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RESEARCH ARTICLE

Why does the Quiet Eye improve aiming accuracy? Testing a motor preparation hypothesis with brain potential

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Abstract

The purpose of the present study was to determine whether the Quiet Eye (QE) acquired over time is associated with motor preparation processes by using movement-related cortical potentials (MRCPs). Eighteen male, right-handed college students voluntarily participated in this study. Participants performed a dart throw while wearing an eye-tracking system and electrode cap to measure electroencephalogram waveforms (EEG). After performing the dart task, participants were randomly assigned to a Quiet Eye training group (QET) or control training group (CT). Six subjects were excluded due to incomplete electroencephalography (EEG) data. MRCPs were analysed separately within 4 QE categories: High performance score and Long fixation time (HL), High performance score and Short fixation time (HS), Low performance score and Long fixation time (LL), and Low performance score and Short fixation time (LS). Results revealed that although the QET group acquired QE characteristics, MRCPs did not differ between the two groups. Thus, a longer-term experimental design may be necessary to observe EEG changes. Furthermore, QE durations may relate to not only motor programming but also online control.

Keywords Quiet Eye · Movement-related cortical potentials · Motor programming · QE training · Longitudinal design · Darts

Introduction

Aiming, which requires accurately throwing or shooting an object near a target, is the most fundamental skill across various sports. For instance, accurate free throw completion rates in basketball are associated with game outcomes (Sampaio and Janeira 2003). Therefore, how athletes improve their aiming skills is an essential theme in sports science.

The Quiet Eye (QE), which refers to an expert's gaze behaviour when successfully aiming towards a target, has attracted much research attention regarding mechanisms underlying aiming accuracy (e.g. Vickers 1996; Harle and Vickers 2001; Causer et al. 2010; Moore et al. 2012). The QE is defined as the final, steady fixation (or tracking gaze) that is directed towards a specific target location (e.g. the tip of a basketball ring) or object (e.g. top and/or edge of a golf ball) within 3° of visual angle (or less) for a minimum of 100 ms prior to the critical final movement (Vickers 2007, p. 77, 2009, 2016). Cross-sectional studies have observed that the QE durations of elite performers are significantly longer than near-elite or lower skilled performers on an aiming task. For example, Vickers (1996) demonstrated that expert free throw shooters (≥ 75% success rate) and near-expert free throw shooters (≤ 60% success rate) differ regarding the duration of the QE (expert shooters: 1000 ms; near-expert shooters: 400 ms). In addition to this inter-individual difference, expert free throw shooters differ in their QE durations

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during successful hits (1000 ms) and misses (800 ms). These intra- and inter-individual differences in QE durations have also been confirmed in various sport settings such as volleyball, darts, billiards, golf, soccer, and skeet shooting (Vickers and Adolphe 1997; Vickers et al. 2000; Williams et al. 2002; Vine et al. 2011; Wood and Wilson 2011; Causer et al. 2010).

However, the mechanism(s) underlying the effect of QE on aiming accuracy is still debated and several hypotheses have been proposed (i.e. Vickers 1996; Williams et al. 2002; Causer et al. 2010; Gonzalez et al. 2015a). One dominant explanation is the motor preparation hypothesis. Vickers (1996) suggested that fixations with a prolonged duration towards a specific target location during movement preparation are essential for programming direction, force, and velocity parameters necessary for optimal aiming movement (see also Vickers 2009). In addition, long QE durations are suggested to extend the critical motor preparation period that consists of response selection and the fine tuning of movement parameters for motor programming (Moore et al. 2012). According to this assumption, Williams et al. (2002) tested whether QE durations are related to a motor preparation process. Here, visual gaze behaviours of skilled and less skilled players were recorded when participants performed successful and unsuccessful billiards shots of varying difficulty. Since more complex motor responses require longer pre-programming times (e.g. Henry 1980), it was expected that if QE durations were related to motor programming, more complex shots would require longer QE durations. The results supported this hypothesis; QE durations increased as a function of shot difficulty. Additionally, when preparation time was reduced by 25% and 50%, performance decrements were observed irrespective of skill level. The authors reported that the QE is related to accurate motor programming in terms of movement direction, force, and velocity during the preparation phase (see also Causer et al. 2010; Fegatelli et al. 2016).

Horn et al. (2012) investigated QE durations and the effects of variable versus blocked training in a dart-throwing task. They hypothesized that random target changes (to different targets at similar distances) would produce long QE durations due to the increased programming demands of having set a parameter to the response from one trial to the next, compared to the consistency of the blocked target presentation (same target and distance). From the result of the experiment, random training groups showed longer QE durations than did block training groups. Horn et al. (2012) also concluded that longer QE durations are a functional element of programming demand as did Williams et al. (2002).

In addition to the aforementioned behavioural evidence, Mann et al. (2011) recently examined the relationship between QE durations and motor preparation via movement-related cortical potentials (MRCPs). The MRCP is a negative shift in electroencephalographic (EEG) signal that occurs 1 s or longer prior to a self-paced voluntary movement (Kornhuber and Deecke 1965). Furthermore, the MRCPs include several components that result from different cortical activities (Ikeda et al. 1992). First, a slow rising negativity, called the Bereitschaftspotential (BP), emerges from the supplementary motor area (SMA) and is widely distributed across the scalp. Next, a later negativity, starting about 400 ms prior to the onset of a movement and referred to as the negative slope (NS'), also emerges from the SMA and is involved in specific movement preparation (Deecke and Kornhuber 1978). A final negativity, immediately before movement onset, which is called the motor potential (MP), mainly arises from M1: primary motor cortex (Deecke et al. 1982; Toma et al. 2002). These MRCP components are assumed to be associated with the cortical processes involved in planning and preparing voluntary movement (Shibasaki and Hallett 2006). Based on this interpretation of functional MRCPs, Mann et al. (2011) examined QE durations and MRCPs with expert (Low-handicap: 0–2) and near-expert (High-handicap: 10–12) golfers during a putting task. In their study, three electrodes were positioned over the left, mid-line, and right-central (primary motor cortex: C3, Cz, and C4 of the International 10–20 system for EEG recordings) sites to concentrate on those cortical regions known to have implications in motor planning and execution, as well as source generators of the MRCP. Furthermore, an additional cluster of electrodes was positioned over the parietal cortex (P3, P4), a region associated with visuo-motor control and suspected to have implications in QE functioning. Results revealed that experts exhibited prolonged QE durations (experts: 2500 ms; near-experts: 2200 ms) and greater cortical activation in the MRCP within the right primary motor cortex (C4) and the parietal cortex (P4) than did near-experts. Here, activity in C4 likely reflects activation within the SMA, which may serve to retrieve and augment requisite motor commands from memory (Roland 1984). Thus, the QE may improve aiming accuracy by enhancing efficient motor preparation processing.

The motor preparation hypothesis is likely a valid explanation for performance enhancement observed in the QE literature, and MRCPs seem to be suitable indicators for testing this hypothesis. Conversely, although Mann et al. (2011) reported compelling findings, their study included participants who did not show typical QE features (i.e. QE are significantly longer when the performance is successful than unsuccessful). It is necessary to compare MRCPs in all contexts where participants are demonstrating QE to fully indicate the relationship between QE and motor preparation processes. To this end, a longitudinal design seems suitable for resolving this issue. In fact, Harle and Vickers (2001) conducted a 6-month QE training for college basketball teams and found that QE durations increased as free throw performance improved. Consistent with this finding, other researchers have confirmed that the acquisition of longer QE durations through training leads to improved aiming accuracy (e.g. Wood and Wilson 2011; Moore et al. 2012). Additionally, Bezzola et al. (2011) investigated developmental differences within neural structures among novice golfers who received intensive golf training (40 h) and those who did not. Although they did not focus on the QE, the authors observed that neural structures, such as grey matter-related adaptations in motor functions, visuospatial function, and body perception/control differed between both groups after training. In other words, a longitudinal design appears to be effective for assessing neural changes underlying motor preparation derived from QE training.

The purpose of the present study was to determine, using MRCPs, whether the QE acquired over time is associated with motor preparation. We measured MRCPs during a dart-throwing task after QE and control training. To examine the relationship between the QE and MRCPs, MRCPs were analysed separately within 4 QE categories: High performance score and Long fixation time (HL), High performance score and Short fixation time (HS), Low performance score and Long fixation time (LL), and Low performance score and Short fixation time (LS). If the QE affects motor preparation processes, MRCP amplitudes for the QE training group during HL trials, which is the effective QE feature, should increase as compared to MRCP amplitudes for the control training group during HL trials.

Methods

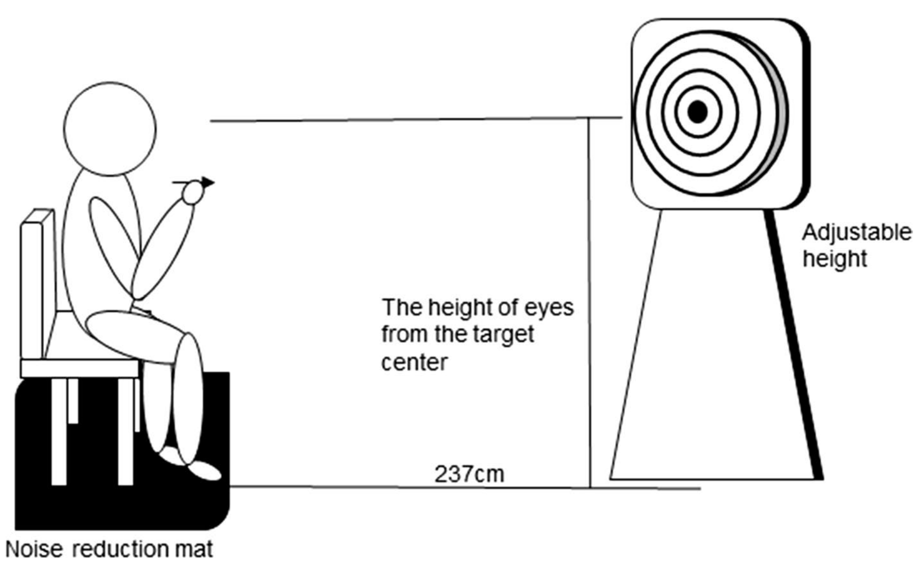
Participants

Eighteen male right-handed college and graduate students of a college specialized for sports and physical education ($M = 22.3 \pm 1.96$ years) voluntarily participated. Although their professional sport domains varied (e.g. soccer, baseball, track and field athletics, canoes, fin swimming), none of them were darts expert. All participants had self-reported normal or corrected to normal vision. Half of the participants were randomly assigned to a Quiet Eye training group (QET) and the other half to a control training group (CT). Adequate EEG data were not available for six participants (QET: three participants, CT: three participants) due to the inclusion of artefacts related to body movement; these participants were excluded from any further analyses. All participants were informed of the experimental procedures and provided written informed consent. The local ethics committee of the National Institute of Fitness and Sports in Kanoya, Japan, approved this study in accordance with the Declaration of Helsinki.

Experimental task

The experimental task comprised throwing a dart while aiming for the centre of the dartboard (DartsGame S-43, Nissin Industry Co., Japan) and seated 2.37 m away (see Fig. 1). A series of 10 concentric circles were depicted on the board (diameter 43 cm), which shared a common midpoint (diameter 1.5 cm). Participants were instructed to throw the dart towards the centre as accurately as possible. A score of 100 points was awarded if the dart hits the centre. The score decreased by 10 points outside of the centre. For example,

Fig. 1 Experimental setup and task



the participant was awarded 90 points if the dart was close to the centre, 10 points if the dart was far away from the centre, and no points if the dart hits outside the board. The position of the dartboard's centre was adjusted according to the height of the participants' eyes.

Instrumentation

Gaze behaviour

Gaze behaviour was recorded using an eye-tracking system (EMR-9 glass type, NAC Image Technology Inc., Tokyo, Japan). This system uses a 'dark pupil method' in which the relationship between two eye features, the pupil and corneal reflection, is computed to locate gaze within a scene (NAC Image Technology Inc. 2009). The eye-tracking camera was set at a 62° angle, and data were recorded at a sampling frequency of 60 Hz. The QE was defined as the final fixation on a specific location (the centre of the dartboard) in the visuo-motor workspace within 3° of visual angle for a minimum of 100 ms (Vickers 2007, p. 77, 2009, 2016). The onset of the QE occurs prior to extending the arm towards the target, and (Vickers et al. 2000) the offset occurs when the gaze deviates off the centre of the dartboard by more than 3° of visual angle for a minimum of 100 ms; therefore, trials that did not satisfy this definition were deleted from the data. The start and end of the QE was calculated at 33 ms per frame using images of the view camera of EMR-9 glass type and video camera images of dart-throwing movement of participants. The two images were combined using video editing software (Premiere Elements 10, Adobe).

Electroencephalogram (EEG)

During the experimental task, EEG data were recorded with an electrode cap containing sintered Ag/AgCl electrodes, referred to as linked electrodes. Continuous EEG recording was obtained from three sites (Cz, C3, C4) based on the International 10–20 system. As mentioned above, MRCP from central sites reflects motor preparation processes. As we focused on testing motor preparation hypothesis, we chose these three sites. Vertical electrooculogram (EOG) data were recorded from the upper and lower canthi of the left eye, and horizontal EOG signals were recorded using electrodes placed 1 cm lateral to the outer canthi. Impedances for the ear and eye electrodes were below 3 kΩ (and below 5 kΩ for the scalp electrodes). The participants were fitted with a cap electrode located midway between Fp1 and Fp2. The EEG and EOG signals were sampled at 500 Hz, filtered with a band pass filter (ranging from DC to 200 Hz), and recorded using Neuroscan software.

Electromyogram (EMG)

To determine movement onset for the EEG analyses, EMG activity from the surface of the right arm (Triceps Brachii: TB and Biceps Brachii: BB) muscles was recorded using EMG electrodes. The TB and BB muscles were chosen due to their role in dart throwing (Vickers et al. 2000). The EMG signals were filtered during acquisition with a bandwidth of 5–500 Hz and a gain of × 1000. The signals were sampled at 1 kHz (16 bit, PowerLab, AD Instruments, Japan). Onset and termination of EMG activity was recorded and stored for offline analyses (Chart 4, AD Instruments, Australia) on a personal computer.

Procedure

Participants were seated on a chair that was placed on a rubber mat at 237 cm from the dartboard. Additionally, the target centre was adjusted to match the participant's eye level. We required darts to be thrown in the sitting rather than standing posture to minimize contamination of EMG noise that comes from complex and dynamic movement into EEG data. To measure EMG signals, disposable electrodes (Vitrode F-150S, Nihon Koden, Tokyo, Japan) were attached to the centre of the TB and BB muscles and the distance between recording electrodes was 1 cm. The electrode cap was pulled over the participant's head. Finally, participants were fitted with an eye-tracking system.

Participants performed three dart throws as practice trials. After the practice trials, all participants threw a dart 100 times during a pre-test. To measure MRCPs, participants were instructed to throw 3 s after setting up the dart. During the pre-test, participants were provided a 1–2-min break every 10 throws. Outcome feedback was given after every trial. Beginning the following day, participants performed a training task (details below) for 3 weeks. The post-test was performed the day following the completion of training. The post-test procedure was the same as the pre-test.

Training regimen

The training tasks were adapted from previous QE training research (Harle and Vickers 2001; Vine et al. 2011; see Table 1). The CT group received three coaching pointers related to the mechanics of dart throwing (derived from http://www.dartslive.com/jp/enjoy/throw/). The same three pointers were also given to the QET group. Training pointers matched in this way to ensure that both groups received instructions related to the same temporal components of a throw (see Table 1). Both groups performed the training in the sitting posture as was the case with the test sessions. Participants performed 9 training sessions (900 throws in total) over 3 weeks (100 throws per day). Training sessions lasted

Table 1 Training protocol

QE training	Control
1. Take your stance at the line	1. Take your stance at the line
2. While fixing the elbow, aware of the arms so as to draw a fan	2. While fixing the elbow, aware of the arms so as to draw a fan
3. While gazing the centre of target, in the state of holding a dart the phrase slowly ‘Nothing other than centre’	
4. Hold the dart in your throwing stance and maintain QE focus on a centre of target for approximately 3.0 s. Keep you gaze stable on the one location, accompanied by the words ‘sight focus’. Maintain QE on centre prior to the extension of the arm	
5. Without moving the elbow, throw to fly a paper airplane. Fingers all away at the same time	5. Without moving the elbow, throw to fly a paper airplane. Fingers all away at the same time
6. After throwing, pointing to the location aimed at your fingertips	6. After throwing, pointing to the location aimed at your fingertips
7. During throwing time, there is no need to maintain your gaze on the centre of target	

approximately 30 min. After each training session, feedback was given regarding average scores from 100 throws.

Dependent measures and data analyses

Dart performance, QE durations, and MRCPs were chosen as dependent measures. Dart performance was determined from the average score during each test and training session. A two-way repeated measures analysis of variance (ANOVA) was conducted: 2 (group: QET, CT) × 11 (time: from pre- to post-test including 9 training sessions).

It has been reported that QE durations are longer during successful hits relative to misses. Accordingly, a mean QE duration value was calculated by classifying into high-score (i.e. top 30%) and low-score (i.e. bottom 30%) categories during each test. These data were analysed using a 2 (group: QET, CT) × 2 (test: pre-test, post-test) × 2 (score: High score, Low score) ANOVA.

To obtain MRCPs, EEG waveforms were averaged from 2000 ms prior to 500 ms after TB onset (i.e. movement initiation). Just as with QE durations, EEG waveforms were averaged by classifying into a high-score (i.e. top 30%) and low-score (i.e. bottom 30%) categories for each test phase. Averages were also obtained at long (i.e. top 15%) and short durations (i.e. bottom 15%) for the high- and low-score categories. Therefore, the EEG data were analysed across four QE conditions: (1) High performance and Long fixation time (HL), (2) High performance and Short fixation time (HS), (3) Low performance and Long fixation time (LL), (4) Low performance and Short fixation time (LS). This score-based matching enabled direct comparisons between the behavioural and EEG data. The three MRCP components were extracted as follows: (1) the mean negativity measured between 1500 and 500 ms prior to EMG onset, referred to as BP, (2) the mean negativity measured between 500 and 200 ms prior to EMG onset, referred to as NS’, and (3) the peak MRCPs amplitude between 200 and 0 ms prior to movement, referred to as MP. In order to investigate differences in MRCPs due to QE features, we compared MRCPs in the CT group. EEG epochs with an amplitude exceeding ± 100 μV at any channel were excluded from analyses. All other EEG epochs visually distinguished epochs with small artefact under the guidance of those with EEG research experience and excluded them from the analysis. MRCP components were separately analysed using a 2 (group) × 4 (QE features: HL, HS, LL, LS) ANOVA at three sites (Cz, C3, C4) from post-test data where the QE was acquired. Degrees of freedom values for all F-ratios were adjusted using the Greenhouse–Geisser procedure. All post hoc pairwise comparisons were performed using a Bonferroni correction. Effect sizes were estimated using partial eta square (η^2_{p}).

Results

Performance

To validate the effect of QE training, we compared dart performance between the QET and CT groups. Figure 2 displays performance across two tests and nine trainings for both groups. The 2 (Group) × 11 (Test and Training session) ANOVA revealed a significant main effect for test and training session, $F(2.5, 25.2) = 9.54$, $p < .01$, $\eta^2_{\mathrm{p}} = .36$, indicating that participants significantly improved throughout the training sessions. However, there was no significant main effect for group or any interaction. Thus,

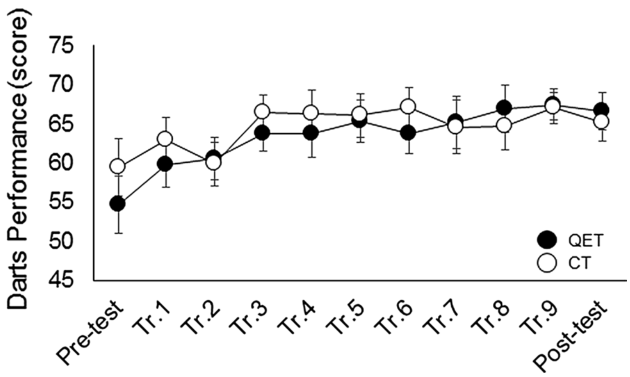


Fig. 2 Mean darts performance across test and training conditions

although QE training improved dart performance, control training was equally effective.

Quiet Eye durations

We expected that longer QE durations would emerge for successful relative to unsuccessful throws. Therefore, if the QET group acquired the QE after training, we predicted that only the QET group would exhibit longer QE durations after training, particularly after successful throws. This prediction was supported by a 2 (Group) × 2 (Test) × 2 (Score: High score, Low score) MANOVA (Fig. 3). There was a significant group × test, $F(1, 10) = 16.38$, $p < .01$, $\eta_p^2 = .62$, and group × score interaction, $F(1, 10) = 6.57$, $p < .05$, $\eta_p^2 = .39$. A simple main effects analysis indicated that QE durations within the QET group increased from pre-test ($M = 3.71 \pm 1.05$ s) to post-test ($M = 5.58 \pm 0.65$ s), and QE durations were significantly longer in the QET group ($M = 5.58 \pm 0.65$ s) than the CT group ($M = 3.25 \pm 0.6$ s) at post-test. Furthermore, when performance was high, QE durations within the QET group ($M = 4.88 \pm 2.0$ s) were longer than when performance was lower ($M = 4.4 \pm 1.31$ s), but this effect

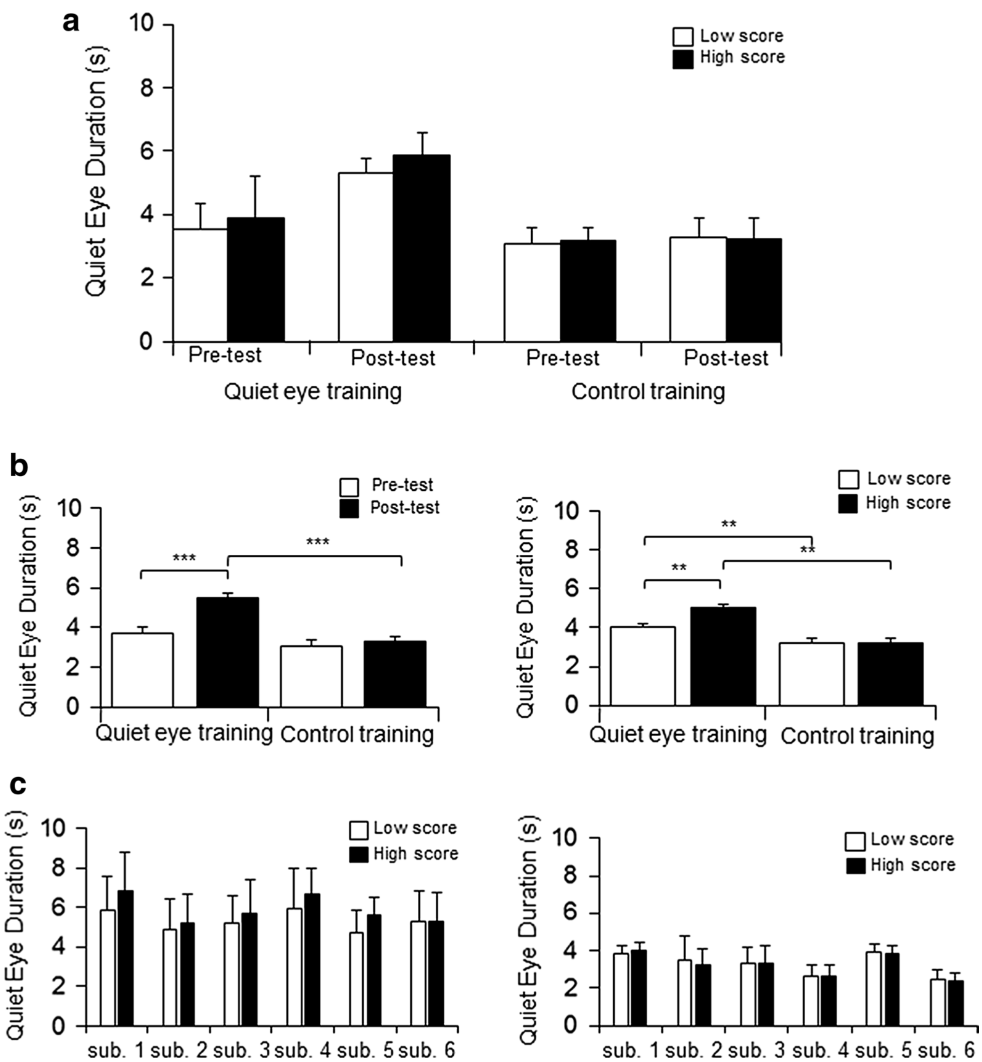


Fig. 3 QE durations across test and performance conditions. **a** Mean QE durations for low and high scores between the QET and CT groups across pre-test and post-test. **b** Mean QE durations for pre-test and post-test between the QET and CT groups and mean QE durations for low and high scores between the QET and CT groups. **c** QE duration data from a single participant in terms of low and high scores across QET and CT groups. Significant differences are denoted, **$p < .01$, ***$p < .001$

was not observed in the CT group. Therefore, our results demonstrated that only the QET group acquired the QE after training, even though group differences in actual performance were not observed.

MRCP amplitudes

We expected that MRCP amplitudes among participants who acquired the QE through training would be higher at C3 than that of the CT group. Furthermore, we expected higher MRCP amplitudes with improved performance in longer QE durations. A 2 (Group) × 4 (QE features) repeated measures ANOVA demonstrated no significant main effect or interaction at any of the recorded BP, NS', and MP (Fig. 4).

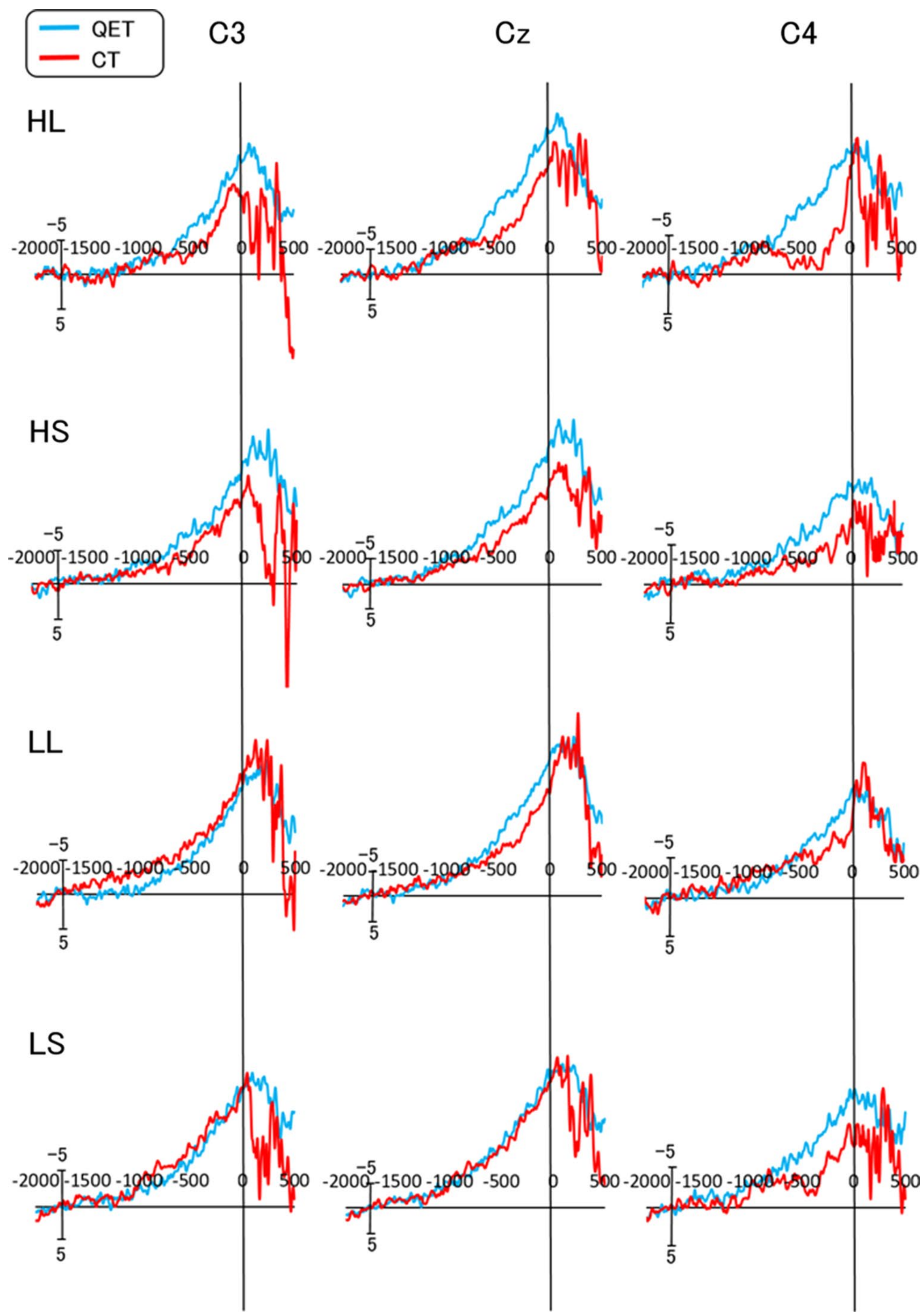


Fig. 4 Inter-group comparisons of MRCPs across conditions. The parallel line shows the elapsed time of movement. The vertical line shows the muscle activity at the moment the elbow flexion occurred when throwing darts

Discussion

The purpose of the present study was to determine, using MRCPs, whether the QE acquired by training is associated with motor preparation. To this end, we compared MRCPs between participants who did and did not acquire QE after training. While only the QET group demonstrated longer QE durations during successful throws relative to unsuccessful throws, there were no significant group differences in MRCPs (i.e. BP, NS', and MP) after training.

There was no significant difference in the dart performance from pre- to post-test between the training regimens. In other words, both group had improved dart performance (QET: from 54.6 to 66.5, CT: from 59.4 to 65.1; Fig. 1). However, QE durations after training within the QET group increased significantly (from 3730 to 5525 ms; Fig. 3b, left panel). Conversely, the CT group did not have a significant increase in QE durations (3077–3266 ms) despite improved performance. Furthermore, QE durations during successful throws (4886 ms) were longer for the QET group relative to unsuccessful throws (4408 ms); this was not observed within the CT group (3198 ms on hits and 3181 ms on misses). Thus, these results indicate that the QET group acquired an effective QE strategy. Therefore, comparison of post-test MRCPs is a valid means for assessing the QE during motor preparation.

Mann et al. (2011) reported that during a putting task, golfers with the Low-handicap exhibited larger MRCP amplitudes. Thus, we hypothesized that if the QE influences motor preparation processes, MRCP amplitudes within the QET group during successful throws (HL) should be larger than those during successful throws (HL) among the CT group. However, we did not observe MRCP differences between the two groups. One possible explanation for this lack of a difference could be the limited amount of training offered in the current study. Previous studies observing results in support of the motor programming hypothesis examined skilled players (Williams et al. 2002; Mann et al. 2011). In other words, prior studies employed experts who had at least 2 years of billiards experience or 12 years of golf experience. Indeed, Jäncke et al. (2009) reported that neural activation among intermediate and novice golfers and highly skilled (including professional) golfers differed as a function of long-term practice. Additionally, an MRI study with novice golfers who practiced for at least 40 h and a group that did not practice reported group differences in neural activation and performance (Bezzola et al. 2011). Thus, since we only provided about 6 h of training, it may have been difficult for us to observe a QE that would impact MRCP activation. Hence, a longer-term longitudinal assessment may be warranted.

On the other hand, although the hypothesis based on information-processing load of motor programming seems to be an appropriate explanation of the effect of QE according to previous studies (e.g. Williams et al. 2002; Horn et al. 2012), motor programming may not be the only mechanism of QE. For instance, Klostermann et al. (2013) investigated the performance-enhancing effects of experimentally manipulated QE durations using externally paced throwing task. In this task, the onset of the last fixation and the amount of information to be processed were manipulated by presenting the target at different timings (short and long presentations) and locations (random and predictive) during movement unfolding. They showed that the effect of promoting long QE durations on performance is obvious under high load of information-processing abilities. However, the influence of QE durations disappeared as the position of the target became more predictable and as the task requirements became lower. Gonzalez et al. (2015a) suggest that continuous monitoring and online control may play an important role during aiming tasks, highlighting the need to investigate these mechanisms while maintaining information load constant. Thus, it is unlikely that the effect of QE involves only motor programming.

In addition, previous studies have suggested that late information pickup is important for accurate basketball shooting (Oudejans et al. 2002; De Oliveira et al. 2007). In these studies, the relationship between the QE and performance is accomplished by dividing QE durations into 'before movement' (QE early) and 'during movement' (QE late) categories. Oudejans et al. (2002) assessed participants shooting a basketball who could see the target until the ball was released (continuously); thus, instead of motor programming, motor control was possible. Four conditions were devised using a liquid crystal (LC) smart glass display: no vision, full vision, early vision (i.e. vision was occluded during the shooting movement after the ball had been moved past the line of gaze), and late vision (i.e. vision was occluded after initiation of the trial until the ball moved past the line of gaze). Results revealed that information during the final ± 350 ms before releasing the ball was important, and the QE late condition outlined the role of the QE in online control. Recent studies have investigated important visual information, similar to Oudejans et al. (2002), during a golf-putting task (Vine et al. 2017). Here, Vine and colleagues investigated not only putting performance but also QE durations and putting movements. Three conditions were created using an LC smart glass screen: full vision, early vision (i.e. vision occluded from the backswing to impact), and late vision (i.e. vision occluded before initiating the backswing). Performance declined and putting movements changed only during the early vision condition; however, QE durations did not differ across conditions. Thus, the QE reflects the steadying of the eye in order to focus on attention (see Smith and Schenk 2012) and internally programs the motor movement. Additionally, within a golfing context, there is evidence that the backswing of a putter could be considered a pre-programming movement, while only the downswing should be considered reflective of true online control (Craig et al. 2000). From this aforementioned evidence, we argue that QE durations have two primary roles: programming and online control. Future studies should elucidate the relative roles related to pre-programming and online control when examining the QE-visuo-motor performance relationship. This can also include investigations into individual components of the QE (before and after movement initiation) that may account for performance variability.

Conclusion

The current study examined potential mechanisms underlying the role of the QE in improving target-aiming accuracy. A unique contribution of this study was the analysis of MRCPs as a function of QE training. Results revealed that the QET group acquired the QE through training, in line with previous studies (Wood and Wilson 2011; Moore et al. 2012). However, MRCP amplitudes did not differ between groups. Nevertheless, the QE appears to contribute to not only motor programming but also online control. Prior to applying the present findings in an applied sport setting, issues need to be addressed in future work. In addition, as a limitation of this research, participants performed dart tasks while sitting; so it is required to include tasks suitable for actual competition in the future. As reported in recent studies (Gonzales et al. 2015a, b; Vickers 2016), a follow-up study on the mechanism(s) underlying the QE should be conducted using various neuroimaging techniques. Continued replication and extension of the present findings should permit more confident advocacy of QE training protocols for optimizing motor performance.

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Compliance with ethical standards

Conflict of interest Authors declare that there is no conflict of interests relevant to the content of this paper.

Ethical standard All procedures performed in studies involving human participants were in accordance with the ethical standards with the 1964 Declaration of Helsinki.

References

Bezzola L, Merillat S, Gaser C, Jäncke L (2011) Training-induced neural plasticity in golf novices. J Neurosci 31:12444–12448. https://doi.org/10.1523/JNEUROSCI.1996-11.2011
Causer J, Bennett SJ, Holmes PS, Janelle CM, Williams AM (2010) Quiet eye duration and gun motion in elite shotgun shooting. Med Sci Sports Exerc 42(8):1599–1608
Craig CM, Delay D, Grealy MA, Lee DN (2000) Guiding the swing in golf putting. Nature 405(6784):295
De Oliveira RF, Huys R, Oudejans RRD, Van De Langenberg R, Beek PJ (2007) Basketball jump shooting is controlled online by vision. Exp Psychol 54(3):180–186
Deecke L, Kornhuber HH (1978) An electrical sign of participation of the mesial ‘supplementary’ motor cortex in human voluntary finger movement. Brain Res 159(2):473–476
Deecke L, Weinberg H, Brickett P (1982) Magnetic fields of the human brain accompanying voluntary movement: Bereitschaftsmagnetfeld. Exp Brain Res 48(1):144–148
Fegatelli D, Giancamilli F, Mallia L, Chirico A, Lucidi F (2016) The use of eye tracking (ET) in targeting sports: a review of the studies on quiet eye (QE). In: Pietro G, Gallo L, Howlett R, Jain L (eds) Intelligent interactive multimedia systems and services 2016. Smart Innovation, Systems and Technologies, vol 55. Springer, Cham
Gonzalez CC, Causer J, Miall RC, Grey MJ, Humphreys G, Williams AM (2015a) Identifying the causal mechanisms of the quiet eye. Eur J Sport Sci 10:1–11
Gonzalez CC, Causer J, Miall C, Grey M, Humphreys G, Williams AM (2015b) Identifying the functional mechanisms of the QE in expert and novice archers during aiming tasks. Paper presented at the 6th International Conference on Spatial Cognition, “Space and Situated Cognition”, 7–11 September 2015
Harle SK, Vickers JN (2001) Training quiet eye improves accuracy in the basketball free throw. Sports Psychol 15:289–305
Henry FM (1980) Use of simple reaction time in motor program studies: a reply to Klapp, Wyatt, and Lingo. J Motor Behav 12:163–168
Horn RR, Okumura MS, Alexander MG, Gardin FA, Sylvester CT (2012) Quiet eye duration is responsive to variability of practice and to the axis of target changes. Res Q Exerc Sport 83(2):204–211
Ikeda A, Lüders HO, Burgess RC, Shibasaki H (1992) Movement-related potentials recorded from supplementary motor area and primary motor area. Brain 115(4):1017–1043
Jäncke L, Koeneke S, Hoppe A, Rominger C, Hänggi J (2009) The architecture of the golfer’s brain. PLoS ONE 4(3):e4785
Klostermann A, Kredel R, Hossner EJ (2013) The “quiet eye” and motor performance: task demands matter! J Exp Psychol Hum Percept Perform 39(5):1270–1278
Kornhuber HH, Deecke L (1965) Changes in the brain potential in voluntary movement changes in the brain potential in voluntary movement and passive movements in man: readiness potential and reafferent potentials. Pflugers Arch 284:1–17
Mann DT, Coombes SA, Mousseau MB, Janelle CM (2011) Quiet eye and the Bereitschaftspotential: visuomotor mechanisms of expert motor performance. Cogn Process 12(3):223–234
Moore LJ, Vine SJ, Cooke A, Ring C, Wilson MR (2012) Quiet eye training expedites motor learning and aids performance under heightened anxiety: the roles of response programming and external attention. Psychophysiology 49(7):1005–1015
Oudejans RR, van de Langenberg RW, Hutter RV (2002) Aiming at a far target under different viewing conditions: visual control in basketball jump shooting. Hum Mov Sci 21(4):457–480

Roland PE (1984) Organization of motor control by the normal human brain. Hum Neurobiol 2(4):205–216
Sampaio J, Janeira M (2003) Importance of free-throw performance in game outcome during the final series of basketball play-offs. Int J Appl Sports Sci 15(2):9–16
Shibasaki H, Hallett M (2006) What is the Bereitschaftspotential? Clin Neurophysiol 117(11):2341–2356
Smith DT, Schenk T (2012) The premotor theory of attention: time to move on? Neuropsychologia 50(6):1104–1114
Toma K, Matsuoka T, Immisch I, Mima T, Waldvogel D, Koshy B, Hallett M (2002) Generators of movement-related cortical potentials: fMRI-constrained EEG dipole source analysis. Neuroimage 17(1):161–173
Vickers JN (1996) Visual control when aiming at a far target. J Exp Psychol Hum Percept Perform 2:324–354
Vickers JN (2007) Perception, cognition, and decision training: the quiet eye in action. Human Kinetics, Champaign, pp 75–96
Vickers JN (2009) Advances in coupling perception and action: the quiet eye as a bidirectional link between gaze, attention, and action. Prog Brain Res 174:279–288
Vickers JN (2016) Origins and current issues in Quiet Eye research. Curr Issues Sport Sci 1:1–11
Vickers JN, Adolphe RM (1997) Gaze behaviour during a ball tracking and aiming skill. Int J Sports Vis 4(1):18–27
Vickers JN, Rodrigues ST, Edworthy G (2000) Quiet eye and accuracy in the dart throw. Int J Sports Vis 6:30–36
Vine SJ, Moore L, Wilson MR (2011) Quiet eye training facilitates competitive putting performance in elite golfers. Front Psychol 2:8
Vine SJ, Lee DH, Walters-Symons R, Wilson MR (2017) An occlusion paradigm to assess the importance of the timing of the quiet eye fixation. Eur J Sport Sci 17(1):85–92
Williams AM, Singer RN, Frehlich SG (2002) Quiet eye duration, expertise, and task complexity in near and far aiming tasks. J Motor Behav 34(2):197–207
Wood G, Wilson MR (2011) Quiet-eye training for soccer penalty kicks. Cogn Process 12(3):257–266