinally and laterally, from both the target and the range. The accuracy of any given estimate was therefore approximately ± 2.5 yards.

Visual guidance. This was provided using a Kensington handheld Class 2 low-power laser pointer mounted on a 0.9 m high camera tripod positioned 0.7 m from the ball, at a 45-degree angle to the sagittal plane as the golfer addressed the ball. The beam projected at an angle of 38.0 degrees onto the ball (see Figure 1(b)).

Procedure

Subsequent to institutional research ethics committee approval, and his informed consent, the participant attended four separate data collection phases interspersed with one-week intervals during which no golf was played. During each phase the participant was given time to warm-up thoroughly, with and without the eye tracking apparatus *in situ*. At each phase, he reported that the glasses were comfortable and did not significantly impede his vision, or his movements, throughout testing. The number of trials in each phase was determined by a combination

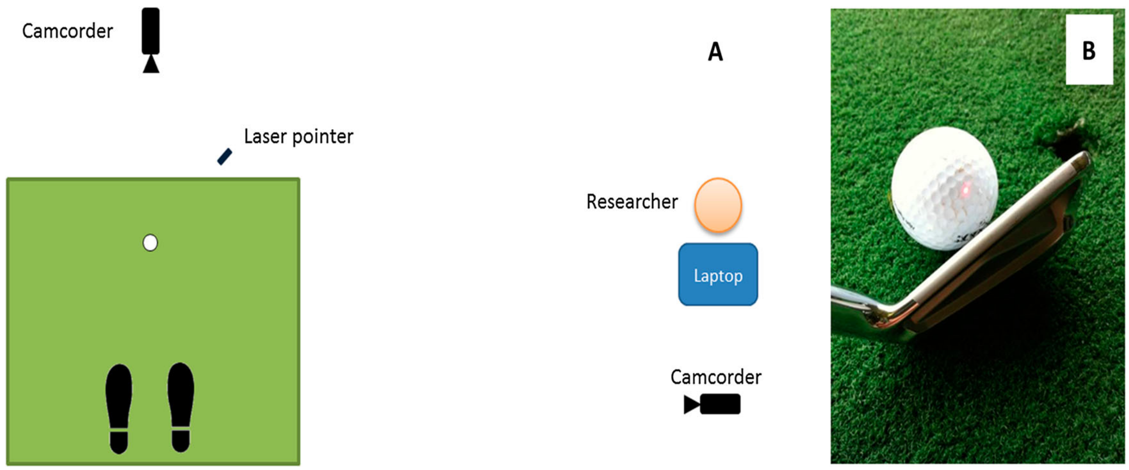

Figure 1. Study setup (a), incorporating visual guide (b).

of the stability of the participant's performance and his self-reported fatigue. Thus, a phase was terminated when the participant's performance displayed a sufficient level of stability – that is, no systematic decline or improvement occurred over at least 10 trials (i.e. approximately one round's worth of strokes with this club), or when the participant reported fatigue.

The golf balls only spanned approximately 1.46 degrees of visual angle at the distance viewed. Therefore recalibration was performed at every trial, to increase the likelihood of detecting minor – but potentially impactful – changes in point-of-gaze. This was achieved by asking the participant to look at the front, rear, top and bottom of the ball's circumference, as viewed from above, in sequence; the corresponding points in the software's graphical user interface window were selected as he confirmed his point-of-gaze. After each recalibration, the participant was asked to look at each point again; further recalibration was performed again if the cursor deviated from those points. Gaze and performance data were recorded for all trials.

Baseline. The participant was required to repeatedly hit shots to the target 200 yards away. For each shot, the researcher performed online inspection of the participant's point-of-gaze in the period from setup to ball strike, making trial-by-trial notes and diagrams in the process; he also recorded the final ball position onto the grid. After 50 trials had been completed (approximately 5 rounds' worth of shots) the researcher shared his notes with the participant, so that he could learn potential relationships between his gaze and his performance. The participant was surprised that his gaze was not typically located where he had intended, and was keen to correct this discrepancy. Hence, the researcher and participant collectively determined an intervention based on the potency of both exogenous cueing for directing gaze (Posner, 1980), and of gaze training for improving kinematics (Moore et al., 2012), to enable the participant to look at the ball in a more consistent and facilitative manner (see below).

Intervention. A laser pointer was introduced, to project a highly visible, and therefore attention-grabbing but otherwise unobtrusive, luminous red dot onto the desired optimal location – the top-rear of the ball (see Figure 1(b)), to act as a visual guide for the participant's gaze.

The participant hit a total of 36 shots to the same target as used at baseline. Before the participant addressed the ball the researcher provided verbal instruction to the participant to "look at the red dot" prior to swinging the golf club. The participant was not given any instructions pertaining to the relative timing or duration of his gaze, such that he could otherwise reproduce his existing routine as faithfully as possible. The researcher provided feedback to the participant regarding his eye movements after each trial in which final fixation (a minimum duration of 3 consecutive frames/120 ms prior to backswing initiation; cf. QE) was not consistently at the desired location; he also asked him to step out of the shot if his eye movements were displaying excessive movement (deviating from the ball and/or moving around too much), not on the desired location (i.e. at the top-rear of the ball), or a combination of the two. If the participant's gaze behaviour was considered appropriate, then no feedback was given.

Intervention phasing-out. The researcher provided verbal feedback after each trial, with the aim of maintaining gaze consistency within and across all trials. The visual guide was initially present for alternate trials. After 10 trials, as gaze behaviour across the 2 conditions had remained highly consistent (i.e. tending towards the intended location when the guide was both present and absent), the frequency of visual guidance was decreased to one in every three trials. After a further 10 trials, this frequency was reduced to once every 4 trials, due to sustained gaze consistency. As the participant continued to demonstrate over the course of 13 trials that he had learnt to reliably maintain his gaze at the optimal location, the guide was removed entirely – for another 10 shots. Variability of practice benefits motor learning in terms of long-term retention of learnt skills (Schmidt & Wrisberg, 2004); hence, we expected that similar oculomotor learning benefits may be manifested at Retention by incorporating this variation.

Retention. In the final phase, which took place one week following the intervention phasing-out phase, the participant's learning of the optimal point-of-gaze during the preceding two stages was assessed. He was required to hit 30 shots, using the same 5-iron, to the target, with no visual guidance or feedback.

Results

Online eye movement data analysis

Baseline. The participant's gaze at the point of addressing the ball was markedly still; arguably, QE was achieved. However, the researcher noticed an unexpected – and potentially serendipitous – finding: that the participant's gaze, although still, was often not at its intended location at the rear of the ball: for 43 of the 50 trials (86.0% of trials), it was on, or near, the bottom-right region of the ball (as viewed from above; see Figure 2(b)).

Intervention. The intervention initially promoted greater variability in the participant's eye movements – potentially an index of the learning process (Schmidt & Wrisberg, 2004). However, despite this, the intervention was successful in shifting the participant's eye movements away from the bottom-right of the golf ball: he fixated there for only 7 of the 36 trials (19.4%). Moreover, there was a greater tendency to fixate at the desired location immediately prior to initiation of the backswing. On receiving the researcher's trial-by-trial feedback, the participant either made the necessary adjustments to his point-of-gaze or did not execute the shot.

Phasing-out. The participant began to improve his ability to maintain gaze on the top-rear of the golf ball: fixation remained at this point immediately prior to backswing initiation for 18 of the 43 trials (41.9%), whereas the bottom-right of the ball was fixated for one trial only. For the remaining trials, the participants' gaze exhibited some variability, in that final fixations were spread across the surface of the ball (see Figure 2(b)).This variability was comparable to that observed at the intervention phase.

Retention. The Retention data clearly show that the new gaze behaviour had been learnt: the participant rapidly and reliably fixated around the intended gaze location for 22 of the 30 trials (73.3%). Furthermore, the participant made no fixations upon the bottom-right region of the golf ball. Gaze variability decreased substantially.

The relationship between point-of-gaze and ball distribution

Figure 2 highlights the correspondence between point-of-gaze and each of the final ball locations (the fairway runs from right to left as viewed). The right-hand images were captured from the scene camera footage, and comprise the crosshair used to identify point-of-gaze for the captured frame, and a "heat map" to illustrate representative eye movements during the trial from which the frame was captured. Each heat map was derived using the ASL analysis software, and was selected for being representative of the majority (~95%) of trials, for which gaze was relatively focused in one area, despite infrequent isolated saccadic movements that exhibited no discernible pattern (NB: in the remaining ~5% of trials, the heat map was more dispersed around the ball).

The participant commented that his typical error was to fade the ball; that is, for the ball's trajectory to arc from left to right; this is mirrored in the ball distribution data shown in Figure 2(a), which shows a greater distribution of balls to the right of the target. In Figure 2(b), the baseline data show that the participant's point-of-gaze was typically located at the bottom-right of the golf ball, as viewed from above.

The second image in Figure 2(b) corroborates the researcher's initial observations, that the participant's point-of-gaze displayed greater variability at Intervention. However, his gaze typically shifted towards the intended location, but was still somewhat proximal to his feet and was also posteriorly oriented. The ball distribution was comparable to that at Baseline, insofar as the standard deviation in the distance from target increased slightly (± 7.68 vs. ± 7.49 yards),

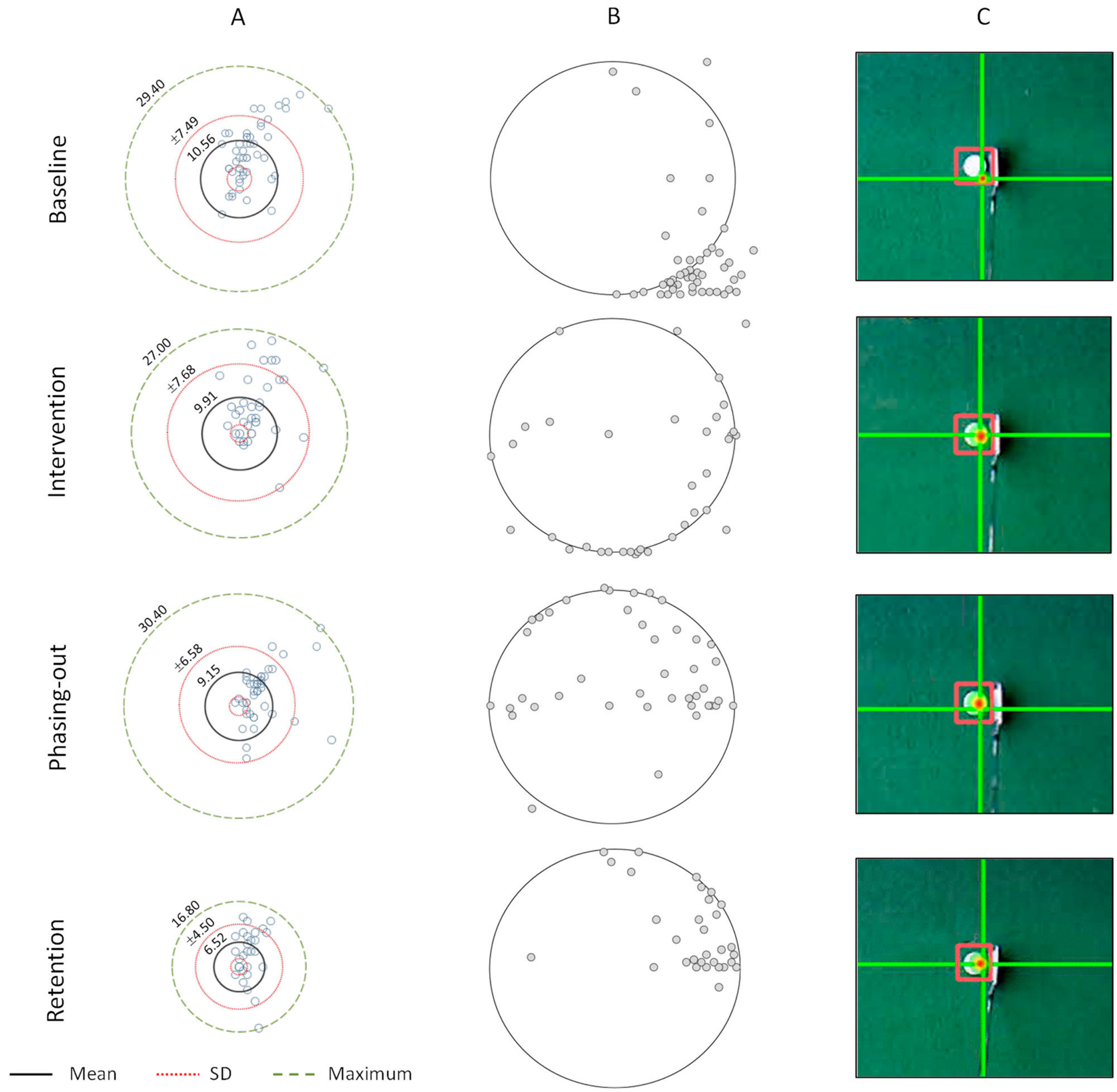

Figure 2. Ball distribution (a), final fixation location for each trial (b) and representative gaze data [heat map and gaze cursor] (c), by phase.

whilst the mean decreased slightly (9.91 vs. 10.56 yards); the distance of the furthest shot also decreased marginally (27.00 vs. 29.40 yards).

At the Phasing-out stage, the participant's point-of-gaze shifted perceptibly to the desired location – at the top-rear of the ball. The associated gaze cross-hair in Figure 2(c) was selected to illustrate that, on some trials, the gaze point intermittently drifted towards its original baseline location, despite an overall tendency towards the intended location (heat map). The ball distribution also improved relative to both Baseline and Intervention phases, such that both the mean distance (9.15 yards) and its associated standard deviation (±6.58 yards) decreased.

The constancy of both point-of-gaze and ball distribution at Retention is evident in the corresponding portion of Figure 2. Whilst the participant still continued to predominantly miss to the right of the target (see Figure 2(a)), the consistency and precision of his gaze fixation culminated in a tighter clustering of balls to the target relative to the other phases, most notably baseline. Specifically, the mean distance from the target during the Retention phase was 6.52 yards (SD = 4.50 yards; Max = 16.80 yards).

Ball final location: trends

Figure 2(a) depicts the radial distance of the ball from the target for every trial, by phase; mean and median values for each phase are also shown. Analysis of the intervention's effectiveness was performed by visual inspection of the data; this was facilitated by introduction of a trend line, developed using a linear regression procedure in which sequential trial numbers were entered as predictors. As can be seen from the figure, the participant hit the ball closer to the target as the study progressed from Baseline to the Retention phase. Furthermore, at Retention, only one shot culminated in a ball location further than 15 yards from the target. This compares favourably with 10 shots greater than this distance in the Baseline phase – of which 7 ended up more than 20 yards from the target.

Discussion

We investigated whether the well-learned gaze behaviour of an experienced golfer could be retrained, using an artificial visual guide to represent optimal point-of-gaze for the full golf swing. Consistent with previous examinations of QE in golf putting (Moore et al., 2012; Vine et al., 2011), we used a naturalistic task in order to ensure that the participant's gaze patterns mirrored those used when out on the golf course. We hypothesised that, by using visual guidance to promote subtle changes in an experienced golfer's ball-directed gaze immediately prior to execution of the full golf swing, we might reliably elicit imperceptible changes in his club kinematics, which in turn would be reflected in tighter distribution of the balls around the target. Subsequent to baseline data collection, a laser pointer was directed at the ball, in an attempt to retrain a potentially erroneous gaze pattern.

In line with our hypotheses, as point-of-gaze became less dispersed, ball distribution lessened noticeably: there was a progressive shift from baseline to Retention, of the participant's point-of-gaze immediately prior to initiation of the backswing, from a region at the bottom-right of the ball towards his originally intended point of fixation: at the top-rear of the ball. This finding suggests that the intervention was successful – and that some degree of *oculomotor relearning* took place (cf. Albouy et al., 2006) – supporting our second hypothesis. Additionally, the variability of this final gaze point increased during intervention, and to a lesser extent as the intervention was phased out, until it reached its minimum at Retention. We propose that the observed shifts in gaze are indices of subtle recalibration of the golfer's internal model of the swing. We also tentatively propose that the variability in final fixation location observed during the intervention phase was a marker of the learning process (Schmidt & Wrisberg, 2004).

Also in line with our hypothesis, visual inspection of ball distribution data showed that the mean dispersion of the participant's shots reduced over the entire study; trend analysis confirmed this. Moreover, his inherent tendency to *fade* the ball – that is, for the ball to arc on a left-to-right trajectory – was markedly diminished at Retention, such that ball dispersion was noticeably less skewed to the right of the target. These findings collectively reinforce the notion that there is a very tight coupling between gaze and bodily movements, as shown previously (Hayhoe et al., 2012; Land & McLeod, 2000). However, to our knowledge, this is the first study to demonstrate the impact of learnt subtle changes to point-of-gaze on the execution of such a highly coordinative motor skill.

If the improvements in accuracy and consistency we observed can be reliably reproduced, then the implications of our findings for skilled performance of a full round of golf are considerable. For an experienced golfer using a 5-iron club, a longitudinal deviation of 3–4 yards may mean the difference between the ball falling short of the green versus rolling onto it; a lateral deviation of the same magnitude may determine whether the ball remains on the fairway. And there is a knock-on effect for the subsequent shot: in the case of falling short, the golfer is required to chip the ball onto the putting green, reducing their chances of holing the next shot relative to a comparatively straightforward putt; in the case of the ball drifting off the fairway, the longer grass is not conducive to a full swing – which typically diminishes ball flight distance and spin. We only examined the effect of the intervention for the 5-iron club, but if the learning effect should transfer to shots played with other clubs, then its impact may be multiplied.

Golf coaches' preferred modus operandi is to use video analysis to monitor the kinematics of a golfer's swing in order to determine the presence of technical faults. However, it would arguably be more beneficial for coaches to monitor their clients' gaze patterns; this is also a very straightforward teaching intervention when compared to one in which kinematic analysis is required, be it online or offline. In this way, gaze data may represent a form of *augmented feedback*, particularly in instances such as that observed here, wherein despite less-than-optimal performance, no technical faults are apparent. However, this type of feedback is likely to be more beneficial to those coaches who work with elite golfers, as these individuals exhibit far fewer, and less detectable, faults in their swings.

There are several limitations of the present study. First, we did not employ a transfer test (e.g. transfer to a more lofted club); this is something that clearly warrants further investigation, in order to determine the potential impact on overall round scores. Second, the number of trials performed in the Intervention phase is low compared to other eye movement training studies (e.g. Vine & Wilson, 2010). However, this number was determined according to the stability of the participant's performance, as well as to minimise fatigue-related effects. Despite the limited number of trials, our intervention was nevertheless successful in reducing variability of both gaze and shot dispersion, suggesting that short-duration gaze retraining interventions may be effective.

The absence of data pertaining to club and/or swing kinematics is a notable omission from our study. We did employ camcorders to record the participant's swing from behind the driving bay, and the club head at ball contact (see Figure 1), but a qualified coach could not pick up any subtle changes in the former footage, and the speed of the latter was insufficient to capture meaningful data. Therefore, a logical progression of this research area would be to utilise suitable technology, notably high speed cameras or motion capture systems, to obtain high-quality club head kinematic data. Moreover, 3D tracking radar technology (e.g. *Flightscope*® or *TrackMan*®) would enable precise measurement of ball flight parameters, such as the angle and speed of the club head at impact, the launch angle of the ball and shot dispersion. This technology can be utilised *in vivo*, providing the researcher or coach with detailed real-time information about very subtle changes in ball flight characteristics as a result of gaze shifts.

Examinations of gaze behaviour in aiming tasks have employed grosser indices of QE, which has typically been defined as gaze that remains within three degrees of visual angle (Vickers, 1996). Whilst this has clearly been effective, in that performance of the associated motor task has tended to improve significantly in a short timeframe, we should note that the performance outcome measures are also comparatively forgiving. For example, in the case of a 12-foot golf putt, the diameter of the hole bisects an angle of 1.72 degrees relative to the centre of the ball before it is struck; this affords a relatively generous margin of error at the point of club-ball contact. Similarly lenient margins are afforded in basketball shooting, football penalty taking – and even rifle shooting, when considering the stillness of the weapon prior to trigger pull. Conversely, in the case of striking a golf ball 200 yards, the angle is a mere 0.03 degrees; the margin of error for translation or rotation of the club head is equally minute. This makes the observed changes in ball distribution all the more remarkable. If oculomotor relearning on such a minute scale can be evidenced in other contexts, then the ramifications of our findings extend far beyond the game of golf, and sports generally. For example, for similarly ingrained everyday tasks, then we may be able to retrain relatively simple motor skills that have somehow become dysfunctional, perhaps through disuse, physical injury, stroke, Parkinson's disease or other pathology.

Disclosure statement

No potential conflict of interest was reported by the authors.

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