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RESEARCH REPORT

Quiet eye and the Bereitschaftspotential: visuomotor mechanisms of expert motor performance

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Abstract Concurrent exploration of the Bereitschaftspotential (BP) and quiet eye period (QE) was implemented to assess potential mechanisms underlying psychomotor skills that differentiate expert and near-expert performers. Twenty golfers were classified by their USGA handicap rating as either a high handicap (HH; near-expert) or low handicap (LH; expert) to permit skill-based inferences. Participants completed 90 trials during which QE duration, BP activity, and putting performance were recorded. The application of single-subject analyses illustrated that LH golfers were more accurate and less variable in their performance than the HH group. Systematic differences in QE duration and BP were also observed, with experts exhibiting a prolonged quiet eye period and greater cortical activation in the right-central region compared with non-experts. A significant association between cortical activation and QE duration was also noted. The results of this investigation lend support to the motor programming/preparation function of the QE period. Practical and theoretical implications are presented and suggestions for future empirical work provided.

Keywords Readiness potentials · BP · QE · Motor planning · Attention · Expertise · Sport · Individual differences

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Introduction

The golf putt, which accounts for approximately 43 percent of the game's strokes (Pelz 2000), is a self-paced, closed motor task. The difficulty of the putt lies in the golfer's ability to synchronize sensory information with the mechanisms necessary to plan and control the appropriate motor response (Craig et al. 2000; Pfurtscheller and Neuper 2003). Successful performance mandates that the golfer attend to cues related to distance, direction, and force, elements that are directly influenced by a multitude of environmental conditions (e.g., slope, grain direction). Accordingly, the visual system must orient to and process the most salient perceptual cues necessary to ascertain both distance and direction information, while working memory is called upon for matching stroke tempo with the requisite stroke force.

An extensive body of evidence suggests that the visual system is the dominant perceptual system by which all other systems are attuned (Abernethy 1996; Janelle et al. 2000; Posner et al. 1976; Van Wynsberghe et al. 1995). Accordingly, researchers have extensively relied upon gaze behaviors to infer the attentional factors involved in the performance of numerous sports skills. Of particular interest has been to determine how search characteristics differentiate relative expert and novice performers. Mann et al. (2007) conducted a meta-analysis of nearly three decades of empirical work in this area. Findings supported the critical role of visual attention in the expert advantage, revealing that experts consistently exhibit fewer *fixations* ($\bar{r}_{pb} = 0.26$) of longer *duration* ($\bar{r}_{pb} = 0.23$) than non-expert comparison groups. While not a direct measure of attention per se, the longer the eye remains fixated on a given target, the more information is thought to be extracted from fixated cues in the display. Given the typically dynamic context of sport, researchers have interpreted visual search strategies involving fewer fixations of longer duration as more efficient, permitting more time for more detailed information extraction from only the most relevant environmental cues (Williams et al. 1999; Mann et al. 2007).

In addition to saccadic eye movements, the past 15 years have seen great interest in the duration of the final fixation to a target. A robust observation is that experts exhibit an extended *quiet eye* period relative to non-experts. According to Vickers (1996a, 2007), the quiet eye (QE) is a temporal period when task-relevant environmental cues are processed and motor plans are coordinated for the successful completion of an upcoming task. Specifically, the QE period is defined as the elapsed time between the last visual fixation to a target and the initiation of the motor response (Vickers 1996a, b). As such, the QE appears to functionally represent the time needed to organize the neural networks and visual parameters responsible for the orienting and control of visual attention (Vickers 1996a, b). Although it has been argued that prolonged fixations are not essential for successful performance (de Oliveira et al. 2006, 2008; Oudejans et al. 2002) and other factors such as postural and attentional fatigue may preclude prolong QE duration (Behan and Wilson 2008), collective analysis of the extant literature reveals that experts exhibit longer quiet eye periods ($\bar{r}_{pb} = 0.62$) when compared with less skilled performers (Mann et al. 2007). Furthermore, intragroup variability has been reported, suggesting that longer quiet eye periods correspond with increased accuracy (Harle and Vickers 2001; Janelle et al. 2000; Vickers 1996a, b; Vickers and Adolphe 1997).

Despite consistency in the body of QE findings, the underlying mechanism(s) responsible for the robust QE-specific expertise differences remains unknown. From a pure visuomotor perspective, the QE may serve to maximize cerebral efficiency, as reflected in cortical patterns indicative of elite performance (Janelle et al. 2000). Previous research has consistently reported cortical quieting in visuospatial and motor coordination tasks in the left hemisphere as compared to the right hemisphere at temporal, mid-frontal, occipital, and parietal regions (e.g., Crews and Landers 1993; Haufler et al. 2000). As mentioned, elite athletes generally make fewer fixations of longer duration, suggesting a level of information processing efficiency that permits more time to be spent on task-relevant cues and less time in search of these cues. A prolonged QE may permit a similar advantage; as task-salient cues are prioritized during visual search, particularly during the final fixation, cortical resources are likely reallocated away from analytical processing and irrelevant sensory cues and toward the visuospatially dominant perceptuomotor processes that are critical for effective motor programming and execution.

Janelle et al. (2000) attempted to ascertain whether QE was associated with spectral indices (alpha and beta power) of cortical activation among elite and sub-elite marksmen. Elite level performance was characterized by significantly longer QE periods and pronounced hemispheric asymmetry. With regard to the latter finding, greater right hemisphere activation was identified among elite shooters, suggesting quieting of the left hemisphere (indicating a reduction in verbal analytical processing) relative to the visuospatially dominant right hemisphere. Such promising findings suggest a relationship between the QE period and cerebral efficiency, but the association between the QE and spectral asymmetry was not reported and would not likely emerge given the nature of spectral EEG in particular. EEG spectral activity is limited in terms of the degree of inference that can be made from the spontaneous rhythmic oscillations in voltage (Fabiani et al. 2000) to specific brain functions or psychological processes. Furthermore, and more importantly, the spectral technique decomposes the continuous EEG signal into specific frequency bands (i.e., alpha, 8–12, beta, 13–36) to assess the cortical activity associated with a behavioral state, thereby ameliorating its temporal characteristics.

Event-related potentials (ERP) have been used in a number of psychophysiological investigations to evaluate athletes' attentional and preparatory states preceding task execution (e.g., Crews and Landers 1993; Konttinen and Lyytinen 1992). The ERP is derived from the average of multiple responses and represents the temporal relationship of cortical activation to a specific event, thereby providing a time-locked index of the psychological correlates of performance (Fabiani et al. 2000). The bereitschaftspotential (BP), first described by Kornhuber and Deecke (1965), is one class of ERP that lends itself well to the study of the preparatory period preceding task execution. The BP is a negative potential that precedes an actual, intended, or imagined event by 1–1.5 s and indexes anticipatory attention and movement preparation (Jahanshahi and Hallett 2003).

The BP is a visually distinct waveform comprised of three components, each of which is temporally and cortically diverse. The early slow rising negativity ($\mathrm{BP}_{\mathrm{early}}$) reflects the activation of the supplementary motor area (SMA) and begins approximately 1500 ms prior to movement onset. The early activation of the $\mathrm{BP}_{\mathrm{early}}$ has a widespread scalp distribution with maximal potentials recorded at the vertex (Deecke 1987). The SMA serves to retrieve and/or augment the requisite motor commands from memory (Roland 1984; Roland et al. 1980), and applying repetitive transcranial magnetic stimulation (rTMS) to SMA has been shown to interfere with the stabilization of motor memory immediately following and 6 h after a blocked practice session (Tanaka et al. 2009).

Accordingly, the more elaborate the motor sequence, the more precise the corresponding movement should be, as indexed by an increase in SMA activation (and increased negativity of the BP). The second component, known as the $\mathrm{BP}_{\mathrm{late}}$, is characterized by a change in the steepness of the waveform's slope, which occurs approximately 400–500 ms prior to movement onset, and is known to reflect the activation of the primary motor cortex (MI; Deecke 1987; Shibasaki et al. 1980). Changes in $\mathrm{BP}_{\mathrm{late}}$ have been shown to reflect skill differences, such that a decrease in negativity is evident in the hemisphere ipsilateral to the active limb (Taylor 1978); however, the amplitude contralateral to the active limb increases during skilled performance (Chairenza et al. 1990; Papakostopoulos 1978). Finally, $\mathrm{BP}_{\mathrm{peak}}$, which reflects the coordinated activation of the SMA and MI, is most pronounced over the hemisphere contralateral to the responding hand and occurs approximately 50–60 ms prior to movement onset. As Brunia and van Boxtel (2000) state, the components of the readiness potential collectively index resource allocation prior to the initiation of voluntary, self-paced, motor acts.

Preparatory activity in the general context of sensorimotor transformations implicates an integrated neural path linking perception to action (Toni and Passingham 2003). The BP reflects activation of subcortical and cortical generators (cortico-basal ganglia-thalamo-cortical circuitry) necessary not only in motor execution but also in its preparation (Rektor 2003). The BP has therefore been speculated to play a role in the detection and pairing of task-relevant environmental features with the requisite elements of response execution (Brunia and van Boxtel 2000).

Sport psychophysiologists have applied the slow negative ERP paradigm to research with golfers (Crews and Landers 1993), archers (Landers et al. 1994), and marksmen (Konttinen and Lyytinen 1992; Konttinen et al. 1999), revealing that elite performance is characterized by an increase in cortical negativity in the period immediately preceding task performance ($\mathrm{BP}_{\mathrm{peak}}$), a pattern indicative of the requisite motor program among experts. More recently, Di Russo et al. (2005) found that when performing a non-sport-specific movement task (simple finger flexion), the BP was longer for elite shooters than a non-experienced control group, and specific to movement expertise.

Conceptually, the QE period is thought to represent the time needed to organize both the neural networks and visual parameters responsible for the orienting and control of visual attention (Vickers 1996a, b). Throughout the preparation and movement phases of skill execution, the visual attention centers (i.e., occipital and parietal cortex) disseminate requisite commands to motor regions of the cortex (i.e., motor cortex, premotor cortex, supplementary motor area, basal ganglia, and cerebellum), each of which are reflected in BP components. Therefore, the cortical generators responsible for the BP, which have been shown to correspond with the preparation and execution of a motor task, may in turn benefit from the reallocation of resources during the QE period, allowing for the development of a more refined motor program that results in better performance and greater expertise levels.

Our objective was to determine whether modulations of the QE period and BP discriminate expertise and performance differences while expert (low handicap; LH) and near-expert (high handicap; HH) golfers performed the golf putt. Moreover, we sought to examine whether the QE is associated with components of the BP, given their theorized complimentary processes. Four hypotheses were tested. First, QE was predicted to account for both inter- and intra-group performance variability. More specifically, the LH group was expected to not only exhibit a longer QE duration as compared to the HH group, but the QE duration of both LH and HH groups for successful putts was predicted to exceed the QE duration for missed putts. Given that the BP is representative of the cortical mechanisms responsible for movement preparation and that increased negativity in the mean $\mathrm{BP}_{\mathrm{peak}}$ and mean $\mathrm{BP}_{\mathrm{late}}$ amplitude characterizes greater movement preparation and cerebral efficiency (Chairenza et al. 1990; Papakostopoulos 1978; Taylor 1978), it was expected that the LH group would exhibit a greater $\mathrm{BP}_{\mathrm{late}}$ amplitude coupled with a greater $\mathrm{BP}_{\mathrm{peak}}$ amplitude compared with the HH group. Third, the mean amplitude of the $\mathrm{BP}_{\mathrm{late}}$ and the mean amplitude of the $\mathrm{BP}_{\mathrm{peak}}$ were predicted to discriminate between putts made and putts missed regardless of skill level. Finally, a positive correlation between BP and QE period was predicted. More specifically, we expected the amplitude of the $\mathrm{BP}_{\mathrm{peak}}$ to increase as the duration of the QE period increased.

Methods

Participants

Twenty volunteers were randomly recruited from various golf clubs in the southeastern United States and ranged in age from 18 to 35 years (experts M = 26.0, SD = 6.85; near-experts M = 26.20, SD = 5.83). Participants reported their handicap and were objectively classified according to the United States Golf Association (USGA) handicap system, with the experts (i.e., LH, n = 10) ranging from a 0 to 2 (M = 1.20, SD = 1.23) handicap and the near-experts (i.e., HH, n = 10) ranging from a 10 to 12 (M = 11.30, SD = 0.82) handicap. The LH group (*n* = 10) averaged 14.7 (SD = 5.95) years of playing experience and completed an average of 56.50 (SD = 22.12) rounds of golf over the previous 12 months. In comparison, the HH group ($n = 10$) averaged 12.4 (SD = 4.94) years of playing experience and completed an average of 24.30 (SD = 9.69) rounds of golf over the previous 12 months. All participants were right-handed and right-eye dominant.

Instrumentation

Putting surface

Golf putting performance was assessed using a true and level putting platform. The platform included a nylon NP 50 artificial putting surface (Synthetic Turf International, STI, Jupiter, FL) outfitted with a 4.25-in. regulation size golf hole permitting a 12 foot putt.

Putting performance

The target (i.e., golf hole) was supplemented with an imposed grid used for assessing accuracy, bias, and consistency (Hancock et al. 1995). Specifically, a 30 in. × 40 in. matrix progressing in 1-in. increments on both the vertical and horizontal axes was projected onto the putting surface with a Sharp Notevision LCD Projector (Model XG-NV2U, Tokyo, Japan). The coordinate (0,0) indicates the center of the golf hole. The image was projected after each stroke and removed prior to each subsequent stroke to avoid latent visual assessment of performance or impairment of performance potentially induced by the display of the grid.

Gaze behavior

A BIOPAC electro-oculogram amplifier (EOG 100B; BIOPAC Systems, Inc., Santa Barbara, CA) with a bandpass range from DC to 100 Hz was used to record eye movements, specifically QE duration. Analog data were sampled at 1000 Hz using an MP 150 analog/digital converter and recorded online with AcqKnowledge 7.0 (BIOPAC Systems, Inc., Santa Barbara, CA) software installed on a Dell XPS computer (Dell Inc., Austin, TX). The EOG 100B amplifier is a biopotential amplifier designed to record changes in the corneal–retinal potential as the eye navigates the visual environment relative to head position (Duchowski 2002). Simply stated, as the eye moves in the horizontal and vertical planes, the corneal–retinal potential adjusts accordingly and is reflected in voltage changes in the range of 15–200 μV with corresponding eye movements measuring approximately 20 μV/degrees of eye movement. Our objective was to assess the association of the quiet eye period to preparatory cortical activity. As such, the quiet eye period was operationally defined here as the elapsed time between the last visual fixation to the target and the initiation of the motor response (Vickers 1996a, b). Although more contemporary definitions of QE have emerged to include fixations that exceed movement onset (Vickers 2004; Vickers 2007; Vine et al. 2011), Vickers (1996a, b) original definition was preferred as it is more temporally attuned to the preparatory nature and duration of the BP.

Cortical activity (Bereitschaftspotential)

Continuous EEG data were collected and amplified 5000 times using the BIOPAC EEG amplifier (EEG100B; BIOPAC Systems, Inc., Santa Barbara, CA), with a bandpass range from DC to 70 Hz. Analog data were sampled at 1000 Hz using an MP 150 analog/digital converter and recorded online with AcqKnowledge 7.0 (BIOPAC Systems, Inc., Santa Barbara, CA) software. A digital marker was generated using LabVIEW 8.0 (National Instruments, Austin, TX) to facilitate the identification of the EMG fiducial time point on the EEG trace to indicate the onset of the putting stroke and corresponding BP waveform necessary for post-acquisition analysis.

Electromyogram

To determine movement onset, electromyogram (EMG) activity was collected from the extensor carpi ulnaris (ECU) of the right arm and amplified 5000 times using a BIOPAC EMG amplifier (EMG 100B; BIOPAC Systems, Inc., Santa Barbara, CA), with a bandpass range from DC to 70 Hz. Analog data were sampled at 1000 Hz using an MP 150 analog/digital converter and recorded online with AcqKnowledge 7.0 (BIOPAC Systems, Inc., Santa Barbara, CA) software. The EMG data were rectified and used to obtain the fiducial point for averaging the EEG and QE as described below.

Procedure

Upon arriving for testing, participants were informed of the general purpose of the investigation and were provided with a brief tour of the testing equipment and apparatus. Following the tour, each participant was asked to read and complete an informed consent document and a brief demographic questionnaire. Participants were also permitted to ask any questions regarding the experiment.

Upon providing consent, participants were prepared for electro-ocular (EOG), electromyographic (EMG), and electroencephalographic (EEG) measurements in accord with the guidelines put forth by the Society for Psychophysiological Research (Pivik et al. 1993). Vertical (VEOG) and horizontal (HEOG) bipolar electro-oculographic movements were collected to assess QE duration and to control for ocular artifact in the EEG waveform. Four 4-mm Biopac silver/silver chloride (Ag/AgCl) electrodes (EL204) were positioned above and below the right eye, and lateral to each eye, adjacent to the left and right orbital fossi.

EMG activity was recorded using two 10-mm silver/silver chloride (Ag/AgCl) electrodes placed 3 cm apart over the muscle belly of the extensor carpi ulnaris (ECU) of the right arm. EMG activity was sampled at 1000 Hz and amplified (×5000) using the Biopac EMG amplifier (EMG 100B). The continuous EEG was recorded with an array of 6 silver/silver chloride (Ag/AgCl) electrodes in accord with the International 10–20 system (Jasper 1958) using a lycra electrode cap manufactured by Electrode-Cap International, Inc. (ECI, Eaton, OH). A central cluster of electrodes was positioned over the left, mid-line, and right-central (primary motor cortex: C3, Cz, C4) sites to concentrate on those cortical regions known to have implications in motor planning and execution, as well as source generators of the BP (Orgogozo and Larsen 1979; Roland et al. 1980; Rektor et al. 1994; Huckabee, et al. 2003). Furthermore, an additional cluster of electrodes was positioned over the parietal cortex (P3, P4), a region associated with visuomotor control and suspected to have implications in QE functioning (Brunia and van Boxtel 2000). All sites were referenced to linked ears. The mid-frontal (FPz) site served as the ground with electrode impedance being kept below 5 k**Ω**.

After being outfitted with the requisite physiological attire, each participant was individually tested. The testing session consisted of 10 practice trials followed by 90 additional trials (i.e., 2 blocks of 45 putts per block). The practice session served to familiarize the participant to the testing equipment and apparatus. Given that all participants were skilled golfers, a learning effect was not expected, justifying the minimal number of practice putts.

Data analysis

Quiet eye duration has been demonstrated to account for both inter- and intra-group performance variability. Accordingly, both inter- and intra-group differences in QE duration were analyzed using single-subject design methodology. Specifically, the 90 trials from each participant were used in the analysis and each trial was treated as if they were data from a group of subjects (Bates 1996).

Given that the LH group was expected to exhibit a greater BP_{late} amplitude coupled with a greater BP_{peak} amplitude compared with the HH group, BP data were evaluated using a repeated-measure multivariate analysis of variance (RM MANOVA). Given the anticipated association of the three BP components (i.e., early, late, peak) across cortical regions (i.e., C3, Cz, C4, P3, P4), MANOVA procedures were preferred over separate univariate ANOVAs. Cortical activation in each of the BP components across skill level and cortical region was analyzed using a 2 (*Skill*: LH, HH) × 3 ($BP_{\text{component}}$: early, late, peak) MANOVA with repeated measures on the last factor. Post hoc procedures included univariate ANOVAs, each at the .05 level.

The various components of the BP were predicted to account for intra-group (i.e., collapsing across skill) performance variability. That is, the amplitude of the BP_{early}, BP_{late}, and BP_{peak}, across cortical regions, was predicted to discriminate between putts made and putts missed regardless of skill level. The mean amplitude of the BP_{early}, BP_{late}, and BP_{peak} was analyzed using 2 (*Accuracy*: Hits, Misses) × 3 ($BP_{\text{component}}$: early, late, peak) MANOVA with repeated measures on the last factor. Post hoc procedures included univariate ANOVAs, each at the .05 level.

The relationship between the amplitude of the BP_{peak} and QE duration was evaluated using a Pearson product–moment correlation. The calculation of effect size estimates (i.e., Cohen's *d*) served to quantify skill-based differences across the dependent measures.

Results

Participant characteristics

To ensure that performance differences were not attributable to random moderating effects, participant characteristics were held constant with the exception of handicap, practice, and competitive playing experience. Specifically, although the number of years of golf experience ($t_{(18)} = .884$, $P < .360$, $d = .20$) did not differ between the participants, the LH group engaged in significantly more practice ($t_{(18)} = 4.191$, $P < .001$, $d = .70$) and competitive playing experience ($t_{(18)} = 3.892$, $P < .001$, $d = .68$), completing an average of 10.80 (SD = 4.64) competitive events compared with 3.2 events for the HH group (SD = 4.07). Lending further confirmation of task–specific, skill-based differences, the LH group was more successful (made putts) than the HH group ($\chi 2 = 33.59$, $P < .001$, d = .19). Moreover, univariate analyses of variance for RE ($F(1, 895) = 36.305$, $P < .001$, $d = .40$) and BVE ($F(1, 895) = 34.753$, $P < .001$, $d = .39$) indicated that the LH group was significantly more accurate and consistent than the HH group.

Inter- and intra-group performance variability in quiet eye duration

We hypothesized that the QE duration of both the LH and HH groups for successful putts would exceed the QE duration for missed putts. The results of single-subject analyses yielded significantly longer QE duration during hits for participants 1 ($F(1,88) = 5.73$, $P < .05$), 2 ($F(1,88) = 62.78$, $P < .001$), 3 ($F(1,88) = 7.56$, $P < .001$), 4 ($F(1,88) = 6.96$, $P < .01$), and 6 ($F(1,88) = 4.56$, $P < .05$) from the LH group and participants 3 ($F(1,88) = 10.19$, $P < .001$), 4 ($F(1,88) = 4.07$, $P < .05$), 7($F(1,88) = 8.03$, $P < .01$), 8 ($F(1,88) = 3.80$, $P < .05$), 9 ($F(1,88) = 4.79$, $P < .05$), and 10 ($F(1,88) = 8.84$, $P < .01$) from the HH group (Fig. 1a, b). Overall, the LH exhibited a longer QE than HH ($F_{(1,\ 1793)} = 51.989$, $P < .001$, $d = .34$).

BP activity across skill level and cortical region

To investigate the hypothesis that both increased negativity in mean $\mathrm{BP}_{\mathrm{late}}$ and $\mathrm{BP}_{\mathrm{peak}}$ amplitude are characteristics of greater movement preparation, cortical activation levels in each of the BP components (i.e., early, late, peak) across skill level and cortical region (i.e., C3, Cz, C4, P3, P4) were assessed. As anticipated, the interaction of *Skill* with $BP_{\mathrm{component}}$ was not significant (Pillai's Trace = .177, ($F_{(10,\ 66)} = .640$, $P = .774$, $\eta^2 = .177$). An overall significant difference in cortical activity was evident for the main effect of *Skill*, Pillai's Trace = .690, ($F_{(5,\ 14)} = 6.245$, $P = .003$, $\eta^2 = .690$) and $BP_{\mathrm{component}}$, Pillai's Trace = .483, ($F_{(10,\ 66)} = 2.103$, $P = .036$, $\eta^2 = .242$). As highlighted in Fig. 2, the LH group demonstrated greater BP negativity relative to the HH group, and cortical negativity increased from the BP_{early} to BP_{late} component for both groups, reaching maximal negativity immediately prior to movement execution (i.e., BP_{peak}). Follow-up univariate analyses of variance for the main effect of *Skill* revealed significant cortical region differences for C4 ($F_{(1,\ 18)} = 14.171$, $P = .001$, $d = 1.77$) and P4 ($F_{(1,\ 18)} = 8.304$, $P < .010$, $d = 1.36$). Given the relative degree of relatedness among BP components, a multivariate analysis of variance was used to examine the temporal location of the cortical region differences between groups. For C4, the LH group exhibited greater negativity for each $BP_{\mathrm{component}}$ ($\mathrm{C4}_{\mathrm{early}}$, $F_{(1,\ 18)} = 6.023$, $P = .025$, $d = 1.16$; $\mathrm{C4}_{\mathrm{late}}$, $F_{(1,\ 18)} = 17.519$, $P = .001$, $d = 1.97$; and $\mathrm{C4}_{\mathrm{peak}}$, $F_{(1,\ 18)} = 27.425$, $P < .001$, $d = 2.47$) compared with the HH group, while parietal differences were only evident between the two groups during the early component, $\mathrm{P4}_{\mathrm{early}}$ ($F_{(1,\ 18)} = 7.661$, $P = .013$, $d = 1.30$).

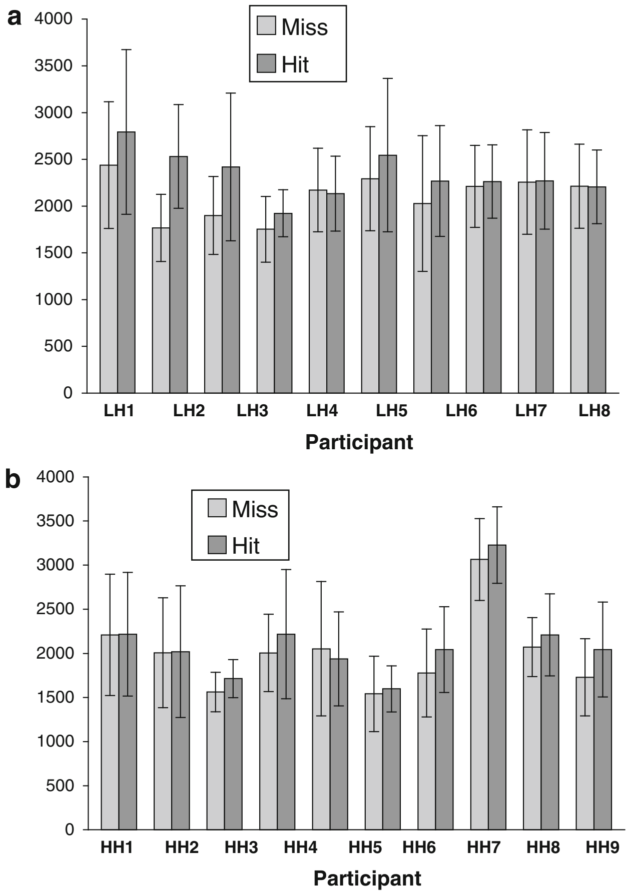

Fig. 1 Single-subject analysis of QE duration for hits and misses across LH (**a**) and HH (**b**) participants

BP activation and putting outcome

To investigate the hypothesis that an increase in $\mathrm{BP}_{\mathrm{peak}}$ amplitude is characteristic of greater task involvement and sensorimotor efficiency, cortical activation levels in each of the BP components (i.e., $\mathrm{BP}_{\mathrm{early}}$, $\mathrm{BP}_{\mathrm{late}}$, and $\mathrm{BP}_{\mathrm{peak}}$) for putts made and missed served as the dependent measures of interest for each cortical region. Although cortical negativity increased across each of the $BP_{\mathrm{components}}$, reaching maximal negativity immediately prior to movement execution (Pillai's Trace = .449, ($F_{(10,\ 146)} = 4.223$, $P < .001$, $\eta^2 = .224$), the omnibus test for *Accuracy* failed to reach significance (Pillai's Trace = .031, ($F_{(5,\ 34)} = .219$, $P = .952$, $\eta^2 = .031$), suggesting that BP negativity did not vary as a function of putting accuracy (i.e., hit or miss). No other differences were noted. Figure 3 provides a graphical depiction of the findings.

Quiet eye duration and $\mathrm{BP}_{\mathrm{component}}$ activation

It has been documented that both the QE period and the cortical and subcortical generators associated with the BP are responsible for the orientating of visual attention and motor planning associated with execution of a self-paced task. A Pearson product–moment correlation was conducted to explore the relationship between QE duration and BP. Although emphasis is placed on the BP_{peak}–*quiet eye*

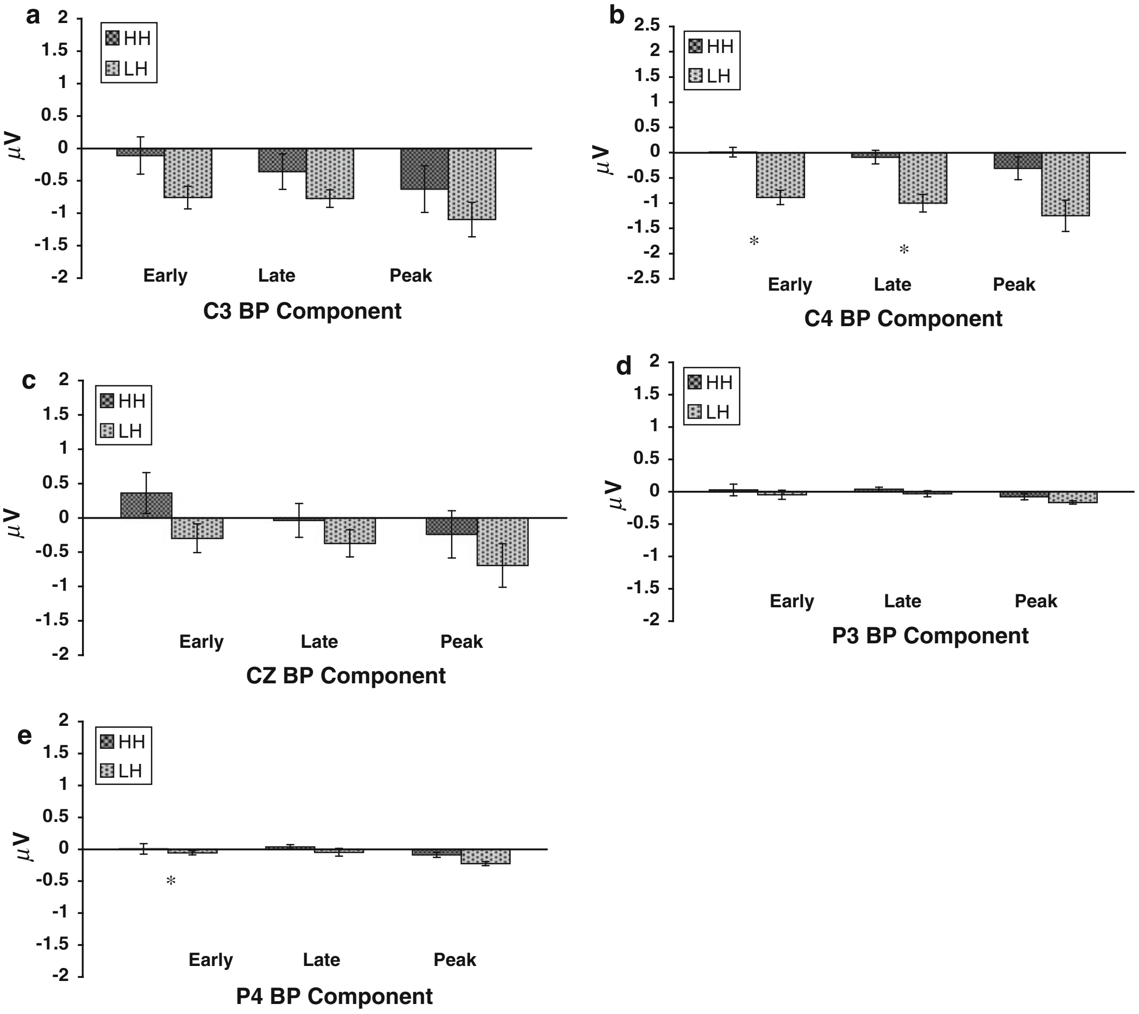

Fig. 2 Skill-based differences (i.e., mean, SE) across cortical regions and BP components. **a** Increase in left-central negativity across BP components for the LH group. **b** Increase in right-central negativity across BP components for the LH group. **c** Increase in negativity at the vertex across BP components for the LH group. **d** Minimal hemispheric differences in the left-parietal region between skill levels. **e** Increase in right-parietal cortical negativity for the $\mathrm{BP}_{\mathrm{early}}$ component (* represents $P < .05$)

duration relationship, the association between each component of the BP and QE was assessed. Results indicated a significant correlation between QE duration and $\mathrm{C3}_{\mathrm{peak}}$ ($r = .3096$, $P = .026$, $d = .65$), $\mathrm{C4}_{\mathrm{peak}}$ ($r = .2874$, $P = .036$, $d = .60$), and $\mathrm{Cz}_{\mathrm{peak}}$ ($r = .2901$, $P = .035$, $d = .61$), suggesting that as QE duration increased so too did BP negativity within the specified regions. No other significant correlations were found ($\mathrm{P3}_{\mathrm{peak}}$ ($r = .1696$, $P = .148$, $d = .34$); $\mathrm{P4}_{\mathrm{peak}}$ ($r = .1574$, $P = .166$, $d = .32$) between QE duration and BP.

Discussion

Psychological efficiency underlies expert performance (Hatfield and Hillman 2001), which is characterized by both cortical asymmetry and efficient cue utilization (i.e., fewer fixations of longer duration and prolonged QE). With the exception of Janelle et al.'s (2000) early work, these two components of expert attention allocation and motor preparation have not been simultaneously explored. We sought to examine a theorized mechanism that underlies the efficacy of the QE period by concurrently assessing QE duration and a premotor electrophysiological index of cerebral efficiency (the BP), among HH and LH golfers during a golf putting task. Four notable findings emerged: (1) individual differences were identified in quiet eye duration across skill level, (2) longer QE was found for experts compared with non-experts, (3) greater BP negativity (particularly in central recording locations) was identified for the expert golfers compared with non-experts, with increasing negativity from early to late components, and (4) QE duration was associated with BP negativity in central cortical regions. Each of these findings is discussed and elaborated below.

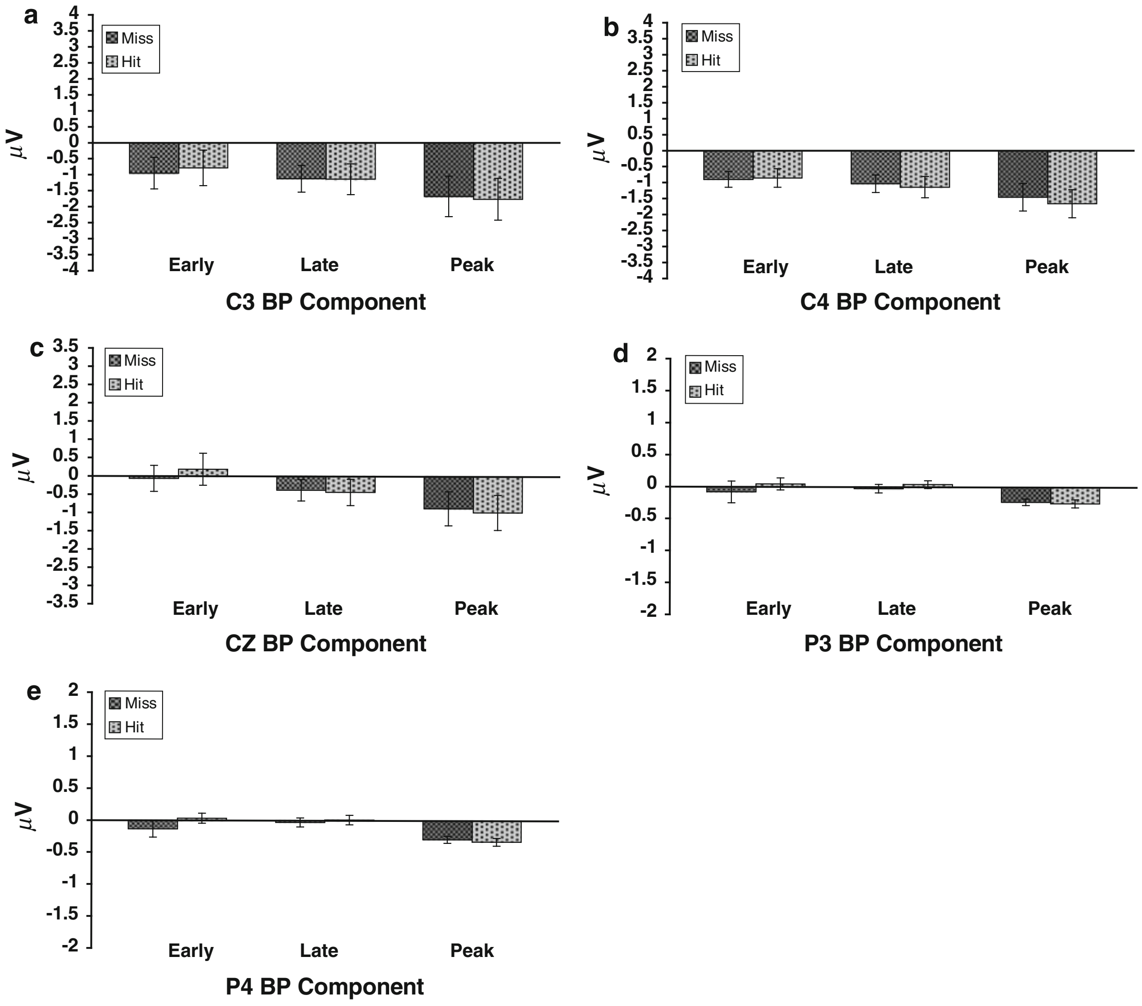

Fig. 3 Performance differences across cortical regions and BP components. **a** and **b** Marked BP negativity across components with minimal differences between hits and misses for left-central and right-central regions, respectively. **c** Pronounced $\mathrm{BP}_{\mathrm{peak}}$ negativity at the vertex. **d** and **e** Greater $\mathrm{BP}_{\mathrm{peak}}$ negativity for left- and right-parietal regions

Inter- and intra-group performance variability on quiet eye duration

The LH group was hypothesized to exhibit a longer QE period relative to HH group, and the QE duration of both the LH and HH groups was predicted to exceed the QE duration for missed putts compared with successful ones. In accord with expectation, the LH group not only performed better on the putting task, but also engaged a longer QE duration relative to the HH group. While not altogether novel, such a replication of previous work is important as it is consistent with the entirety of the published literature. Indeed, the existence of an expertise based extension of the QE is one of the most robust in all of the visual search and expertise literature (Mann et al. 2007).

Contrary to expectations, QE duration did not account for within-group performance differences across all participants. While the between group differences noted above are unequivocally robust, trial-by-trial performance differences are less so. Still, such differences have been identified in prior work with golfers (Vickers 1992), marksmen (Causer et al. 2010; Janelle et al. 2000), basketball players (Vickers 1996b), biathletes (Vickers et al. 1999), and volleyball players (Vickers and Adolphe 1997). A primary difference in the current study relative to those that have identified such within subject differences is that the sample selected for the current study was a bit more heterogeneous (from multiple golf courses) given constraints on selection criteria, potentially increasing within-group variability. Moreover, given the preparatory focus of the paper and the potential linkage to the BP, we chose to truncate QE at movement onset (consistent with Vickers' (Vickers 1996a, b) original conceptualization). Truncation of QE at movement onset may have reduced the expected expertise-related differences as a function of individual performance. Regardless, mean QE duration was longer for the HH group regardless of outcome, and though non-significant, for successful putts compared with missed putts for the HH group. The collective findings indicate greater consistency and duration of the preparatory period for expert golfers, regardless of shot outcome.

BP activity across skill level and cortical region

In line with previous research suggesting that an increase in mean BP_{peak} and mean BP_{late} negativity characterize greater movement preparation and cerebral efficiency (Chairenza et al. 1990; Papakostopoulos 1978; Taylor 1978), we hypothesized that the LH group would show a greater BP_{late} and BP_{peak} amplitude compared with the HH group. Congruent with previous research (Deecke 1987; Konttinen and Lyytinen 1992; Shibasaki et al. 1980), cortical negativity continued to increase across each BP component, reaching maximal negativity immediately prior to movement execution. Furthermore, as hypothesized, skill-based differences were discernible across cortical regions and BP components. Specifically, cortical differences were evident over the right-central ($C4_{early}$, $C4_{late}$, and $C4_{peak}$) and right-parietal regions ($P4_{early}$), indicating the relative increase in attention allocation to the visuospatial cues for the LH group to the HH group. Given the cortical specificity of these findings, it is reasonable to conclude that the LH group allocated more attention to the visuomotor components of the putting task than their HH counterparts. The initial increase in cortical negativity associated with the BP_{early} component as evidenced here (i.e., $C4_{early}$ and $P4_{early}$) likely reflects the activation of the supplementary motor area, which may serve to retrieve and/or augment the requisite motor commands from memory (Roland 1984). This finding supports the contention that the BP may play a role in the detection and pairing of task-relevant information with the necessary components of movement (Brunia and van Boxtel 2000), while reflecting the activation of a neural path linking perception to action (Toni and Passingham 2003).

Differences in activation of the BP_{peak} component of the right-central region (i.e., $C4_{peak}$) for the LH group relative to the HH group are congruent with previous work (Deecke 1987; Shibasaki et al. 1980). Of the three BP components, the BP_{peak} is believed to reflect the coordinated activation of the SMA and MI. Brain activity in M1 and SMA has been associated with visuomotor control (Coombes et al. 2010), and activation of these structures play a critical role in the organization of complex motor sequences that are rehearsed from memory and fit into a precise timing plan (Jahanshahi and Hallett 2003; Tanaka et al. 2009). The elite group should therefore have a more refined cortical representation of the task that facilitates the movement and timing patterns of the golf putt. Practice and experience may contribute to the elevated right-central cortical activation of the LH group relative to the HH group, such that the preparatory period of the LH player reflects attentional processes that permit the assessment, organization, and recall of the requisite motor program from memory. The HH player likely has not developed such refined control, therefore resulting in more deliberate cognitive processes.

Importantly, the QE and BP were closely associated with each other, particularly at the central recording regions. Such a relationship supports Vickers (1996a, b) postulate that the QE is a period of visual orienting and visuomotor preparation, precisely the processes that affect the magnitude and latency of the BP. Of course, correlation cannot confirm or refute a causal relationship between to the two dependent measures. Regardless, both indices appear to be related to the efficiency and quality of motor processing. Such an assertion is consistent with previous work (e.g., Janelle et al. 2000), indicating that elite level performance is characterized by significantly longer QE periods and pronounced hemispheric asymmetry. With regard to the latter finding, greater right hemisphere activation was identified among elite shooters, suggesting quieting of the left hemisphere (indicating a reduction in verbal analytical processing) relative to the visuospatially dominant right hemisphere.

That visual and cortical differences are evident before the golfer actually executes the stroke is consistent with imaging work, showing the efficient organization of the task-related neural networks that are theorized to be manifest by both the QE and the BP. More specifically, whole-brain MRI data lend further support to the results presented here, suggesting that experts develop a specialized motor program evidenced by right brain activation that integrates visual information with the necessary motor commands for performance (Milton et al. 2007). Corroborating the extant spectral work (see Kerick et al. 2004), BP evidence gathered in the current study suggests that the LH players allocate more resources to the visual–spatial processing of the task and fewer resources to the conscious processing of the movement, linking the visual–spatial area of the cortex to movement preparation and performance.

Practical implications and future directions

The extended QE period and the significant relationship between right-central (i.e., C4) cortical activation and QE duration for the LH group relative to the HH group speaks to the cognitive advantage of the expert and supports the notion of relative sensorimotor efficiency of expert athletes. Prolonged fixations, particularly during the final fixation that defines the QE, apparently permit the detailed processing of information and cortical organization necessary for effective motor performance. QE training may facilitate the relative cortical quieting and movement preparation necessary to perform at a higher level. Systematically training the QE, therefore, may augment practice effectiveness by allowing the athlete to process the visual–spatial characteristics of the task while permitting the organization of the neural networks responsible for movement planning.

With specific reference to golf, when addressing the putt, the typical golfer will spend a brief moment estimating the distance, speed, and line of putt to the target. However, at the onset of the putting stroke, most non-expert players revert to conscious processing of the putting stroke. For example, Vickers (2004) reported that non-expert golfers often track the putter-head as it traverses back and through ball contact, a behavior not as evident in highly skilled putters. Such ineffective behavior can interfere with the visual–spatial cues previously attended. Training the QE in this case may aid in alleviating inefficient gaze behavior to enhance performance.

For example, the QE is a process that can be easily integrated into a pre-performance routine. Singer's (1988) five-step strategy is one example of a pre-performance routine that provides a context in which the quiet eye can be embedded. The five-step strategy encompasses the systematic execution of task-relevant thoughts and behaviors designed to elicit the most effective thoughts and emotions for optimal performance. The five steps include:

1. *Readying*. Establishing a routine that involves optimal positioning of the body, confidence, expectations, and emotions.
2. *Imaging*. The creation of a mental image and the associated feelings of performing at one's best.
3. *Focusing Attention*. Directing thoughts to a relevant external cue or thought.
4. *Executing*. Performing the task with a quiet mind, free from distraction.
5. *Evaluating*. Assessing the quality of task execution, outcome, and the quality of the pre-performance strategy.

Stage 3 of the five-step strategy encourages the athlete to focus attention on an external cue; it is at this point when the golfer should direct his/her gaze at a specific spot on the back of the golf ball. Maintaining this fixation for a period of 1.5–3 s may reduce conscious processing of the stroke itself, permitting optimal execution.

Recent neuroscience research addressing structure–function relationship in cognitive anatomy suggests that multiple neuronal systems may serve similar or even compensatory roles via comparable mechanisms or by implementing different cognitive strategies across individuals (Noppeney et al. 2004, 2006). Future research may provide further insight into the BP–QE relationship by addressing individual differences in neuroanatomy as it pertains to the quiet eye period and performance preparation.

Conclusion

The current investigation is the first to assess temporally based brain mechanisms responsible for skill-based QE differences. Our data support the motor programming/movement preparation function of the QE duration. Replication of these findings is needed to bolster empirical support of the QE period for movement preparation and is necessary to determine whether these findings are generalizable to other self-paced tasks. Although it is reasonable to expect that the QE and BP differences found here would correspond with the very best players (i.e., professional), the magnitude and direction of the QE period and relative cortical changes associated with them remain uncertain. Specifically, a unique contribution of this research was the application of single-subject analyses that have underscored the variability not only between skill levels but equally within skill levels. Future research should continue to investigate the unique subtleties associated with individual differences often neglected in traditional expert-novice paradigms. To reiterate, the QE effects reported here are consistent with a remarkably robust and expanding body of literature that is unequivocally supportive of an extended QE among a wide range of expert athletes. Continued replication and extension of these findings will permit confident advocacy of QE training protocols as explicit strategies for optimal performance.

References

Abernethy B (1996) Training the visual-perceptual skills of athletes: Insights from the study of motor expertise. Am J Sports Med 24(6):S-89–S-92

Bates BT (1996) Single-subject methodology: An alternative approach. Med Sci Sports Exerc 28:631–638

Behan M, Wilson M (2008) State anxiety and visual attention: the role of the quite eye period in aiming to a far target. J Sport Sci 26:207–215

Brunia CHM, Van Boxtel GJM (2000) Motor preparation. In: Cacioppo JT, Tassinary LG, Berntson GG (eds) Handbook of psychophysiology, vol 2. Cambridge University Press, Cambridge, pp 507–532

Causer J, Bennett S, Holmes P, Janelle CM, Williams AM (2010) Quiet eye duration and gun motion in elite shotgun shooting. Med Science Sports Exerc

Chairenza GA, Vasille G, Villa M (1990) Goal or near miss! Movement potential differences between adults and children in skilled performance. Int J Psychophysiol 10(2):105–115

Coombes SA, Corcos DM, Sprute L, Vaillancourt DE (2010) Selective regions of the visuomotor system are related to gain induced changes in force error. J Neurophysiol 103(4): 2114–2123

Craig CM, Delay D, Grealy MA, Lee DN (2000) Guiding the swing in golf putting. Nature 405:295–296

Crews DJ, Landers DM (1993) Electroencephalographic measures of attentional patterns prior to the golf putt. Med Sci Sports Exerc 25:116–126

de Oliveira RF, Oudejans RRD, Beek PJ (2006) Late information pick-up is preferred in basketball jump shooting. J Sports Sci 24:933–940

de Oliveira RF, Oudejans RRD, Beek PJ (2008) Gaze behavior in basketball shooting: Further evidence for online visual control. Res Q Exerc Sport 79:399–404

Deecke L (1987) Bereitschaftspotential as an indicator of movement preparation in supplementary motor area and motor cortex. In: Motor areas of the cerebral cortex. Ciba Foundation Symposium, no.132. Wiley, Chichester, pp 231–250

Di Russo F, Pitzalis S, Aprile T, Spinelli D (2005) Effect of practice on brain activity: an investigation in top-level rifle shooters. Med Sci Sports Exerc 37:1586–1593

Duchowski AT (2002) Eye tracking methodology: theory and practice. Springer, London

Fabiani M, Gratton G, Coles MGH (2000) Event related brain potentials: methods, theory, and applications. In: Cacioppo JT, Tassinary LG, Berntson GG (eds) Handbook of psychophysiology, 2nd edn. Cambridge University Press, Cambridge, pp 53–84

Hancock GH, Butler MS, Fischman MG (1995) On the problem of two-dimensional error scores: measures and analyses of accuracy, bias, and consistency. J Mot Behav 27(3):241–250

Harle SH, Vickers JN (2001) Training quiet eye improves accuracy in the basketball free throw. Sports Psychologist 15:289–305

Hatfield BD, Hillman CH (2001) The psychophysiology of sport: A mechanistic understanding of the psychology of superior performance. In: Singer RN, Hausenblas HA, Janelle CM (eds) Handbook of sport psychology, vol 2. Wiley, New York, pp 362–386

Haufler AJ, Spalding TW, Santa Maria DL, Hatfield BD (2000) Neuro-cognitive activity during a self-paced visuospatial task: comparative EEG profiles in marksmen and novice shooters. Biol Psychol 53:131–160

Huckabee ML, Deecke L, Cannito MP, Gould HJ, Mayr W (2003) Cortical control mechanisms in volitional swallowing: the Bereitschaftspotential. Brain Topogr 16(1):3–16

Jahanshahi M, Hallett M (2003) The Bereitschaftspotential: what does it measure and where does it come from. In: Jahanshahi M, Hallett M (eds) The Bereitschaftspotential: movement related cortical potentials. Kluwer Academic/Plenum Publishers, New York, pp 1–17

Janelle CM, Hillman CH, Apparies RJ, Murray NP, Meili L, Fallon EA, Hatfield BD (2000) Expertise differences in cortical activation and gaze behavior during rifle shooting. J Sport Exerc Psychol 22:167–182

Jasper HH (1958) Report of the committee on methods of clinical examination in electroencephalography. J Electroencephalogr Clin Neurophysiol 10:370–375

Kerick SE, Douglass L, Hatfield BD (2004) Cerebral cortical adaptations associated with visuomotor practice. Med Sci Sport Exerc 36:118–129

Konttinen N, Lyytinen H (1992) Physiology of preparation: Brain slow waves, heart rate, and respiration preceding triggering in rifle shooting. Int J Sport Psychol 23:110–127

Konttinen N, Lyytinen H, Era P (1999) Brain slow potentials and postural sway behavior during sharpshooting performance. J Mot Behav 31:11–20

Kornhuber HH, Deecke L (1965) Hirnpotentialänderungen bei Willkürbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. Pflügers Archiv 284:1–17

Landers DM, Han M, Salazar W, Petruzello SJ, Kubitz KA, Gannon TL (1994) Effects of learning on electroencelephalographic and electrocardiographic patterns in novice archers. Int J Sport Psychol 25:313–330

Mann D, Ward P, Williams AM, Janelle CM (2007) Perceptual-cognitive expertise in sport: A meta-analysis. J Sport Exerc Psychol 29:457–478

Milton J, Solodkin A, Hlusk P, Small S (2007) The mind of expert motor performance is cool and focused. NeuroImage 35:804–813

Noppeney U, Friston KJ, Price CJ (2004) Degenerate neuronal systems sustaining cognitive functions. J Anat 205:433–442

Noppeney U, Penny WD, Price CJ, Flandin G, Friston KJ (2006) Identification of degenerate neuronal systems based on inter-subject variability. NeuroImage 30:885–890

Orgogozo JM, Larsen B (1979) Activation of the supplementary motor area during voluntary movement suggests it works as a supramotor area. Science 206:847–850

Oudejans RRD, van de Langenberg RW, Hutter RI (2002) Aiming at a far target under different viewing conditions: visual control in basketball jump shooting. Hum Mov Sci 21:457–480

Papakostopoulos D (1978) Electrical activity of the brain associated with skilled performance. In: Otto DA (ed) Multi-disciplinary perspectives in event-related brain potentials research. U.S. Environmental Protection Agency, Office of Research and Development, Washington, pp 134–137

Pelz D (2000) Putting bible: the complete guide to mastering the green. Doubleday, New York

Pfurtscheller G, Neuper C (2003) Movement and ERD/ERS. In: Jahanshahi M, Hallett M (eds) The Bereitschaftspotential: movement related cortical potentials. Kluwer Academic/Plenum Publishers, New York, pp 191–205

Pivik RT, Broughton RJ, Coppola R, Davidson RJ, Fox N, Nuwer MR (1993) Guidelines for the recording and quantitative analysis of electroencephalographic activity in research contexts. Psychophysiology 30:547–558

Posner MI, Nissen MJ, Klein RM (1976) Visual dominance: an information processing account of its origins and significance. Psychol Rev 83:157–171

Rektor I (2003) Intracerebral recordings of the bereitschaftspotential. In: Jahanshahi M, Hallett M (eds) The Bereitschaftspotential: movement related cortical potentials. Kluwer Academic/Plenum Publishers, New York, pp 61–77

Rektor I, Feve A, Buser P, Bathien N, Lamarche M (1994) Intracerebral recording of movement related readiness potentials: an exploration in epileptic patents. Electroencephalogr Clin Neurophysiol 107:277–286

Roland PE (1984) Organization of motor control by the human brain. Hum Neurobiol 2:205–216

Roland PE, Larsen B, Lassen NA, Skinhoj E (1980) Supplementary motor area and other cortical areas in organization of voluntary movements in man. J Neurophysiol 43:118–136

Shibasaki H, Barrett G, Halliday E, Halliday AM (1980) Components of the movement-related cortical and their scalp topography. Electroencephalogr Clin Neurophysiol 49:213–226

Singer RN (1988) Strategies and metastrategies in learning and performing self-paced athletic skills. Sport Psychologist 2:49–68

Tanaka S, Honda M, Hanakawa T, Cohen LG (2009) Differential contribution of the supplementary motor area to stabilization of a procedural motor skill acquired through different practice schedules. Cereb Cortex

Taylor M (1978) Bereitschaftspotential during the acquisition of a skilled motor task. Electroencephalogr Clin Neurophysiol 45:568–576

Toni I, Passingham RE (2003) Movement preparation: neuroimaging studies. In: Jahanshahi M, Hallett M (eds) The Bereitschaftspotential: movement related cortical potentials. Kluwer Academic/ Plenum Publishers, New York, pp 269–281

Van Wynsberghe DM, Noback C, Carola R (1995) Human anatomy and physiology, 3rd edn. McGraw-Hill, New York

Vickers JN (1992) Gaze control in putting. Perception 21:117–132

Vickers JN (1996a) Visual control while aiming at a far target. J Exp Psychol Hum Percept Perform 22:342–354

Vickers JN (1996b) Control of visual attention during the basketball free throw. Am J Sports Med 24(6):S93–S96

Vickers JN (2004) The quiet-eye. It's the difference between a good putter and a poor one. Here's proof. Golf Digest 1:96–101

Vickers JN (2007) Perception, cognition, and decision training: the quiet eye in action. Human Kinetics, Champaign

Vickers JN, Adolphe RM (1997) Gaze behavior during a ball tracking and aiming skill. Int J Sports Vis 4(1):18–27

Vickers J, Williams AM, Rodrigues ST, Hillis F, Coyne G (1999) Eye movements of elite biathlon shooters during rested and fatigued states (abstract). J Exerc Sport Psychol 21:116

Vine SJ, Moore LJ, Wilson MR (2011) Quiet eye training facilitates competitive putting performance in elite golfers. Frontiers Psychol 2(8):1–9

Williams AM, Davids K, Williams JG (1999) Visual perception and action in sport. E & FN Spon, London