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Quiet eye training expedites motor learning and aids performance under heightened anxiety: The roles of response programming and external attention

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Abstract

Quiet eye training expedites skill learning and facilitates anxiety-resistant performance. Changes in response programming and external focus of attention may explain such benefits. We examined the effects of quiet eye training on golf-putting performance, quiet eye duration, kinematics (clubhead acceleration), and physiological (heart rate, muscle activity) responses. Forty participants were assigned to a quiet eye or technical trained group and completed 420 baseline, training, retention, and pressure putts. The quiet eye group performed more accurately and displayed more effective gaze control, lower clubhead acceleration, greater heart rate deceleration, and reduced muscle activity than the technical trained group during retention and pressure tests. Thus, quiet eye training was linked to indirect measures of improved response programming and an external focus. Mediation analyses partially endorsed a response programming explanation.

Descriptors: Anxiety, Heart rate deceleration, Kinematics, Motor learning, Quiet eye, Visuomotor control

The control of gaze is a critical determinant of accuracy in the execution of visually guided motor tasks (Vickers, 2011). Indeed, recent research has demonstrated that improved motor performance can be attained when individuals are trained to employ more efficient gaze control (Vine, Moore, & Wilson, 2011). Furthermore, gaze training interventions have been shown to facilitate motor performance that is robust against the detrimental effects of anxiety (Vine & Wilson, 2010). However, the mechanisms through which such interventions exert these beneficial effects have yet to be established (Vine et al., 2011). The present study was designed to shed light on these issues.

The Quiet Eye

Research has characterized the gaze control associated with numerous motor tasks. One particular gaze strategy, termed the quiet eye (Vickers, 1996)—defined as the final fixation towards a relevant target prior to the initiation of a movement (Vickers, 2007)—has been shown to underlie higher levels of skill and performance; with longer quiet eye durations characterizing greater expertise and accuracy (see Vickers, 2007, for a review). However, it should be noted that the quiet eye duration–performance relationship is not strictly linear; above a threshold value of quiet eye duration, further increases may provide no further benefit. An optimal range of quiet eye durations may therefore exist for particular motor tasks (e.g., a couple to several seconds in golf putting), and, accordingly, exceeding these durations may be counterproductive by inducing attentional and/or postural fatigue (Behan & Wilson, 2008).

The quiet eye is trainable. Recent research has shown that both elite and novice performers can be trained to develop longer and more effective quiet eye durations, leading to improved performance compared to control groups (Causer, Holmes, & Williams, 2011; Vine et al., 2011; Vine & Wilson, 2010, 2011). For example, Vine and Wilson (2011) examined the effect of quiet eye training on the gaze control and basketball free-throw performance of novice participants. The quiet eye trained group displayed longer quiet eye durations and greater free-throw accuracy than the control group in retention tests, indicative of improved learning.

The quiet eye is also sensitive to the influence of anxiety. Research has demonstrated that under conditions of heightened anxiety quiet eye durations are reduced, negatively impacting upon performance (Behan & Wilson, 2008; Causer, Holmes, Smith, & Williams, 2011; Vickers & Williams, 2007; Wilson, Vine, & Wood, 2009). Collectively, previous research implies that if individuals can be trained to actively maintain longer quiet eye durations when experiencing elevated anxiety, the negative effects of anxiety on performance may be attenuated (Behan & Wilson, 2008; Wilson et al., 2009). Indeed, recent research has supported this possibility

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(Vine & Wilson, 2010, 2011). For example, Vine and Wilson (2010) showed that a quiet eye trained group maintained longer quiet eye durations and performed a golf-putting task more accurately than a control group under heightened anxiety.

Processes Underpinning Quiet Eye Training

Researchers have highlighted a number of processes through which quiet eye training might aid learning and performance under elevated anxiety, consisting of both visuomotor control and psychological control elements (Vine et al., 2011). First, from a cognitive neuroscience perspective, longer quiet eye durations may extend the duration of a critical period of motor preparation (i.e., response selection and programming stages) during which the parameters of the movement (e.g., direction and force), as well as the timing and coordination of the limbs, are fine-tuned and programmed (Mann, Coombes, Mousseau, & Janelle, 2011; Vickers, 1996). Thus, longer quiet eye durations should result in movement kinematics that are more likely to translate to successful motor performance (Vickers, 2011). While recent research has revealed an association between the quiet eye and a more direct cortical measure of motor programming (the Bereitschaftspotential; Mann et al., 2011), changes in movement parameters can nonetheless provide useful indirect measures of response planning and control (Causer, Holmes, & Williams, 2011).

Research has demonstrated that by encouraging gaze to be directed to key locations, quiet eye training interventions can indirectly cause beneficial changes in movement kinematics. For example, Causer, Holmes, and Williams (2011) found that elite shotgun shooters exhibited more expertlike gun kinematics as a result of quiet eye training, including reduced gun barrel displacement and peak velocity. Thus, one potential mechanism through which quiet eye training might facilitate the acquisition of motor skills is by extending a critical period of response programming and thereby creating more expertlike movement kinematics. Recent research has demonstrated that anxiety and competitive pressure can disrupt movement kinematics (Causer, Holmes, Smith, & Williams, 2011; Cooke, Kavussanu, McIntyre, & Ring, 2010). Therefore, by ensuring that performers maintain effective gaze control, quiet eye training interventions might aid performance under elevated anxiety by ensuring that accurate response programming and expertlike movement kinematics are also preserved.

Second, the quiet eye may exert a less “direct” effect on motor performance, by helping performers achieve a period of neuromuscular quiescence prior to movement execution by focusing attention externally towards a single relevant cue (Vine et al., 2011). According to the Intake-Rejection Hypothesis (Lacey & Lacey, 1974, 1980), an external focus of attention induces a deceleration in heart rate immediately prior to task execution. Numerous studies have offered support for this hypothesis (Neumann & Thomas, 2009, 2011; Radlo, Steinberg, Singer, Barba, & Melnikov, 2002). For example, Radlo and colleagues (2002) found that focusing attention externally at the target while performing a dart-throwing task was associated with a pronounced deceleration in heart rate prior to the throw and more accurate performance.

Research has also demonstrated that an external focus of attention is associated with reduced electromyographic (EMG) activity (Lohse, Sherwood, & Healy, 2010; Zachry, Wulf, Mercer, & Bezodis, 2005). For instance, Lohse and colleagues (2010) found that an external focus of attention (on the bull’s-eye and flight of the dart) resulted in reduced muscle activity in the triceps brachii of the dart-throwing arm and superior performance. Interestingly, movement kinematics did not change as a function of focus of attention. As anxiety and competitive pressure can disrupt heart rate deceleration (Hassmen & Koivula, 2001) and increase muscle activity (Cooke et al., 2010), a quiet eye strategy might aid performance under heightened anxiety by ensuring that an effective external focus of attention and physiological state (i.e., greater heart rate deceleration and reduced muscle activity) is maintained.

The Present Study

The aim of the present study was to evaluate potential underlying processes through which a quiet eye training intervention aids the learning and performance under heightened anxiety of novice participants in a golf-putting task. We predicted that, compared to a group adopting the current best practice of focusing on technical points (technical trained group), participants in a quiet eye trained group would perform better in retention tests, due to longer quiet eye durations, more expertlike putting kinematics (i.e., lower clubhead acceleration), and physiological processes reflective of an external focus of attention (i.e., greater heart rate deceleration and reduced muscle activity). Additionally, we predicted that participants in a quiet eye trained group would perform better in a pressure test, compared to those in a technical trained group, as they should continue to adopt their efficient gaze control, expertlike putting kinematics, and physiological control. In comparison, technical trained group participants would display significantly poorer gaze control (i.e., shorter quiet eye durations), disrupted putting kinematics and heart rate deceleration, and increased muscle activity in the pressure test, compared to retention tests. Finally, to examine if response programming and external attention account for the effects of quiet eye training on learning and performance under elevated anxiety, we conducted mediation analyses (Baron & Kenny, 1986) to evaluate potential mediators (putting kinematics, muscle activation, heart rate deceleration) of performance at retention and when under heightened anxiety. If only kinematic variables mediated performance, this would provide indirect support for the role of response programming; whereas if only heart rate deceleration and/or muscle activity variables mediated performance, this would offer indirect support for an external attention explanation. If both kinematic and physiological variables mediated performance, this would offer indirect support for both explanations.

Method

Participants

Forty undergraduate students (mean age, 19.55, *SD* = 1.65 years) volunteered to participate in the study. All participants declared having no official golf handicap or prior formal golf-putting experience, and thus were considered novice golfers (Cooke et al., 2010). Furthermore, all were right-handed, reported normal or corrected vision, and were individually tested. The protocol was approved by the local ethics committee, and written informed consent was obtained from each participant.

Measures

Cognitive anxiety. Cognitive state anxiety was measured using the cognitive subscale from the Mental Readiness Form-3 (MRF-3; Krane, 1994). This scale is anchored between (1) *not worried* and (11) *worried*.

Performance. Both the mean radial error (the average distance the ball finished from the hole in cm) and percentage of putts successfully holed in each test were recorded as measures of task performance. Zero was recorded and employed in the calculation of mean radial error on trials where the putt was holed (Cooke et al., 2010; Vine et al., 2011). Furthermore, on trials where the ball hit the boundary of the putting green (90 cm behind the hole), the largest error possible was recorded (90 cm). This occurred on 456 (11%) of the 4,000 trials (Pretest = 165 quiet eye, 172 technical; Retention 1 = 15 quiet eye, 20 technical; Pressure = 16 quiet eye, 19 technical; and Retention 2 = 20 quiet eye, 29 technical).

Quiet eye duration. Gaze was measured using an Applied Science Laboratories (ASL; Bedford, MA) Mobile Eye Tracker. This lightweight system utilizes two features: the pupil and corneal reflection (determined by the reflection of an infrared light source from the surface of the cornea) to calculate point of gaze (at 30 Hz) relative to eye and scene cameras mounted on a pair of spectacles. A circular cursor, representing 1° of visual angle with a 4.5 mm lens, indicating the location of gaze in a video image of the scene (spatial accuracy of ± 0.5° visual angle; 0.1° precision), was viewed by the research assistant in real time on a laptop screen (Lenovo R500 ThinkPad) installed with Eyevision (ASL) recording software. Participants were connected to the laptop via a 10-m firewire cable, and the researcher and laptop were located behind the participant to minimize distractions. The video data were recorded for subsequent offline analysis.

The quiet eye duration was operationally defined as the final fixation towards the ball prior to the initiation of the backswing (Vickers, 2007). A fixation was defined as a gaze maintained on an object within 1° of visual angle for a minimum of 100 ms. Quiet eye onset occurred before the backswing and quiet eye offset occurred when the gaze deviated off the fixated object by 1° or more, for greater than 100 ms (Wilson et al., 2009). Gaze data was analyzed using Quiet Eye Solutions software (www.QuietEyeSolutions.com). This software allows for frame-by-frame coding of both the motor action (recorded from the Mobile Eye's scene camera at 30 Hz) and the gaze of the performer, and automatically calculates quiet eye duration. Consistent with previous research (e.g., Vine & Wilson, 2010), a subset of putts—every fourth for pretest and every second for test phases (10 putts per test)—were selected for frame-by-frame video analysis (a total of 1,600 putts). The researcher was blind to the test and status (group) of each participant when analyzing the data, and minimized potential bias during testing by following the same written protocols for all tests. A second analyst blindly scored 10% of the quiet eye data, and inter-rater reliability was assessed using the interobserver agreement method (Thomas & Nelson, 2001). This method estimates reliability using a formula that divides the number of commonly coded quiet eye durations (i.e., within 33.33 ms or one frame) by the sum of the commonly coded quiet eye durations and quiet eye durations coded differently. This analysis revealed a satisfactory level of agreement at 91% (Vine & Wilson, 2011).

Cardiac activity. An electrocardiogram was measured using two silver/silver chloride spot electrodes (Cleartrace, ConMed, Utica, NY) in a modified chest configuration in order to measure cardiac activity. The modified chest configuration consisted of two active electrodes positioned on the right clavicle and lower left rib and a reference electrode positioned on the left clavicle. The electrocardiographic signal was amplified (Bagnoli-4, Delsys, Boston, MA), filtered (20–450 Hz), and digitized at 2,500 Hz with 16-bit resolution (Power 1401, Cambridge Electronic Design, Cambridge, UK) using Spike2 software (Cambridge Electronic Design). The mean heart rate during each test was derived from the intervals between the R-waves of the electrocardiogram and was used to check the effectiveness of the anxiety manipulation. We also determined the phasic change in heart rate 6 s prior to putter-ball contact until 1 s after putter-ball contact (Neumann & Thomas, 2011). A heart rate value for each 0.5-s epoch was calculated from the R–R intervals using time-based methods (Graham, 1978). Change in heart rate was calculated by subtracting the heart rate at 6 s prior to putter-ball contact from the heart rate in each 0.5-s epoch, such that a negative change reflected a deceleration in heart rate.

Putting kinematics. While measuring clubhead displacement is an indirect measure of motor control and coordination, it is frequently adopted in the golf-putting literature (e.g., Cooke et al., 2010; Delay, Nougier, Orliaguet, & Coello, 1997). Acceleration of the clubhead in three axes was recorded using a triaxial accelerometer (LIS3L06AL, ST Microelectronics, Geneva, Switzerland). Acceleration on the x, y, and z axes corresponded to lateral, vertical, and back-and-forth movement of the clubhead, and assessed clubhead orientation, clubhead height, and impact velocity, respectively. The signals were conditioned by a bespoke buffer amplifier with a frequency response of DC to 15 Hz. Both accelerometer and amplifier were mounted in a 39 mm × 20 mm × 15 mm plastic housing secured to the rear of the clubhead. A microphone (B5 Condenser, Behringer, Germany) connected to a mixing desk (Eurorack UB802, Behringer, Germany) was used to detect the putter-ball contact on each trial. These signals were digitized at 2,500 Hz. A computer program determined clubhead kinematics for each putt from the onset of the downswing phase of the putting stroke until the point of putter-ball contact. The average acceleration was calculated for the x, y, and z axes. The values from all trials in each test were averaged to provide a test mean value for each kinematic variable (Cooke et al., 2010).

Muscle activity. EMG activity of the extensor carpi radialis muscle of the left arm was recorded, due to previous research implicating this muscle as most influential in the golf-putting stroke (Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011; Cooke et al., 2010). Muscle activity was measured using single differential surface electrodes (DE 2.1, Delsys) and an amplifier (Bagnoli-4, Delsys) with a ground electrode on the collar bone. EMG signals were amplified, filtered (20–450 Hz), and digitized (2,500 Hz). The EMG signal for each trial was rectified, and the phasic change in muscle activity 6 s prior to putter-ball contact until 1 s after putter-ball contact was computed. The mean amplitude (microvolts) was averaged for 1-s intervals to derive a value for each 0.5-s epoch (e.g., the mean activity from 2 to 3 s prior to putter-ball contact was used to calculate the value 2.5 s prior to putter-ball contact). Phasic change in muscle activity was calculated by subtracting the activity at 6 s prior to putter-ball contact from the activity in each 0.5-s epoch, such that a negative change reflected a reduction in muscle activity.

Procedure

The pretest, training, and test phases took place over 7 days and involved taking straight putts from three 10-ft (3.05 m) locations to a regulation hole (diameter = 10.80 cm) on a relatively fast-running artificial putting green (length = 6 m, width = 2.5 m; Stimpmeter reading = 3.28 m (10.77 ft)). All participants used a standard

Table 1. *Training Instructions Given to the Quiet Eye and Technical Trained Groups During the Training Phase*

Quiet eye training instructions	Technical training instructions
1. Assume your stance, and ensure your gaze is located on the back of the ball.	1. Take your stance with your legs shoulder width apart.
2. After setting up over the ball, fix your gaze on the hole.	2. Set your position so that your head is directly above the ball looking down.
3. Make no more than 3 fixations towards the hole.	3. Keep your clubhead square to the ball.
4. Your final fixation should be a quiet eye on the back of the ball. The onset of the quiet eye should occur before the stroke begins and last for 2 to 3 s.	4. Allow your arms and shoulders to remain loose.
5. Ensure you direct no gaze towards the clubhead during the putting stroke.	5. The putting action should be pendulumlike, making sure that you accelerate through the ball.
6. The quiet eye should remain on the green for 200 to 300 ms after the club contacts the ball.	6. After contact, follow through but keep your head still and facing down.

length (90-cm) steel-shafted blade style golf putter (Sedona 2, Ping, Phoenix, AZ) and regular-size (diameter = 4.27 cm) white golf balls. On day one (session 1), after providing informed consent, participants were fitted with the physiological recording equipment and with the eye-tracker, which was calibrated and then checked every 10 putts to ensure point-of-gaze was being accurately recorded.

Next, participants performed a block of 40 putts during which performance, gaze, cardiac activity, muscle activity, and putting kinematic data were continuously recorded. These data acted as a baseline (pretest) measure. The physiological recording equipment was then removed. Participants then began their respective training regime (quiet eye or technical; see Training Protocol), and performed two blocks of 40 putts. The training points were reiterated by the experimenter before each block of 40 putts. Three blocks of 40 putts were then performed on days two and three (sessions 2 and 3), to complete a total of 320 training putts (8 blocks of 40 putts). The number of trials performed during the training phase is in line with previous training studies for self-paced motor skills in novices (e.g., Vine & Wilson, 2010, 2011).

On day five (session 4), participants were once again fitted with the physiological recording equipment and the eye-tracker. Calibration was repeated before the participants performed a retention test consisting of a single block of 20 putts without the guidance associated with their training regime. On day seven (session 5), participants performed 20 competition putts in a pressure test aimed at manipulating levels of cognitive anxiety (see Anxiety Manipulation). Finally, they performed a second retention test (identical to retention 1) to form an A-B-A (retention-pressure-retention) design (Vine & Wilson, 2010). Performance, gaze, cardiac activity, muscle activity, and putting kinematic data were recorded throughout, whereas cognitive anxiety was assessed prior to and after each block of these 60 test phase putts. Finally, participants were thanked and debriefed.

Training Protocol

Participants were randomly assigned to either a quiet eye or technical trained group. The technical trained group received six technical coaching points related to the mechanics of their putting stroke based on Pelz (2000). The quiet eye trained group underwent a training regime adapted from previous quiet eye training research (Vine & Wilson, 2010). First, the quiet eye trained group viewed a video of an elite prototype who exhibited an optimal quiet eye as displayed in past gaze research (Vickers, 2007). The researcher directed quiet eye trained participants to the key features of the elite prototype's gaze control while asking questions to elicit their understanding. Second, six specific quiet eye training points were explained and were coupled to reflect similar phases of the putt as the technical instructions (i.e., preparation, aiming, putter-ball alignment, putting stroke, postcontact) to minimize differences in the focus and timing of instructions (see Table 1). It is worth noting that the quiet eye instructions make no mention of changes in movement kinematics.

Anxiety Manipulation

Several techniques were used prior to the pressure test to create social comparison and evaluative threat, which are known to increase levels of cognitive anxiety (Baumeister & Showers, 1986). First, a competition was set up whereby participants were informed that the best performing individual would receive a £50 ($75) cash reward. Second, participants were told that their performance would be compared with others taking part and may be used as part of a presentation to their fellow students. Finally, noncontingent feedback was used, whereby participants were informed that their previous 20 putts (retention test 1) would place them in the bottom 30% when compared to those who had already taken part. They were instructed to try and improve upon their performance, otherwise their data would be of no use for the study.

Statistical Analysis

Pretest and test phase (retention 1, pressure, and retention 2) cognitive anxiety, heart rate, performance, quiet eye duration, and putting kinematic data were each subjected to 2 (Group) × 4 (Test) mixed design analysis of variance (ANOVA). Significant main and interaction effects were followed up with least significant difference (LSD) post hoc *t* tests. Pretest and test phase phasic heart rate and muscle activity change data were subjected to 2 (Group) × 4 (Test) × 15 (Epoch) mixed design ANOVAs, with significant interaction effects followed by contrast analyses. In all ANOVAs, the degrees of freedom were corrected for sphericity assumption violations using the Huynh-Feldt correction procedure, and uncorrected degrees of freedom are reported along with the corrected probability values and the epsilon value. Effect sizes were calculated using partial eta squared (η_p^2) for omnibus comparisons. Finally, to determine if significant changes in process variables

Table 2. *Mean (*SD*) Cognitive Anxiety, Heart Rate, and* z*-Axis Clubhead Acceleration for Quiet Eye and Technical Trained Groups During Pretest, Retention Tests, and Pressure Test*

	Pretest		Retention 1		Pressure		Retention 2	
	Quiet eye trained	Technical trained	Quiet eye trained	Technical trained	Quiet eye trained	Technical trained	Quiet eye trained	Technical trained
Percentage of putts holed (0–100%)	19.75 (8.75)	17.60 (7.95)	27.50 (8.51)	19.50 (10.99)	26.25 (7.59)	16.25 (7.05)	26.50 (13.29)	19.75 (8.35)
Cognitive anxiety (1–11)	2.60 (1.20)	3.75 (1.54)	2.63 (1.20)	3.15 (1.32)	5.60 (1.24)	5.68 (1.67)	2.53 (0.94)	3.25 (1.52)
Heart rate (bpm)	86.70 (9.04)	85.87 (11.96)	91.91 (11.65)	89.71 (13.14)	96.09 (12.75)	94.22 (12.55)	86.30 (11.38)	90.25 (15.10)
z-axis acceleration ($m.s^{-2}$)	5.35 (1.01)	5.41 (1.03)	4.56 (0.74)	4.26 (1.15)	4.52 (0.70)	4.22 (1.46)	4.55 (0.78)	4.14 (1.40)

mediated any performance differences between groups, mediation analyses were performed using multiple regression analyses for retention and pressure tests (Baron & Kenny, 1986). To simplify the presentation and discussion of the mediation results, the retention test data were aggregated.

Results

Anxiety Manipulation Checks

The 2 (Group) × 4 (Test) ANOVAs yielded significant Test main effects for both self-reported cognitive anxiety, $F(3,114) = 67.42$, $p < .001$, $\acute{\varepsilon} = .88$, $\eta_p^2 = .64$, and heart rate, $F(3,114) = 11.31$, $p < .001$, $\acute{\varepsilon} = .91$, $\eta_p^2 = .23$; both were higher during the pressure test than the pretest and retention tests. There were no significant Group main or interaction effects, indicating that both groups had comparable levels of cognitive anxiety and heart rates across tests. The results are presented in Table 2.

Performance (Percentage of Putts Holed and Mean Radial Error)

The 2 (Group) × 4 (Test) ANOVAs yielded significant Group main effects for percentage of putts holed, $F(1,38) = 12.44$, $p < .001$, $\eta_p^2 = .24$, and mean radial error, $F(1,38) = 11.53$, $p < .005$, $\eta_p^2 = .23$. There were also significant Test main effects for percentage of putts holed, $F(3,114) = 2.96$, $p < .05$, $\eta_p^2 = .07$, and mean radial error, $F(3,114) = 38.65$, $p < .001$, $\acute{\varepsilon} = .50$, $\eta_p^2 = .50$. Furthermore, there were significant interaction effects for mean radial error, $F(3,114) = 3.91$, $p < .05$, $\acute{\varepsilon} = .50$, $\eta_p^2 = .09$, but not percentage of putts holed, $F(3,114) = 1.68$, $p = .18$, $\eta_p^2 = .04$. Follow-up analyses revealed that the quiet eye trained group holed a higher percentage of putts than the technical trained group ($p < .001$). Moreover, both groups holed more putts after training (from pretest to retention tests; both *p*s < .05). However, there were no differences in the percentage of putts holed between retention and pressure tests (both *p*s > .09). The percentage of putts holed during the pretest and test phase are presented in Table 2.

Follow-up *t* tests on the significant interaction effect for mean radial error revealed no differences between the groups at pretest ($p = .90$), however, the quiet eye trained group displayed lower mean radial error than the technical trained group during retention and pressure tests (all *p*s < .001). Within-group analyses revealed that both the quiet eye and technical trained groups displayed improvements in mean radial error (lower) between pretest and retention test 1 (both *p*s < .001). Indeed, mean radial error (percentage of putts holed) over the 8 training blocks was 36 (22%), 30 (24%), 31 (22%), 25 (23%), 25 (21%), 28 (21%), 24 (24%), and 24 (23%) for the quiet eye trained group and 43 (22%), 39 (22%), 40 (20%), 36 (21%), 33 (22%), 36 (20%), 33 (19%), and 30 (22%) for the technical trained group. Significant between-group differences in mean radial error arose at block 1 ($p < .05$); however, no between-group differences in the percentage of putts holed were evident. Furthermore, while the quiet eye trained group displayed no change in mean radial error between retention tests and the pressure test (both *p*s > .08), the technical trained group displayed higher mean radial error during the pressure test than the retention tests (both *p*s <.05). The pretest and test phase mean radial error results are presented in Figure 1.

Quiet Eye Duration

The 2 (Group) × 4 (Test) ANOVA yielded a significant main effect for Group, $F(1,38) = 48.93$, $p < .001$, $\eta_p^2 = .56$, Test, $F(3,114) = 67.68$, $p < .001$, $\acute{\varepsilon} = .61$, $\eta_p^2 = .64$, and a significant interaction effect, $F(3,114) = 28.42$, $p < .001$, $\acute{\varepsilon} = .61$, $\eta_p^2 = .43$. Follow-up *t* tests on the significant interaction effect revealed no quiet eye duration differences between the groups at pretest ($p = .92$); however, the quiet eye trained group displayed longer quiet eye durations than the technical trained group during the retention and pressure tests (all *p*s < .001). Within-group analyses revealed that both the quiet eye and technical trained groups displayed improvements in quiet eye duration (longer) between pretest and retention test 1 (both *p*s < .001). However, while the quiet eye trained group displayed no change in quiet eye duration between the retention tests and the pressure test (both *p*s > .81), the technical trained group displayed shorter quiet eye durations during the pressure test than the retention tests (both *p*s < .05). The quiet eye results are presented in Figure 1.

Putting Kinematics

The 2 (Group) × 4 (Test) ANOVAs revealed significant Group main effects for *x*-axis, $F(1,32) = 7.74$, $p < .01$, $\eta_p^2 = .20$, and *y*-axis, $F(1,32) = 10.54$, $p < .005$, $\eta_p^2 = .25$, acceleration. The quiet eye trained group displayed less lateral (*x*-axis acceleration) and vertical (*y*-axis acceleration) movement of the clubhead during the downswing phase of the putting stroke than the technical trained group across tests. Significant Test main effects emerged for *x*-axis, $F(3,96) = 23.10$, $p < .001$, $\acute{\varepsilon} = .66$, $\eta_p^2 = .42$, and *z*-axis, $F(3,96) = 23.57$, $p < .001$, $\acute{\varepsilon} = .53$, $\eta_p^2 = .42$, acceleration. The *z*-axis acceleration finding indicates that both groups were characterized by reduced impact velocity (lower acceleration in the

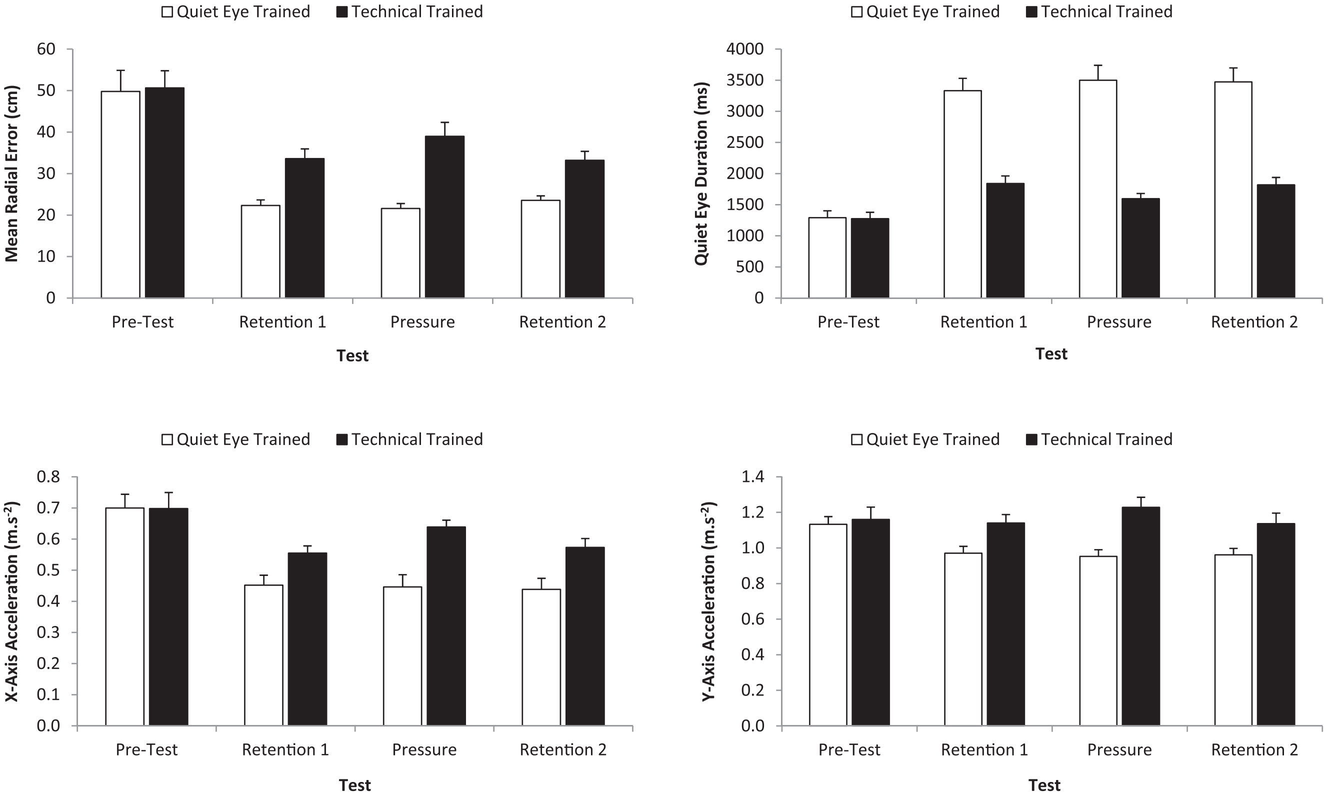

Figure 1. Mean (*SE*) radial error (cm) (A); quiet eye duration (ms) (B); *x*-axis clubhead acceleration ($m.s^{-2}$) (C); and *y*-axis clubhead acceleration ($m.s^{-2}$) (D) for the quiet eye and technical trained groups during pretest, retention tests, and pressure test.

back-and-forth plane) during the retention and pressure tests than pretest (all ps $< .001$; see Table 2).

The analyses also revealed significant interaction effects for *x*-axis, $F(3,96) = 4.50$, $p < .05$, $\acute{\varepsilon} = .66$, $\eta_p^2 = .12$, and *y*-axis, $F(3,96) = 3.02$, $p < .05$, $\acute{\varepsilon} = .74$, $\eta_p^2 = .09$, acceleration. Follow-up *t* tests revealed no difference between groups at pretest (both ps $> .85$); however, the quiet eye trained group displayed less *x*- and *y*-axis acceleration than the technical trained group during the retention tests and pressure test (all ps $< .01$). Within-group analyses revealed that while only the quiet eye trained group displayed an improvement in *y*-axis acceleration (reduced) between pretest and retention test 1 ($p < .05$), both the quiet eye and technical trained groups displayed improvements in *x*-axis acceleration (reduced; both ps $< .05$). Furthermore, while the quiet eye trained group displayed no change in *x*- or *y*-axis acceleration between the retention tests and the pressure test (all ps $> .28$), the technical trained group displayed greater *x*-axis acceleration during the pressure test than the retention tests (both ps $< .05$). The *x*- and *y*-axis acceleration results are presented in Figure 1.

Phasic Heart Rate Change

The patterning of heart rate in the 6 s before and 1 s after the ball was struck were similar for the two groups during the pretest but diverged during the subsequent tests, with the quiet eye group displaying earlier and more profound bradycardia (Figure 2). Inspection of the 95% confidence intervals was used to determine whether heart rate change was significantly different from 6 s prior to putter-ball contact (heart rate deceleration change was deemed significant if zero was outside the confidence interval; Neumann & Thomas, 2011). These analyses revealed that the technical trained group displayed a deceleration in heart rate that began 0.5 s prior to putter-ball contact during all tests. In contrast, the quiet eye trained group exhibited a deceleration in heart rate that began 1.0 s prior to putter-ball contact during the pretest and then at 4.5 s, 5.5 s, and 4.5 s during retention test 1, pressure test, and retention test 2, respectively.

A 2 (Group) × 4 (Test) × 15 (Epoch) ANOVA on heart rate change revealed significant main effects for Group, $F(1,35) = 16.17$, $p < .001$, $\eta_p^2 = .32$ (quiet eye < technical), Test, $F(3,105) = 10.28$, $p < .001$, $\eta_p^2 = .23$ (retention 1, pressure, and retention 2 tests < pretest), and Epoch, $F(14,490) = 53.06$, $p < .001$, $\acute{\varepsilon} = .15$, $\eta_p^2 = .60$ (putter-ball impact epoch < all other epochs), as well as interaction effects for Group × Test, $F(3,105) = 3.63$, $p < .05$, $\eta_p^2 = .09$, Group × Epoch, $F(14,490) = 6.57$, $p < .005$, $\acute{\varepsilon} = .15$, $\eta_p^2 = .16$, and Test × Epoch, $F(42,1470) = 3.59$, $p < .005$, $\acute{\varepsilon} = .15$, $\eta_p^2 = .09$. To interrogate these effects, a series of Group × Epoch polynomial contrast analyses were conducted for each Test: The preparatory changes in heart rate were best characterized by significant group differences in the quadratic trends for epoch at retention test 1 ($p < .001$, $\eta_p^2 = .38$), pressure test ($p < .001$, $\eta_p^2 = .39$), and retention test 2 ($p < .001$, $\eta_p^2 = .38$), but not at pretest ($p = .20$, $\eta_p^2 = .04$). These analyses also revealed that overall group differences were present at retention test 1 ($p < .001$, $\eta_p^2 = .30$), pressure test ($p < .001$, $\eta_p^2 = .15$), and retention test 2 ($p < .001$, $\eta_p^2 = .21$), but not at pretest ($p = .20$, $\eta_p^2 = .04$).

Finally, between-group *t* tests on the absolute values 6 s prior to putter-ball contact confirmed no significant differences in heart rate at pretest ($p = .69$), retention test 1 ($p = .94$), pressure test ($p = .75$), and retention test 2 ($p = .69$). These analyses indicate that the

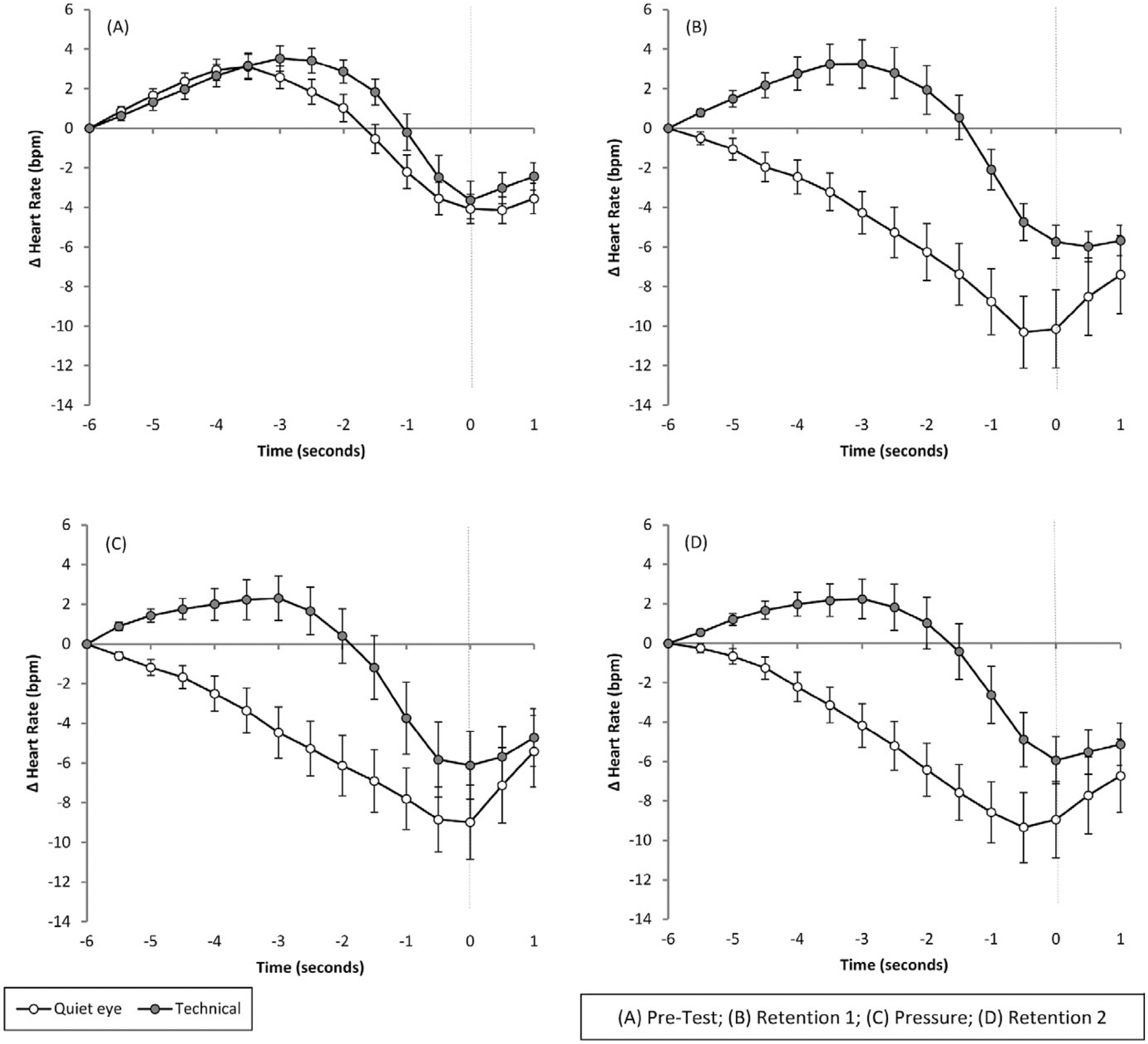

Figure 2. Mean (*SE*) heart rate change (bpm) in the 6 s prior to and 1 s following putter-ball contact for the quiet eye trained and technical trained groups during pretest (panel A), retention tests (panels B & D), and pressure test (panel C).

between-group differences in the patterning of heart rate change were not driven by differences 6 s prior to putter-ball contact.

Phasic Muscle Activity Change

The patterning of muscle activity before and after putter-ball contact were similar for both groups before training but differed between groups after training, with the quiet eye group exhibiting less preshot muscle activity (Figure 3). Inspection of the 95% confidence intervals (Neumann & Thomas, 2011) revealed that the technical trained group displayed an increase in muscle activity that began 3 s, 4.5 s, 1 s, and 0.5 s prior to putter-ball contact during pretest, retention test 1, pressure test, and retention test 2, respectively. In contrast, the quiet eye trained group exhibited an increase in muscle activity that began 2 s prior to putter-ball contact during pretest, but a decrease in muscle activity that began at 4.5 s, 5 s, and 5 s prior to putter-ball contact during retention test 1, pressure test, and retention test 2, respectively. This decrease lasted until 2.5 s, 3 s, and 3 s prior to putter-ball contact during these tests and was followed by an increase in muscle activity from 0.5 s, 1 s, and 0.5 s prior to putter-ball contact during retention test 1, pressure test, and retention test 2, respectively, until 1 s after putter-ball contact during all tests.

The Group × Test × Epoch ANOVA on muscle activity change yielded significant main effects for Group, $F(1,35) = 7.49$, $p < .01$, $\eta_p^2 = .18$ (quiet eye < technical), Test, $F(3,105) = 5.76$, $p < .005$, $\acute{\varepsilon} = .87$, $\eta_p^2 = .14$ (retention 1, pressure, and retention 2 tests < pretest), and Epoch, $F(14,490) = 24.72$, $p < .001$, $\acute{\varepsilon} = .18$, $\eta_p^2 = .41$ (putter-ball impact epoch > all other epochs). Furthermore, Group × Test, $F(3,105) = 5.05$, $p < .005$, $\acute{\varepsilon} = .87$, $\eta_p^2 = .13$,

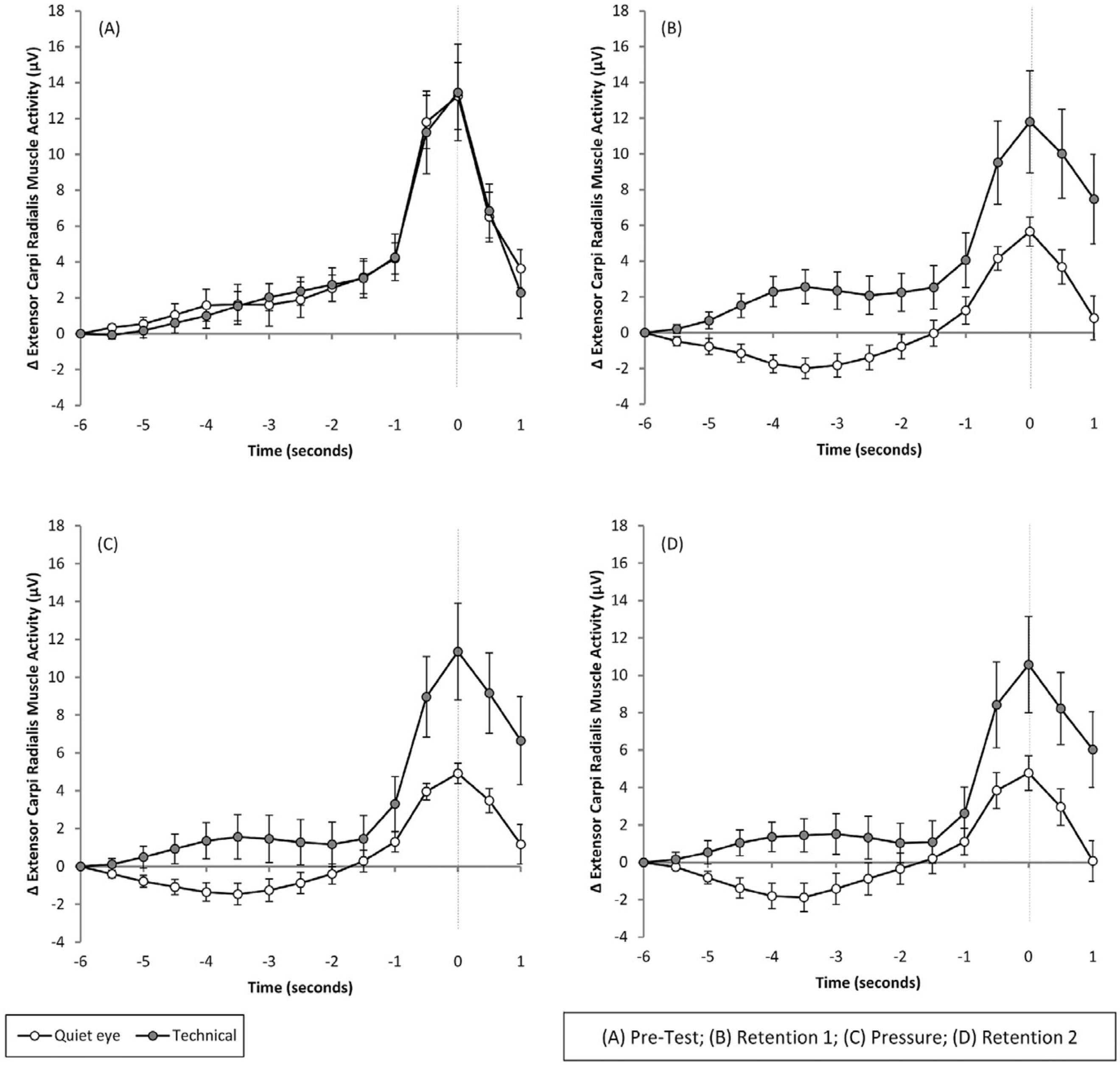

Figure 3. Mean (*SE*) left arm extensor carpi radialis muscle activity change (μV) in the 6 s prior to and 1 s following putter-ball contact for quiet eye trained and technical trained groups during pretest (panel A), retention tests (panels B & D), and pressure test (panel C).

and Test × Epoch, $F(42{,}1470) = 5.06$, $p < .001$, $\acute{\varepsilon} = .87$, $\eta_p^2 = .13$, interaction effects were noted. Separate Group × Epoch polynomial contrast analyses for each Test indicated that the preparatory changes in muscle activity were best characterized by significant group differences in the fifth order trends for Epoch at retention test 1 ($p < .04$, $\eta_p^2 = .11$), pressure test ($p < .02$, $\eta_p^2 = .13$), and retention test 2 ($p < .005$, $\eta_p^2 = .19$), but not at pretest ($p = .62$, $\eta_p^2 = .01$). In addition, they revealed that overall group differences in muscle activity were present at retention test 1 ($p < .001$, $\eta_p^2 = .27$), pressure test ($p < .002$, $\eta_p^2 = .24$), and retention test 2 ($p < .009$, $\eta_p^2 = .17$), but not at pretest ($p = .87$, $\eta_p^2 = .00$).

Importantly, between-group *t* tests revealed no differences in absolute muscle activity values 6 s prior to putter-ball contact at pretest ($p = .77$), retention test 1 ($p = .93$), pressure test ($p = .84$), and retention test 2 ($p = .78$). These analyses showed that the group differences in the patterning of muscle activation were not due to initial differences in muscle activity.

Mediation Analyses

To establish mediation, four criteria must be met (Baron & Kenny, 1986). First, the independent variable must predict the dependent variable: Group (coded: quiet eye group = 1, technical trained = 0) predicted mean radial error in the retention tests, $\beta = -.59$, $t = -4.55$, $p < .001$, and the pressure test, $\beta = -.62$, $t = -4.86$, $p < .001$. Second, the independent variable must predict the potential mediator variables: Group predicted *x*-axis acceleration in the retention tests, $\beta = -.48$, $t = -3.29$, $p < .005$, and the pressure test,

$\beta = -.61$, $t = -4.61$, $p < .001$); y-axis acceleration in the retention tests, $\beta = -.49$, $t = -3.37$, $p < .005$, and the pressure test, $\beta = -.62$, $t = -4.69$, $p < .001$); and phasic heart rate change in the retention tests, $\beta = -.48$, $t = -3.34$, $p < .005$. However, Group failed to predict phasic heart rate change in the pressure test, $\beta = -.27$, $t = -1.70$, $p = .10$, and phasic muscle activity change in the retention tests, $\beta = -.23$, $t = -1.47$, $p = .15$, and the pressure test, $\beta = -.21$, $t = -1.30$, $p = .20$.

Third, the mediator variable must predict the dependent variable: x-axis acceleration predicted mean radial error in the pressure test, $\beta = .46$, $t = 3.06$, $p < .01$; and y-axis acceleration predicted mean radial error in the retention tests, $\beta = .56$, $t = 4.09$, $p < .001$, and the pressure test, $\beta = .43$, $t = 2.82$, $p < .01$. Finally, the effect of the independent variable on the dependent variable must be reduced in the presence of the mediator. The original effect of Group (coded: quiet eye group = 1, technical trained = 0) on mean radial error yielded β coefficients of $-.59$ and $-.62$ at retention and pressure tests, respectively. To test whether these effects were reduced, mean radial error was regressed on both the independent variable (i.e., Group) and the potential mediator variables, entered separately. These analyses revealed that y-axis acceleration predicted mean radial error, $\beta = .38$, $t = 2.57$, $p < .05$, and reduced the direct effect of Group on mean radial error, $\beta = -.38$, $t = -2.62$, $p < .05$, at retention tests. A Sobel test confirmed that this reduction in the effect of Group on performance was significant, $z = -1.99$, $p < .05$. Furthermore, bootstrapping analyses, based on a 10,000 sampling rate, revealed a significant indirect effect for Group on mean radial error through y-axis acceleration, 95% CI -6.80 to -0.42. Accordingly, y-axis acceleration can be considered a partial mediator of the between-group differences in mean radial error during the retention tests. However, x-axis acceleration, phasic heart rate change, and phasic muscle activity change failed to mediate the differences in mean radial error during the retention tests. Furthermore, no variable was found to mediate the differences in mean radial error that occurred during the pressure test.

Discussion

Previous research has highlighted the beneficial effects of quiet eye training on both skill learning and performance when anxious (e.g., Vine & Wilson, 2011). However, the various processes through which such interventions exert these positive effects are poorly understood (Vine et al., 2011). Therefore, the aim of the present study was to examine group differences in the gaze, kinematic, and physiological measures underpinning performance, in order to allow an indirect comparison of response programming and external attentional focus explanations for the benefits of quiet eye training.

Performance

As with all other measures taken, there were no differences in performance between the groups at baseline (pretest), enabling any subsequent changes to be attributed to the training interventions. Both groups experienced significant improvements in the percentage of putts holed and mean radial error from pretest to retention, indicating that learning had occurred. However, as hypothesized, the quiet eye trained participants holed a higher percentage of putts (Table 2), and achieved lower radial error than their technical trained group counterparts across retention tests (Figure 1A). The results therefore support the efficacy of the intervention for expediting learning and suggest that quiet eye training early in the learning process confers a performance advantage compared to technical instructions (Vine & Wilson, 2011); corresponding to 7.5% more putts being holed, and the ball finishing about 10 cm closer to the target on misses.

Furthermore, despite both groups experiencing similar significant increases in self-reported anxiety and physiological arousal in the pressure condition (Table 2), the quiet eye trained group managed to maintain pressure test radial error at retention test levels, while the technical trained group had significantly higher radial error during the pressure test compared to the retention tests (Figure 1A). Moreover, the quiet eye trained group successfully holed a higher percentage of putts than the technical trained group during the pressure test. Thus, consistent with previous research (Vine et al., 2011; Vine & Wilson, 2010, 2011), the results suggest that the quiet eye training intervention acted to protect performers from the adverse effects of heightened anxiety upon performance. It must be recognized that while the self-reported anxiety scores doubled in the pressure test from retention (Table 2), they are still somewhat moderate, and are unlikely to be as high as those experienced when more is at stake for the performer.

Quiet Eye

The quiet eye data (Figure 1B) revealed the same interaction effects (between pretest and retention tests, and between retention and pressure tests) as the performance error data, thus supporting our hypotheses. While both groups displayed a significant increase in quiet eye duration from pretest (~1,200 ms) to the first retention test, the quiet eye trained participants displayed significantly longer durations (~3,400 ms) across retention tests than their technical trained counterparts (~1,800 ms). The "learning" results are therefore consistent with evidence that better performance in aiming tasks is underpinned by more effective gaze control; maintaining quiet eye durations within an optimal "window" (between 2,000 and 3,500 ms in golf putting; Vickers, 2007, 2011). By training one group to adopt the gaze control strategies of experts, they were able to "cheat experience" and move further along the learning curve than their technical trained counterparts. Furthermore, the quiet eye trained group were able to adhere to their training instructions and maintain effective gaze control (longer quiet eye durations) in the pressure test. In comparison, the technical trained group displayed a significant reduction in quiet eye duration when placed under pressure (Figure 1B).

Putting Kinematics

The putting kinematic data suggest that, in line with previous research (e.g., Delay et al., 1997; Sim & Kim, 2010), reduced x-axis (lateral; Figure 1C) and y-axis (vertical; Figure 1D) clubhead acceleration was associated with successful putting performance. As predicted, the quiet eye trained group displayed significant reductions in lateral and vertical clubhead acceleration between pretest and retention tests and significantly lower lateral and vertical clubhead acceleration across retention tests than their technical trained counterparts. In effect, reduced lateral (x-axis) acceleration helps ensure that the sweet spot of the putter is more reliably contacted and aligned with the hole, and the flatter plane of the stroke (more parallel to the ground; y-axis) helps ensure that the center of the ball is struck. These results are congruent with previous research (e.g., Causer, Holmes, & Williams, 2011), and demonstrate that the quiet eye training intervention indirectly crafted a change in putter kinematics, making putter movement more expert-like, despite training instructions being related to gaze control only

(Table 1). Furthermore, mediation analyses confirmed that vertical clubhead acceleration partially mediated the between-group differences in performance during the retention tests. Taken together, these kinematic results suggest that the quiet eye trained group's superior performance following training may be due to them displaying a more accurate and consistent putter-ball contact than the technical trained group, offering indirect support for a response programming explanation for their accelerated learning (Vickers, 1996, 2011).

As predicted, the quiet eye trained group displayed no significant change in lateral clubhead acceleration between the retention tests and the pressure test. Conversely, the technical trained group displayed significantly greater lateral acceleration during the pressure test (Figure 1C). The latter result is consistent with the work of Cooke and colleagues (2010), who found that elevated pressure increased lateral clubhead acceleration among untrained novice golfers, causing the clubhead to be misaligned at putter-ball contact and putts to be pushed or pulled wide of the hole. The absence of pressure effects on the quiet eye trained group's putting kinematics suggests a preservation of efficient response programming and clubhead control (Vine et al., 2011).

Phasic Heart Rate and Muscle Activity Change

The phasic heart rate change data revealed that the quiet eye trained group displayed a heart rate pattern that was significantly different to that displayed by the technical trained group in retention and pressure tests, despite no significant differences being present at pretest (Figure 2). The technical trained group displayed no significant variation in their heart rate pattern across any of the conditions, and maintained a phasic heart rate pattern consistent with novice golfers (Neumann & Thomas, 2009, 2011). In contrast, the quiet eye trained group revealed a phasic heart rate change pattern across retention and pressure tests that is congruent with the pattern exhibited by elite and experienced golfers (Neumann & Thomas, 2009, 2011). Rather than an increase in heart rate for the first 3 s (as evident for the technical trained group and quiet eye group at pretest), the quiet eye trained group displayed an earlier and more pronounced deceleration in heart rate prior to the golf putt.

According to the Intake-Rejection Hypothesis (Lacey & Lacey, 1974, 1980), this phasic heart rate change reflects a greater external focus of attention towards task relevant cues compared to the technical trained group. The quiet eye data (Figure 1B) provide a more direct measure of the location of visual attention; however, they are supported by this physiological finding. The absence of a pressure effect on the heart rate deceleration of the quiet eye trained group confirms that they were able to maintain an effective external focus of attention, despite the potentially distracting influence of increased anxiety. However, contrary to predictions, elevated anxiety also had no significant effect on the heart rate pattern displayed by the technical trained group (see Figure 2B,C,D). Therefore, while external focus-induced neuromuscular quiescence might explain the benefits of quiet eye training in expediting learning, it cannot explain the performance advantage shown under heightened anxiety.

The phasic muscle activity change data reveal broadly similar between-group relationships as already discussed for heart rate change (see Figure 3). The technical trained group again revealed no changes in the pattern of muscle activity across all four conditions, whereas the quiet eye trained group had different activity patterns following training. As well as revealing an initial (although small) reduction in muscle activity until 3 s prior to putter-ball contact, muscle activity at contact was approximately half that registered by the technical trained group in retention and pressure conditions. Anxiety again had no effect on the phasic muscle activity patterns of either the quiet eye trained or technical trained group (see Figure 3B,C,D). These results suggest that the quiet eye training intervention resulted in a generalized reduction in the activity of the extensor carpi radialis muscle prior to and during the golf putt. As the results reveal a similar pattern to the heart rate data, they support previous research (e.g., Lohse et al., 2010; Zachry et al., 2005), which suggests that a reduction in muscle activity prior to movement may be associated with an external focus of attention.

An important caveat to the discussion of the ANOVA results is that even though similar group and interaction effects were found for a number of performance and process variables (Figure 1), this is a necessary rather than sufficient criterion for inferring mediation. Indeed, the formal mediation analyses (Baron & Kenny, 1986) indicated that only vertical clubhead acceleration mediated between-group performance differences in both retention tests. No process measures mediated performance differences under elevated anxiety. Researchers therefore need to be careful about inferring mediation based on an examination of similar interaction effects only (cf. Cooke et al., 2010, 2011; Vine & Wilson, 2011). The search for mediators to explain the performance advantages of quiet eye training might require a focus on direct (neural) measures (e.g., Mann et al., 2011), rather than the indirect measures examined in the current study. However, it must also be noted that mean radial error, while a typically adopted performance measure in golf putting, is not very precise (Hancock, Butler, & Fischman, 1995), especially when considered against the precision of the process measures (e.g., 1 degree of accuracy in gaze measurement). For example, mean radial error does not take account of clustering, or side-to-side versus back-to-front error.

Future research may wish to examine these and other mechanisms in expert/intermediate level golfers. Furthermore, future research may also consider including more than one comparison group to manipulate differences in the focus of attention. First, by manipulating the duration of the quiet eye, it would be possible to determine the minimum threshold and optimal window for the quiet eye, as well at what duration longer durations become counterproductive. Second, the training instructions provided to the comparison group in the current study primarily focused on technique (Table 1) and may therefore have induced a less optimal, internal focus of attention (e.g., Zachry et al., 2005). By including a further experimental group, provided with external focus instructions (but without reference to length of duration), it may have been possible to understand more about the specific benefits of quiet eye training, above those offered by simply focusing externally. However, the present study was designed as a randomized control trial, examining if and how a quiet eye training intervention might be more effective than the current "industry" gold-standard approach to teaching putting. The technical instructions were developed by one of the game's leading putting coaches and thus provided a useful first comparison for quiet eye training.

To conclude, the current study investigated some possible mechanisms through which a quiet eye training intervention might expedite learning and protect performance against increased anxiety. Our results replicated previous findings revealing performance advantages after training and under heightened anxiety, and further validated the efficacy of quiet eye training for aiming skills. In retention and pressure tests, quiet eye trained participants revealed both more expertlike putting kinematics and more effective external focus of attention (as evidenced by longer quiet eye durations, earlier and greater heart rate deceleration, and reduced muscle activity prior to task execution) than their technical trained counterparts. Mediation analyses revealed that only vertical clubhead acceleration and no physiological variables mediated the relationship between training group and retention test performance. Thus, collectively, the results provide indirect support for a response programming explanation. However, as the mediation analyses failed to establish causal relations between all expected process measures and performance under increased anxiety, further research is required to untangle *how* quiet eye training provides its performance advantage for anxious individuals. The findings of such research are likely to have important implications for the delivery of both training instructions and psychological interventions in applied settings where accurate aiming is of vital importance (e.g., sport, surgery, military, and patient rehabilitation).

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