

1 **Commit to your putting stroke: exploring the impact of Quiet Eye**
2 **duration and neural activity on golf putting performance.**

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35 **Abstract**

36 Introduction: There is a growing interest in characterizing the cognitive-motor processes that underlie
37 superior performance in highly skilled athletes. The aim of this study was to explore neural markers
38 of putting performance in highly skilled golfers by recording mobile EEG (electroencephalogram)
39 during the pre-shot period.

40 Methods: Twenty-eight right-handed participants (20 males) with a mean age of 24.2 years (± 6.4)
41 and an average handicap of $+1.7 (\pm 6.4)$ completed a testing session. Following the warm-up,
42 participants completed 140 putts from a distance of 8ft (2.4m), with putts taken from 5 different
43 positions. While putting, participants wore an eye tracker and a gel-based EEG system with 32
44 electrodes. Time and frequency domain features of the EEG signals were extracted to characterize
45 Movement-Related Cortical Potentials (MRCP) and rhythmic modulations of neural activity in theta,
46 alpha, sensorimotor and beta frequency bands associated with putting performance.

47 Results: Eye-tracking data demonstrate that mean Quiet Eye durations are not a reliable marker of
48 expertise as the same duration was found for both successful and unsuccessful putts. Following rigorous
49 data processing data from 12 participants (8 males, mean age 21.6 years ± 5.4 , average handicap $+1.5$
50 ± 4.4) were included in the EEG analysis. MRCP analysis revealed performance-based differences,
51 with unsuccessful putts having a greater negative amplitude in comparison to successful putts. Time
52 frequency analysis of the EEG data revealed that successful putts exhibit distinct neural activity
53 profiles compared to unsuccessful ones.

54 Discussion: For successful putts, greater suppression of beta was present in the central region prior to
55 the putt. By contrast, increased frontal theta power was present for unsuccessful putts immediately
56 before the putt (consistent with hesitation and the need for motor plan adjustments prior to
57 execution). We propose that neural activity may provide plausible insights into the mechanisms
58 behind why identical QE durations can lead to both success and failure. From an applied perspective,
59 this study highlights the merits of a multi-measure approach to gain further insights into performance
60 differences within highly skilled golfers. We discuss considerations for future research and solutions
61 to address the challenges related to the complexities of collecting clean EEG signals within
62 naturalistic sporting contexts.

63 **1 Introduction**

64 Putting constitutes a fundamental aspect of the sport of golf, wherein a putter is required to strike the
65 ball into the hole when it lies on (or just short of) the green. From a practical standpoint, proficient
66 putting is paramount, due to its significant impact on overall performance and subsequent success
67 (Baugher et al., 2016). From a scientific perspective, the nature of golf putting offers an ideal
68 platform for investigating the cognitive processes underlying skilled performance. The process of
69 putting involves a routine that makes it amenable to study; preceding the initiation of the putting
70 action and the commencement of the backswing, there exists a phase of motor preparation during
71 which the golfer assumes a static posture with the putter head positioned just behind the ball (referred
72 to as the "address" in golf terminology). Investigating the processing that occurs during this pre-shot
73 period, leading up to the putt, should furnish insights into the underlying cognitive and neural
74 mechanisms governing action preparation (Gallicchio et al., 2017).

75 Over recent years, researchers investigating the putting motor preparation period have predominantly
76 focused on investigating eye movements stillness, or Quiet Eye (QE), a metric derived from eye-
77 tracking recordings. QE is defined as the final fixation or tracking gaze on a specific location that has

78 an onset prior to the start of a final, critical movement (Vickers, 2007). When applied to golf putting,
79 research has recommended maintaining a steady vision on the back of the ball (Vickers, 1996).
80 Optimal QE duration is thought to involve the player keeping their eyes fixated on the ball for 2000–
81 3000 ms before starting the backswing and throughout the stroke. After making contact, the player
82 sustains this focus on the spot where the ball was for an additional 200 milliseconds, known as QE
83 dwell time. Crucially, researchers have claimed that QE duration can differentiate between successful
84 and less successful performances, even among experts (Wilson et al., 2016), however, these results
85 are not unequivocal as Mann et al.'s (2011) found QE durations between successful and unsuccessful
86 putts did not vary for both low and high handicap groups. Additionally, van Lier et al. (2010)
87 discovered that optimal QE duration (defined to have ended when initiating the backswing) was not
88 associated with performance. Similarly, when practitioners have tried to apply these findings, with
89 elite golfers, the findings have been mixed (Farrow & Panchuk, 2016). In particular, it has proved
90 difficult to explain why, across multiple putts, the same QE duration can lead to both success and
91 failure (Farrow & Panchuk, 2016). Consequently, in an effort to gain greater insight into the
92 processes supporting successful putting, the current study investigates performance using a multi-
93 methods approach that combines eye tracking with a measure of neural activity derived from scalp
94 recorded EEG.

95 Investigating neural activity within the pre-motor preparation phase has already shown some promise
96 as a method for discriminating between successful and unsuccessful performance. Currently, the
97 brain waves mainly explored in golf putting in the frequency domain are the theta band (4 - 7 Hz),
98 the alpha band (8 - 12 Hz), the beta band (12 - 30 Hz), and the sensorimotor rhythm (SMR: 12 - 15
99 Hz). Superior golf putting performance has been linked to changes in relative theta power (Chen et
100 al., 2022; Kao et al., 2013; Reinecke et al., 2011). For instance, Kao et al. (2013, 2014) discovered
101 that midline theta power (i.e., FZ, CZ, PZ, OZ sites) was significantly lower for the best fifteen putts
102 compared to the worst fifteen putts **in a sample of professional and amateur golfers (handicap not**
103 **stated, $n = 12$)**. Reinecke et al. (2011) observed that superior performance was associated with an
104 increase in theta power over the left frontal scalp (electrode F3, however, only used F3, Fz, F4 in
105 their analysis) **with golfers who had an average of 7.9 ± 6.4 handicap (considered immediate skilled,**
106 **$n = 20$)**. Critically, **as well as the differences in skill level**, the definition of superior performance may
107 have differed across the studies: the Kao et al. studies used holed putts, whereas, Reinecke et al.
108 (2011) did not state a direct performance measure. Also, the timings of the epoch varied across these
109 studies: Reinecke et al. (2011) used an average across the putting period (2 minutes), whereas Kao et
110 al. used -3 seconds prior to initiation of the movement.

111 There are also mixed findings in studies employing neurofeedback training to encourage superior
112 performance, revealing both a decrease in frontal midline theta (Fm θ) power **in three highly skilled**
113 **(handicap = 0) golfers** (Kao et al., 2014) and a significant reduction in theta power (Chen et al.,
114 2022). In contrast, superior performance without neurofeedback training was associated with a
115 notable increase in theta power (Chen et al., 2022). **Although Chen et al. (2022) did try and match the**
116 **skill level across the group, the variation in skill level (reflected in the high standard error) within**
117 **each group must be considered when interpreting the findings. For example, the function specific**
118 **group ($n = 12$, mean handicap = 12.00 ± 11.02) exhibited much greater variation than either the**
119 **tradition instruction group ($n = 12$, mean handicap = 14.00 ± 7.38) or the sham control group ($n = 12$,**
120 **mean handicap = 18.00 ± 8.86).** Nonetheless, taken together, the existing findings provide evidence
121 that successful putting performance is associated with changes in theta power, specifically over
122 frontal recording electrodes.

123 Following previous findings, the current study aims to gain clarity on the direction of the theta effect,
124 and specific timings of the modulations throughout the pre-preparation period related to performance,
125 **when considering a sample of highly skilled golfers**. Furthermore, through using the multi-measure
126 approach we would like to gain insight into underlying cognitive and neural mechanisms governing
127 action preparation (Gallicchio et al., 2017). For example, in golf putting, lower $Fm\theta$ levels may
128 suggest reduced mental engagement, according to Kao et al. (2013, 2014) **in professional and highly**
129 **skilled golfers**. A reduction in mental engagement seems in contrast to the response programming
130 explanation (Williams et al., 2002) which is the dominant proposal as to how and why QE duration
131 works (Walters-Symons et al., 2017). Aligned with the response programme explanation, a longer
132 QE enhances performance due to a longer period for cognitive programming (Vickers, 1996; Vickers,
133 2007; Williams et al., 2002). To help gain insight into the timings and potential link to QE durations,
134 our study aims to explore fluctuations in theta power throughout the pre-putt preparation period using
135 both the whole length of the pre-putt preparation period (-3 s) and at 500 ms time intervals.

136 Modulations in the alpha band have also been found to be associated with improved golf putting
137 performance **in a mixed sample of expert and novice golfers** (Cooke et al., 2014). As with theta,
138 however, there remains uncertainty regarding the direction of the alpha effect. For example, studies
139 have reported both an increase (Baumeister et al., 2008) and a decrease (Babiloni et al., 2008; Cooke
140 et al., 2014) in alpha power over frontocentral recording sites for successful compared to
141 unsuccessful putts. **It must be acknowledged that differences in skill level may be contributing to the**
142 **ambiguity in the findings as the expert group in Baumeister et. (2008) had large variations in skill**
143 **level (average handicap = 8.3 ± 7.5). It could be argued the sample was more homogeneous in**
144 **Babiloni et al., (2008) and Cooke et al., (2014), studies as participants in Babiloni et al. (2008)**
145 **regularly competed in national and international competitions and practiced at least five times a week**
146 **(no formal handicap was stated) and in Cooke et al. (2014), participants had a golf handicap < 5**
147 **(average handicap = 1.50 ± 2.32).** Discrepancies in findings may arise from variations in task design
148 (e.g., examination of expert vs. novice /expert golfers), the specifics of the analysis (including epoch
149 duration and electrode selection), and the specific analytical methods employed. It is important to
150 note that in Cooke et al. (2014) and Cooke et al. (2015), the size of the hole was adjusted, and was
151 reduced to half its original size for expert participants, whereas a standard hole size was used in
152 Babiloni et al. (2008) and Baumeister et al. (2008). Another significant observation is that alpha
153 modulation may change throughout the pre-shot period. For instance, Cooke et al. (2014) identified a
154 two-phase pattern of alpha oscillations among expert golfers, characterized by an initial increase
155 followed by a sudden decrease in alpha power in the last second before movement initiation. Our
156 study, therefore, aims to explore fluctuations in alpha power throughout the pre-putt preparation
157 period, examining the whole length of the pre-putt preparation period (-3 s) in 500 ms time intervals.

158 Successful performance has also been associated with a greater reduction in beta power in the last
159 seconds preceding golf putts (Cooke et al., 2014). While these findings are from a single study (and
160 one that only analyzed limited electrode sites F3, Fz, F4, C3, Cz, C4) they align with broader
161 evidence suggesting a decrease in beta power relative to baseline in sensorimotor tasks, particularly
162 in tasks requiring accuracy (Kilavik et al., 2013). It has been suggested that this reduction in beta
163 power may reflect the activation of sensorimotor networks (Pfurtscheller & da Silva, 1999),
164 indicating beta involvement in the planning, processing, and execution of actions, including their
165 sensory and cognitive aspects (Pfurtscheller et al., 2003). Consequently, and following the findings
166 of Cooke et al., in the present study we will examine changes in beta power throughout the pre-putt
167 preparation period, but with a larger array of electrodes (31 channels) across the scalp.

168 To the best of the authors' knowledge, the only studies examining sensorimotor rhythm (SMR) have
169 been neurofeedback studies, including those by Cheng et al. (2015), who recruited sixteen elite
170 golfers (average handicap = 0 ± 3.90), and Wu et al. (2023), who recruited forty four professional
171 golfers. In both studies, SMR neurofeedback training was found to enhance performance, with
172 participants who received the training exhibiting greater SMR power (at Cz for Cheng et al., 2015,
173 and Cz & CPz for Wu et al., 2023) compared to the control group. Here it is notable that the samples
174 examined are homogeneous across the two studies, which aids comparison and may have contributed
175 to the consistency in findings. These results are encouraging, especially given there are differences in
176 the methodologies employed between the two studies. Nonetheless, in Cheng et al. (2015) it remains
177 uncertain whether putt distances might have influenced the outcomes, as they were individualized
178 and not reported. This lack of standardization means that distances could have differed between the
179 control and intervention groups. Additionally, performance in Cheng et al. (2015) was measured
180 using error distance, rather than counting holed putts. In contrast, Wu et al. (2024) standardized the
181 distance across all trials. Furthermore, they (Wu et al., 2024) assessed performance by asking
182 participants to putt towards a hole and record the percentage of successful putts, which is more
183 representative of competitive golfing scenarios. At this stage, further study is required to gain greater
184 insight into SMR and performance.

185 Another form of electroencephalography (EEG) analysis that sheds light on the processes involved in
186 planning and preparing voluntary motor movement is the Movement-Related Cortical Potentials
187 (MRCP) (Shibasaki & Hallett, 2006). The change in amplitude of MRCPs over time is typically
188 regarded as an index of motor preparation (Wright et al., 2012). The readiness potential (RP) is a
189 marker of particular interest to study. The RP is an event-related potential that consists of a negative
190 deflection in EEG that begins around 2 seconds before self-initiated movements (Shibasaki & Hallett,
191 2006). Two studies (Mann et al., 2011; Xu et al., 2021) have analyzed neural activity in golf putting
192 using MRCP and RP relative to performance. The results have been inconsistent across the two
193 studies, however, critically there were skill level differences within the participants recruited. Mann
194 et al. (2011) included both experts ($n = 10$, average handicap = 1.20 ± 1.23) and near-experts ($n =$
195 10 , average handicap = 11.30 ± 0.82), whereas Xu et al. (2021) examined twenty-one novice
196 golfers. Mann et al. (2011) did not find any significant differences in MRCP amplitudes between
197 successful and unsuccessful putts (analyzing C3, Cz, C4, P3, and P4 separately). By contrast, Xu et
198 al. (2021) did report performance-based differences, with greater increased negativity for successful
199 in comparison to unsuccessful putts; however, clear RP (Cz) were not evident in their figures
200 presented. In addition, both of these studies used electrooculogram (EOG) data to measure gaze
201 behavior (rather than an eye tracker). There were, however, substantial differences in the putting
202 paradigm employed across these studies. In Mann et al. (2011) the golfers putted to a standardized
203 hole from 12ft, whereas in Xu et al. (2021) golfers putted the ball into a modified hole from 2m. In
204 this case the center of the hole had a radius of 5 cm rather than the standard 10.4 cm. Outside the
205 hole, however, there were three imposed concentric circles with radii of 10, 15, and 20 cm. A “hit”
206 was recorded if the golf ball went into the hole or circle and a “miss” was recorded if the golf ball
207 went outside the outermost circle to balance the ratio of the two conditions. At this stage, given the
208 methodological inconsistencies and the variation of skill level further research with a homogenous
209 sample of expert golfers is merited before conclusions can be drawn.

210 Our study aims to assess whether QE duration and neural activity can be used as reliable markers
211 associated with successful putting in highly skilled golfers. This study therefore addresses two
212 specific hypotheses: i) there will be a difference in QE duration as a function of performance, and ii)
213 successful performances will be distinguishable from unsuccessful performance based on neural
214 activity. Given our interest in highly skilled golfers, our theoretical starting point for the expertise-

215 based differences in neural activity was informed by the neural efficiency framework (Del Percio et
216 al., 2009) and previous research. We therefore predicted that successful performance would be
217 associated with greater suppression of frontal theta, an increase in alpha power (high band 10-13 Hz),
218 greater suppression of beta (Cooke et al., 2014) and an increase in SMR power. In addition, for the
219 RP, we predicted that performance related differences would be observed, with less negativity for
220 successful putts in comparison to unsuccessful putts.

221 **2 Methods and Materials**

222 **2.1 Participants**

223 Twenty-eight participants (20 males, 8 females), all of whom were right-handed, with normal or
224 corrected vision, were included in the study. The mean age of the participants was 24.2 years (\pm 6.4),
225 and the average handicap was +1.7 (\pm 6.4). On average, participants had been playing golf for 12.8
226 years (\pm 5.69), practiced for 15.5 hours per week (\pm 11.5), made 31.3 putts per round (\pm 2.84), achieved
227 greens in regulation 56.2% of the time (\pm 10.1), and scored an average of 85% (\pm 21.1) from 6 feet
228 straight. For the sample of 12 participants (4 females, mean age 21.6 years \pm 5.4, average handicap
229 +1.5 \pm 4.4) participants had been playing golf for an average of 12.2 years (\pm 6.54), practiced for 16
230 hours per week (\pm 12.5), made 31.1 putts per round (\pm 3.10), achieved greens in regulation 57% of the
231 time (\pm 10.6), and scored an average of 88% (\pm 21.6) from 6 feet straight.

232 **2.2 Protocol**

233 Participants attended testing sessions individually. They were fitted with a mobile eye tracker (ASL
234 XG Mobile Eye Tracker) and EEG system comprising 32 Ag/AgCl electrodes fitted in an elastic cap
235 according to the 10-20 International montage and connected to a portable amplifier (ANT-neuro,
236 Enschede, The Netherlands). Calibration of the eye tracker was performed using five colored markers
237 positioned near the participant's feet while standing in a putting posture and addressing a golf ball.
238 During calibration, participants were instructed to adopt a normal putting stance and maintain their
239 gaze steady on the center of each marker, in a pre-designated order, for a duration of 100-200 ms.
240 Participants used their own putter and Srixon AD333 Tour golf balls throughout the eye tracker
241 calibration and the putting task. At the beginning of the putting task, participants completed a
242 standardized warm-up protocol consisting of 12 practice putts, including 6 straight and 6 sloped
243 putts, on an indoor artificial surface with a stimp meter rating of 10.2. Following the warm-up,
244 participants completed a putting task (see Figure 1) involving 140 straight putts taken from a distance
245 of 8 feet (2.4m) from 5 different putt positions (5 cm apart). The putts were taken in blocks of 10 and
246 randomization was applied within each of the seven blocks, with the constraint that they putted twice
247 from each location in each block of ten putts. Each participant had a different order. The putt position
248 was marked on the surface with a UV light so there were no obvious markings on the putt surface to
249 slow down the learning of the positions. Re-calibration of the eye tracker occurred at the start of each
250 putting block and whenever necessary (e.g., after a pupil recognition loss >100ms or if the calibration
251 had been lost).

252 **2.3 Measures**

253 **2.3.1 Task Performance**

254 Performance was assessed by the number of successful (holed) putts. Professional golfers, on
255 average, have a probability rate of 50% success from 8ft (Professional Golfers' Association Tour,
256 2024).

257 2.3.2 Quiet Eye Measures

258 Visual search behaviors were examined using EyeVision software (ASL Results Pro Analysis,
259 formerly Argus, ASL) installed on a laptop (Dell Inspiron6400) captured at a frame rate of 30 Hz. All
260 analyses were conducted post-testing. The onset of Quiet Eye (QE) had to occur before movement
261 initiation of the backswing but could continue through the putting movement (Causer et al., 2017).
262 QE offset was determined when gaze deviated from the target (ball or fixation marker) by more than
263 3° of visual angle for longer than 100 ms (Vickers, 2007).

264 2.3.3 EEG Features

265 EEG data were recorded with a sampling rate of 500 Hz, a 0.016– 250 Hz bandpass filter, and a notch
266 filter set at 50 Hz. The electrode AFz served as the ground and CPz as a common reference site.
267 Electrode impedance was measured prior to each recording session and set below 10 kΩ using
268 electrode gel. Similarly, impedances were checked throughout the session to maintain <10 kΩ. To
269 timestamp the event of contact between the ball and putter, an acoustic box was connected to the
270 EEG amplifier and a trigger code was sent via an acoustic box designed to capture the sound when
271 the putter made contact with the ball. Although capturing the point of contact, does mean movement
272 will be included within the epoch, to be able to analyze QE duration and neural activity,
273 timestamping the initial of the movement is not sufficient as it is important to capture the QE period
274 occurring before movement initiation, and after movement initiation (Walters-Symons et al. 2017).
275 The raw EEG data was first visually inspected, and portions of data outside of the putt periods and
276 characterized by noise spread across all electrodes (due to transient changes in electrode impedance
277 related to participants movements) were discarded. The electrodes (with the exception of prefrontal
278 sensors FP1, FPz, and FP2) displaying abnormal power spectral activity (+/- 3 SD from mean signal
279 recorded across included electrodes) were spherically interpolated using neighboring sensors signals.
280 On average, 3.6 (SD = 1) electrodes were interpolated across participants. A 1Hz to 30 Hz bandpass
281 filter was applied (filter order: 1600, -6 dB, cut-off frequencies: 0.5 and 30.5 Hz) to the EEG signals.
282 The data was re-referenced to the averaged electrodes. The filtered data then underwent a two step
283 cleaning process aimed at parsing signals **of artifactual sources (non-brain) from actual neural**
284 **activity**. In a first step, the filtered data was segmented into consecutive, non-overlapping one second
285 segments. The signals of segments that were above or below three standard deviations from the
286 overall mean of all segments were discarded. An extended infomax Independent Component
287 Analysis (ICA; (Makeig et al., 1996) was performed on the remaining data, with parameters
288 adjustments to consider the rank deficiency of the data following average re-referencing and channel
289 interpolation. The resulting Independent Components (ICs) were classified into categories using the
290 IClab (Pion-Tonachini et al., 2019). As a second step, the weights of the ICA decomposition were
291 back projected to the filtered data (prior to rejecting one second segments). The ICs flagged as
292 originating from muscles, eyes, line noise, and other non-brain sources by IClab with a probability
293 threshold above 70% were discarded. This resulted in the rejection of an average of 12 ICs (SD = 3).
294 The proportion of remaining IC components after parsing non brain sources is in line with the
295 guidelines proposed by Klug and Gramann (2020; 2021). This approach allows to apply in the first
296 step a more thorough but restrictive preprocessing to ensure the quality of the ICA decomposition
297 and then apply a less constraining data processing approach. **Following these processing steps, 3.5**
298 **second epochs were extracted (3 seconds pre contact and 500ms post contact).**

299 2.4 Data Analysis

300 In all analyses statistical significance threshold was set at $\alpha = .05$. To establish if there was a
301 performance difference in QE, a paired t-test was conducted comparing mean QE duration for
302 successful and unsuccessful putts.

303 An extraction of event-related spectral perturbation (ERSP; (Makeig, 1993) features was performed
304 through a time–frequency decomposition of the epoched data through the convolution of complex
305 Morlet wavelets. The number of wavelet cycles ranged from 3 to 30 following a 0.8-step increase to
306 estimate frequencies ranging from 3 to 30 Hz in 54 linearly spaced frequency steps. The spectral
307 power at each frequency was baseline-corrected using a decibel (dB) transform relative to a baseline
308 period of 500ms (-3 to -2.5 seconds) prior to the period of interest (-2.5 seconds to 0ms) performed
309 on a single-trial basis (Grandchamp & Delorme, 2011). For ERSP analysis, the *a priori* frequency
310 bands were selected based on the wider cognitive neuroscience and sporting literature, as follows:
311 Theta (4-7 Hz), Alpha (8-12 Hz), Alpha Low (8-10 Hz), Alpha High (11-13 Hz), SMR (12-15 Hz)
312 and Beta (12-30 Hz). The changes in overall power over the investigated frequency bands were then
313 extracted for 5 consecutive time bins of 500 ms between the baseline period and the putt onset. In
314 accordance with Del Percio et al. (2009) who adopted a neural efficiency framework approach, a
315 series of Repeated Measures (2 x 5) ANOVAs with factors of Performance
316 (Successful/Unsuccessful), Time (-2500 to -2000ms, -2000 to -1500ms, 1500 to -1000ms, -1000 to -
317 500ms, -500ms to 0ms) were separately carried out at each electrode cluster (Frontal: F3, Fz,
318 F4/Central: C3, Cz, C4/Parietal: P3, Pz, P4), for each frequency band (theta, alpha (including
319 low/high), SMR and beta).

320 For the Readiness Potential analysis, the continuous data sets were epoched around the onset of
321 experimental events (-4000 msec to 1000 msec around putt onset). Consistent with the ERSP
322 analysis, the epoched data were then baseline corrected by subtracting the mean voltage recorded
323 within the 500-msec baseline period (-3 to -2.5 seconds) from the signal for each electrode and each
324 trial. Averaging across epochs resulted in the obtention of ERP waveforms for each individual
325 electrode. These waveforms were then average across frontal, central and parietal clusters of
326 electrodes. For each cluster, the readiness potential amplitude was computed as the mean voltage (in
327 microVolts) of the ERP waveforms recorded within two successive 500 msec-long *a priori* time
328 windows ranging from -1000 to 0 msec prior to putting onset. Finally, statistical analyses were
329 carried out on the extracted readiness potential features using a Repeated Measures (2 x 2) ANOVA
330 with factors of Performance (Successful/Unsuccessful), Time (-1000 to -500ms, -500ms to 0ms) was
331 separately carried out at each electrode cluster (frontal/central/parietal). All statistical testing was
332 implemented in JASP version 0.6.13.

333 3 Results

334 3.1 Performance

335 Performance was 69.71% (SD = 6.71%) for the sample of twenty-eight participants. Performance for
336 the sample of 12 participants included in the EEG sample, was 69.61% (SD = 7.37).

337 3.2 QE duration and Performance

338 The mean QE duration for successful putts was 0.86 seconds ($SD = 0.357$ s) and 0.89 seconds ($SD =$
339 0.486 s) for unsuccessful putts for the sample of twenty-eight participants (Figure 2). There was no
340 difference in mean QE duration [$t_{(21)} = -0.670$, $p = 0.510$, $d = -0.143$]. For the sample of 12
341 participants included in the EEG sample, average QE duration for successful putts ($M = 0.71$, $SD =$

342 0.18) and for unsuccessful putts ($M = 0.68$, $SD = 0.14$). There was no difference in mean QE duration
343 [$t_{(21)} = 0.454$, $p = 0.653$, $d = 0.140$].

344 3.3 Neural Activity and Performance

345 After the cleaning and processing stages, only 12 participants were retained with an average of 58
346 ($SD = 8.91$) successful trials and 25 ($SD = 6.12$) unsuccessful trials. The 500ms post putt was
347 removed from the analysis due to noise. The time frequency analysis, revealed a performance*time
348 interaction [$F(4, 44) = 3.125$, $p = 0.024$, $n^2 = 0.041$] for theta (Figure 3) in the frontal cluster (F3, Fz,
349 F4). **As seen in Figure 3, in the last three time windows (-1500ms to 0ms) unsuccessful putts**
350 **exhibited an increase of theta power in comparison to the theta power for the successful putts.** None
351 of the post hoc tests were significant within this RM-ANOVA, although the final time window (-
352 500ms to 0ms/contact) was close (i.e., $p = 0.07$). The RM-ANOVA for theta at the central cluster
353 (C3, Cz, C4) did not reveal a significant difference in performance or a performance* time
354 interaction. The RM-ANOVA for theta at the parietal cluster (P3, Pz, P4) did not reveal a significant
355 difference in performance or a performance* time interaction.

356 **The RM-ANOVA comparing alpha (8-12 Hz) in frontal/central/parietal clusters, did not reveal any**
357 **significant differences or interactions (Figure 3, 4). Additional analysis using low (8-10 Hz) and high**
358 **(11-13 Hz) bands of alpha was also conducted for each of the frontal/central/parietal clusters. The**
359 **analysis did not reveal any significant differences or performance* time interactions however, the**
360 **main effect for performance for low alpha in the frontal cluster (F3, Fz, F4) was close (i.e., $p = 0.06$).**
361 The RM-ANOVA comparing the SMR in central/parietal clusters also revealed no significant
362 differences or interactions. Regarding beta (central cluster), there was a main effect for performance
363 [$F(1,11) = 6.516$, $p = 0.027$, $n^2 = 0.093$], with a greater suppression (mean difference of $-0.484 \pm$
364 0.190 dB) for successful putts in comparison to unsuccessful putts (Figure 4). There was no
365 performance*time interaction. The RM-ANOVA revealed no significant differences in beta power at
366 parietal sites (cluster P3, Pz, P4) or frontal (cluster F3, Fz, F4).

367 Time analysis revealed a clear readiness potentials in both conditions at the frontal cluster with
368 differences for successful shots in comparison to unsuccessful shots (mean difference = $1.706 \pm$
369 0.679 dB), as the RM-ANOVA revealed a main effect for performance [$F(1, 11) = 6.304$, $p = 0.029$,
370 $n^2 = 0.248$] with unsuccessful putts having a greater negative amplitude in comparison successful
371 ones (Figure 5). The RM-ANOVAs for central and parietal clusters did not reveal any significant
372 effects or interactions.

373 4 Discussion

374 The current study aimed to address specific hypotheses, proposing that successful performances
375 could be distinguishable from unsuccessful performance based on QE duration and neural activity.
376 We found there was no difference in mean QE duration based on performance (holed putts vs missed
377 putts). The mean durations of quiet eye (QE) phases alone may not reliably indicate expertise.
378 Critically Mann et al. (2011) and van Lier et al. (2010) also did not find QE duration differed based
379 on expertise. It is worth noting the QE durations were lower than the optimal QE duration 2-3
380 seconds recommended for putting (Vickers, 2007), highlighting the potential need for a training
381 intervention to achieve optimal QE duration. Consistent with our findings, van Lier et al. (2010)
382 found without training, golfers had QE duration less than the recommended duration. By integrating
383 eye tracking with EEG data, a deeper understanding can be gained regarding why identical QE
384 durations can result in either successful or unsuccessful putts and shed light on the timings of optimal
385 QE and the merits of teaching a QE intervention by examining the three seconds prior to contact. For

386 instance, our findings reveal that successful putts exhibit distinct neural activity profiles compared to
387 unsuccessful putts. Successful putts revealed a greater suppression compared to unsuccessful putts.
388 The greater suppression in successful putts may signify activation of sensorimotor networks,
389 indicating enhanced movement planning.

390 Additionally, performance differences in theta frequency were noted, with successful putts displaying
391 a tendency for lower theta power, particularly in the final time window, compared to unsuccessful
392 putts in the frontal region. Increased theta power for unsuccessful putts may indicate hesitation or the
393 need for an adjustment to the motor plan prior to execution, resulting in inefficiency and extra
394 cognitive demands, **in line with the neural efficiency framework (Del Percio et al., 2009). These**
395 **findings are also consistent with the findings of a meta-analysis by Filho et al. (2021) examining self-**
396 **paced sports that provided support for the neural efficiency framework, specifically a decrease in**
397 **theta was linked to optimal performance. From an applied perspective,** our findings shed light on the
398 timings and nuances to the process of putting outlined by Mann et al. (2011), when putting, players
399 must maintain the intended putt line in working memory while focusing on the ball. They must then
400 activate a motor program to accurately strike the ball with the necessary force and direction for the
401 desired outcome (Mann et al., 2011). If there is a disruption in **motor planning or lack of commitment**
402 **to the first intended motor plan, then this will disrupt the performance. Here, we found greater**
403 **suppression of beta activity in the central region during successful performance. In support of our**
404 **findings, Tzagarakis et al. (2010) found the power decrease for beta during motor preparation was**
405 **scaled relative to uncertainty, with the greatest reduction of power associated with certainty.**
406 **Combined with the aforementioned theta findings above, this offers further support that unsuccessful**
407 **putts are associated with uncertainty and hesitation, as the suppression (reduction in power) for**
408 **unsuccessful putts was less than successful putts. The greater suppression for successful putts is**
409 **considered an index of cortical activation (Kilavik et al., 2013; Tzagarakis et al., 2010). While it may**
410 **not indicate more efficient activation on a neural level, we propose that greater beta suppression leads**
411 **to enhanced preparation, which could be considered a form of increased efficiency. Additionally, we**
412 **speculate that** beta suppression may offer insight into the mechanisms underpinning QE duration,
413 especially as the beta suppression onset timings for successful putts are consistent with recommended
414 QE duration of 2-3 seconds (Vine et al. 2011). Furthermore, the monitoring aspects of theta may also
415 offer insight towards the mechanism underpinning the proposed role of QE duration in continuous
416 monitoring and online control (Gonzalez et al., 2015). Taking the findings together, we propose that
417 neural activity may provide plausible insights into the mechanisms behind QE and how and why
418 identical QE durations may lead to both successful and unsuccessful putts. Our findings offer
419 working hypotheses and tentative explanations towards clarifying ambiguities regarding the efficacy
420 of QE recommendations. Moving forwards, further research is required to support these claims.

421 Unexpectedly, our study did not find any performance-based difference in alpha power. These
422 findings contrast with other studies where performance-based differences in alpha power were
423 reported (Babiloni et al., 2008; Baumeister et al., 2008; Cooke et al., 2014) and **do not align with the**
424 **neural efficiency framework.** Our research contributes to the ongoing discourse on the
425 inconsistencies observed in alpha studies related to golf putting (Park et al., 2015). We advocate for
426 further investigation into alpha power and performance during the pre-preparatory phase. **Consistent**
427 **with Pfurtscheller (2003) we found the low and high alpha bands, (in our case low alpha) were more**
428 **sensitive to performance differences so we recommend future research continues to adopt this**
429 **approach.** To facilitate comparison across studies, we recommend adopting standardized
430 methodologies, including consistent epochs, task design, and data analysis approaches.

431 Our findings revealed that it is possible to observe performance-based differences, reflected on the
432 amplitude of the readiness potential with successful putts having a less negative amplitude in
433 comparison to unsuccessful putts, in line with the neural efficiency framework (Del Percio et al.,
434 2009). This finding offers support for the proposal that successful putts are associated with reduced
435 response programming demands (Wright et al., 2011) requiring less energy (Di Russo et al., 2005).
436 These findings may seem contradictory to the beta findings presented above, but recent research has
437 suggested that beta and RP could reflect different phenomena within the movement preparation
438 processes (Gavenas et al., 2023; Parés-Pujolràs et al., 2023). We recommend that future research
439 explores how beta desynchronization in the motor cortex relates to the RP.

440 4.1 Limitations and Future Research

441 We propose the EEG findings are not trivial, as both the definition of experimental event in such a
442 naturalistic context and the processing of neural data acquired while whole body motion was
443 unrestricted posed substantial challenges. To address these challenges and to maintain good signal to
444 noise data, we used a rigorous process for cleaning the EEG data and this did result in a high loss of
445 data. Our study is not without limitations, especially as it is a single study with 12 participants and
446 we would recommend further research with more participants, especially when using repeated
447 measures ANOVAs. We used an acoustic trigger to timestamp the moment the club made contact
448 with the ball, so the movement had to occur during the epoch. Unfortunately meaning we could not
449 accurately detect the initiation of the backswing. We suggest modifying the EEG data time stamping
450 method to precisely capture both the contact point and initiation of movement, crucial for
451 investigating readiness potentials, potentially utilizing lightweight accelerometers on equipment like
452 clubs, if feasible without affecting stroke kinematics. Additionally, we recommend future research
453 utilizes recent technology advancements that allow for the collection of synchronized eye tracking
454 and EEG data acquisition and time stamp the EEG data through fixations (Ladouce et al., 2022). This
455 approach would allow for the working hypotheses of the mechanisms underpinning QE to be
456 explored in detail as a direct analysis of QE duration and EEG can be undertaken. For more detail on
457 this approach and the potential of synchronized eye tracking and EEG data and the feasibility,
458 including outlining current challenges with this approach, are discussed in Ladouce et al. (2017). We
459 would also encourage future researchers to consider participant recruitment, design and trial numbers
460 for a good signal-to-noise ratio. Recruiting a highly skilled sample has clarified some of the
461 ambiguities in prior research regarding the directionality of power and we believe future research
462 with an increased sample size would continue to strengthen the research in this area. Despite the
463 challenges, we believe this study paves the way for further investigation of the neural correlates of
464 sporting performance by showcasing methods to effectively capture neural dynamics of action
465 planning in applied sporting contexts.

466 4.2 Practical Implications

467 This study unveils the challenges encountered during EEG data collection in a practical scenario and
468 proposes solutions to overcome these hurdles. While highlighting the benefits of this approach, it
469 stresses the importance of methodological rigor, especially in EEG data analysis. Golf putting may
470 serve as an applied context to delve deeper into the relationship between beta and MRCPs,
471 specifically readiness potentials, to offer fruitful theoretical insights. Furthermore, the findings
472 demonstrate tentative evidence to guide the efforts to unveil the mechanisms behind QE and clarify
473 its effectiveness (Williams, 2016). We acknowledge that our findings stem from a single study,
474 underscoring the need for future longitudinal studies with consistent methodological approaches to
475 establish a more robust understanding of the relationship between neural activity and expertise. We

476 understand the complexity involved in such research endeavors, both in terms of time investment and
477 methodological intricacies. Nevertheless, we encourage researchers to embrace the multifaceted
478 nature of the sporting domain (Bishop, 2008) when investigating markers of cognitive-motor
479 expertise in golf putting and strive to develop practical recommendations. Only then do we believe it
480 would be appropriate to provide recommendations for athletes, coaches, and practitioners.

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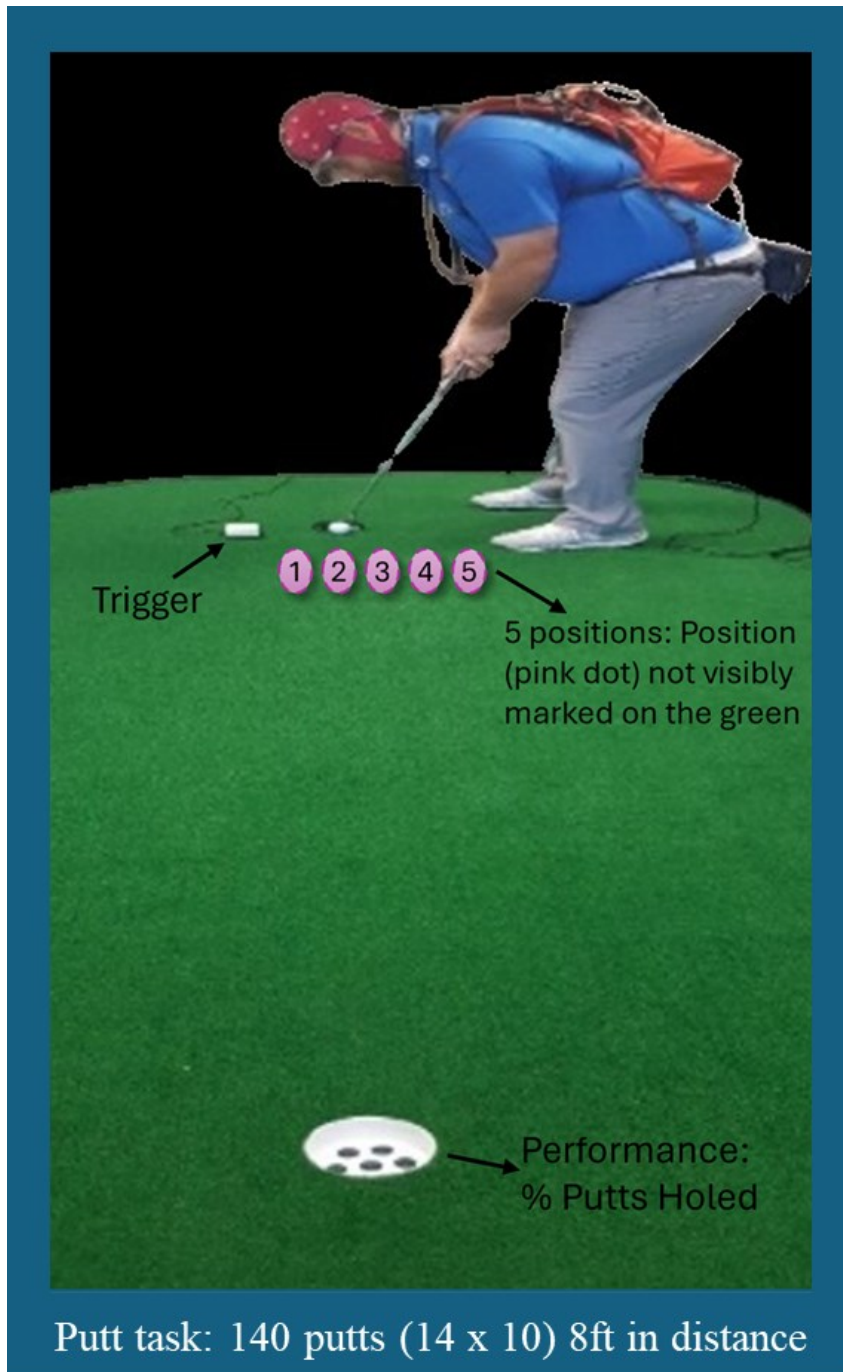
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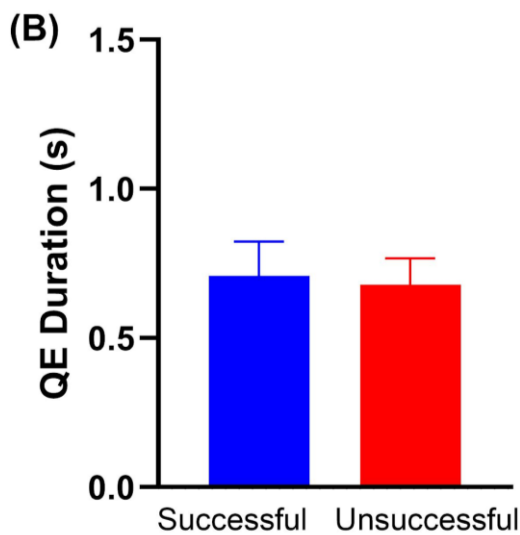
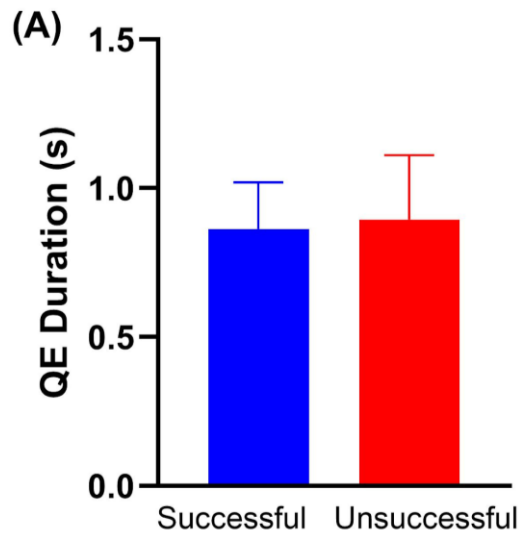
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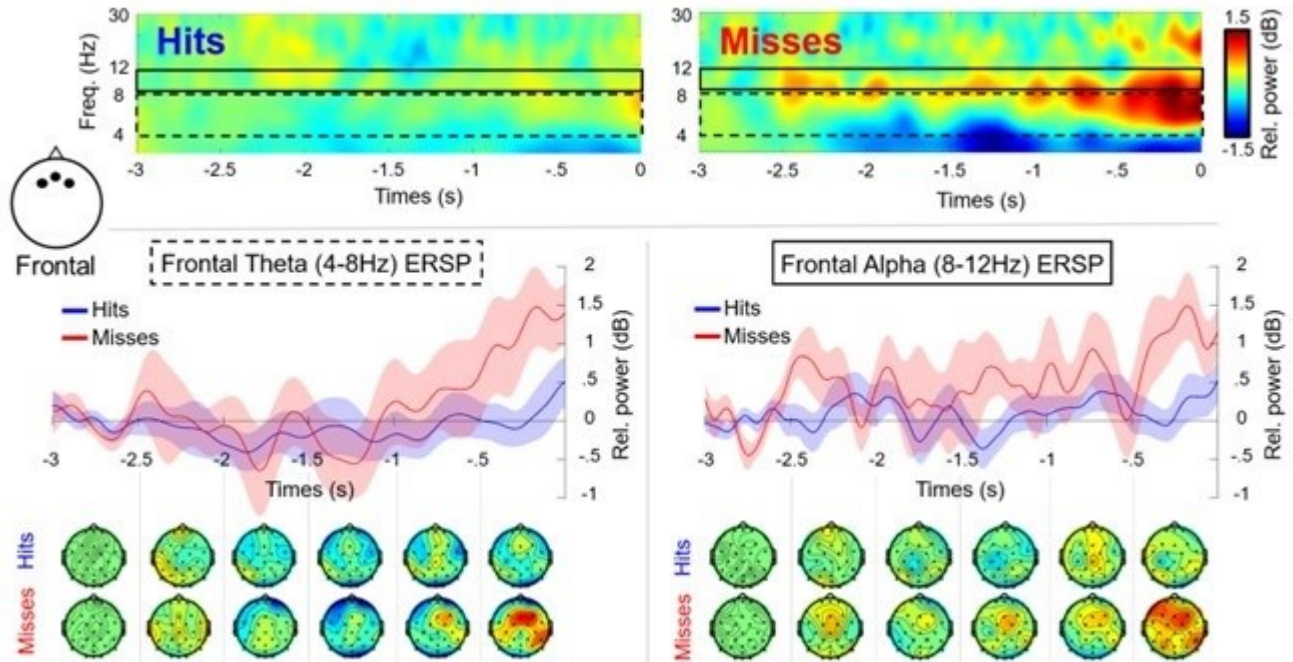
505 **Figure 1.** An image of a participant using the mobile equipment (eye tracking and EEG) whilst
506 completing the putting task.



508 **Figure 2.** There are no performance-based differences in mean QE duration for either the full sample
509 ($n = 28$, Panel A) or the subset ($n = 12$, Panel B) included in the EEG analysis. The error bars on both
510 Panel A and B are 95% CI.

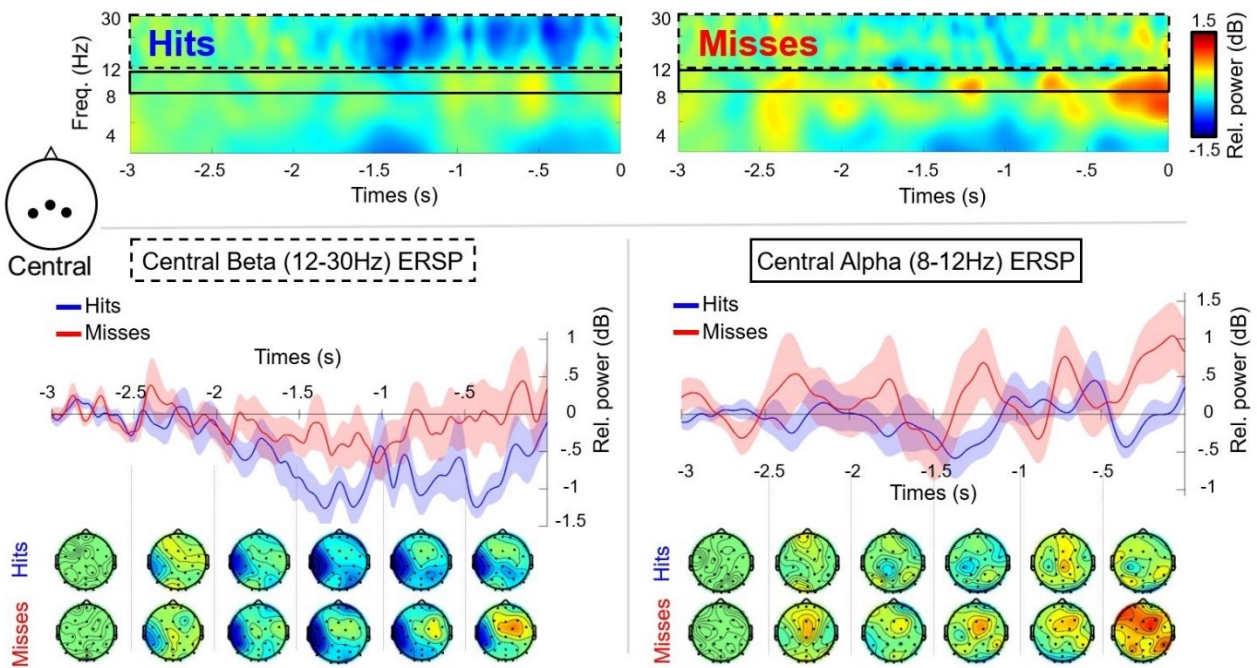


512 **Figure 3.** Time frequency plots and scalp maps showing theta (4-7 Hz) and alpha (8-12 Hz)
 513 oscillations for the frontal cluster (F3, Fz, F4) in the pre-motor preparation period (-3000ms to 0ms)
 514 for successful (Hits: blue) and unsuccessful (Misses: red) putts ($n = 12$). There was a significant
 515 performance*time interaction for frontal theta power, but no other results were significant. The
 516 dashed black box highlights frontal theta activity with associated plot and topographic maps. The
 517 solid black line box shows frontal alpha activity with associated plot and topographic maps.



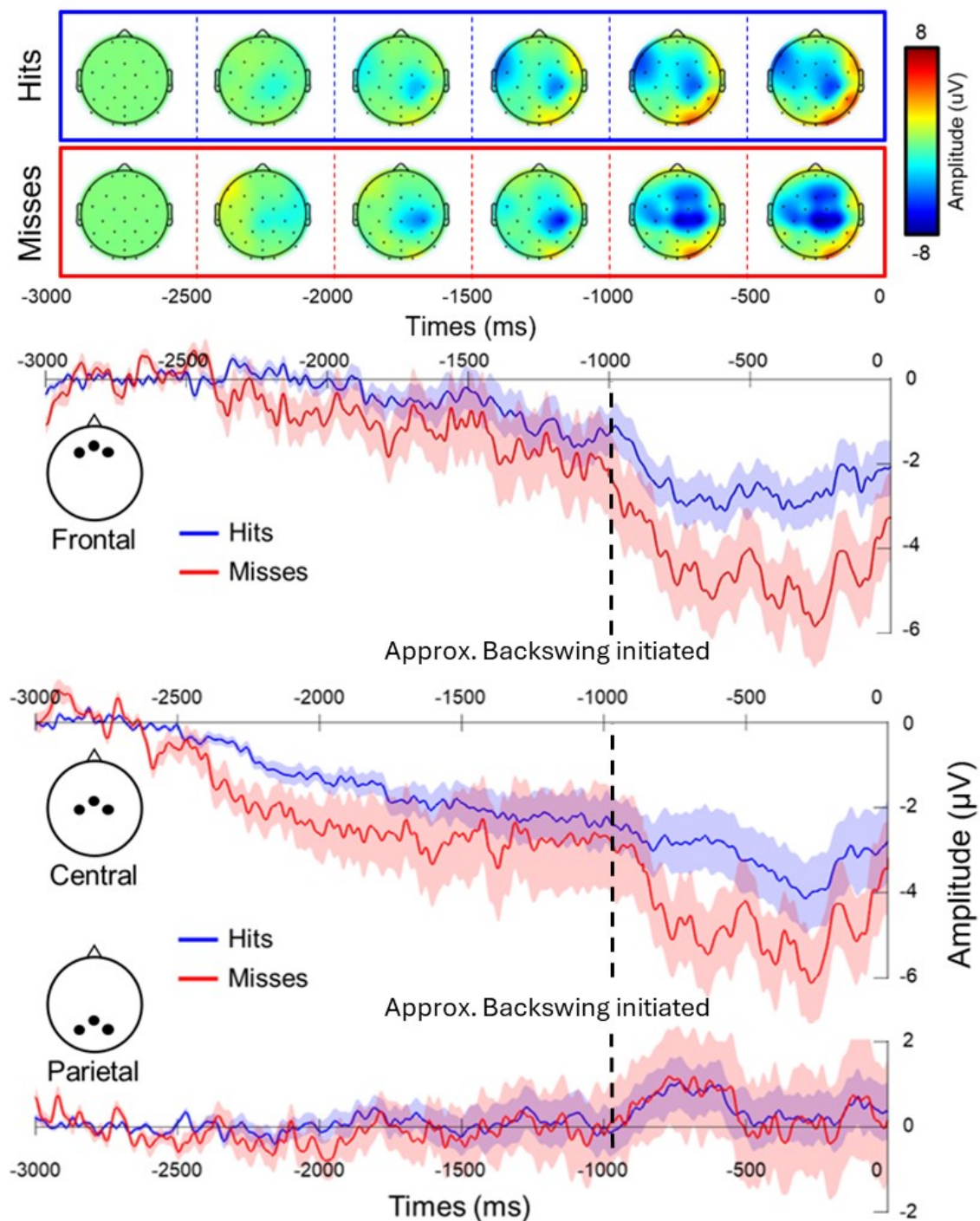
518

519 **Figure 4.** Time frequency plots and scalp maps showing alpha (8-12 Hz) and beta (12-30 Hz)
 520 oscillations for the central cluster (C3, Cz, C4) in the pre-motor preparation period (-3000ms to 0ms)
 521 for successful (Hits: blue) and unsuccessful (Misses: red) putts ($n = 12$). There was a significant main
 522 effect for performance for central beta power, but no other results were significant. The dashed black
 523 box highlights central beta activity with associated plot and topographic maps. The solid black line
 524 highlights central alpha activity with associated plot and topographic scalp maps.



525

526 **Figure 5.** Differences in neural activity in the frontal cluster for successful (Hits: blue) and
 527 unsuccessful (Misses: red) putts for the readiness potential with associated plot and topographic scalp
 528 maps. The choice of trigger has limitations as the motor action (approximate initiation of the
 529 backswing represented by the black dashed line) can be seen as the trigger is aligned to contact (0ms)
 530 not the initiation of the backswing.



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539 **7 Declaration of Interest**

540 The authors declare that the research was conducted in the absence of any commercial or financial
541 relationships that could be construed as a potential conflict of interest.

542 **8 Data Availability Statement**

543 Data will be available for sharing upon request.

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