

The quiet eye effect: A test of the visual and postural-kinematic hypotheses

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1 **The Quiet Eye Effect: A Test of the Perceptual and Kinematic Hypotheses**

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8 *Running head:* Quiet eye: Perceptual and kinematic hypotheses

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Abstract

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The quiet eye effect describes the performance advantage associated with a long ocular fixation on a critical target of an action, prior to and during movement execution. Researchers have advocated a multi-measure approach to shed light on the mechanism(s) behind the association between ocular activity and motor performance. In this study we used psychophysiological methods to test whether the quiet eye period is associated with enhanced visual processing (*visual hypothesis*) or longer movement durations (*postural-kinematic hypothesis*). Thirty-two recreational golfers putted 20 balls to a 2-m distant target on a flat surface. We examined quiet eye duration and time-varying eye quietness using electrooculography, occipital alpha power using electroencephalography, and swing duration using kinematic sensors. Occipital alpha power, an inverse neural marker of visual processing, increased prior to and during swing execution, suggesting decreased visual processing compared to baseline. Correlations revealed that, despite the overall decrease, visual processing decreased less with a longer quiet eye and greater eye quietness. Importantly, swing duration was strongly and positively correlated with both indices of ocular activity: longer quiet eye and greater eye quietness were associated with longer swing duration. Our findings support the postural-kinematic hypothesis, confirming that the duration of the quiet eye is associated with a slow movement execution and question the role of visual processing in the final moments of closed-loop aiming tasks. We anticipate major advancements in the mechanistic understanding of the quiet eye effect as researchers adopt psychophysiological methods to examine eye movements in combination with measures of other biological systems.

Key words: Alpha power, Electrooculography, Golf putting, Kinematics, Visual processing

1 The way we move our eyes has been linked with the precision of movements requiring fine motor
2 control, such as those used in target sports. Research using eye-tracking technology has revealed that,
3 compared to novices, experts make fewer ocular fixations of longer duration on action-related
4 locations prior to and during the execution of a motor skill (Mann, Williams, Ward, & Janelle 2007).
5 The duration of the final ocular fixation on a critical target of the action, labelled the *quiet eye*
6 (Vickers, 1996), has attracted much interest from researchers due to its ability to distinguish skilled
7 from less skilled performers as well as successful from unsuccessful performance of experts (for
8 reviews of studies see Lebeau et al., 2016; Mann, Williams, Ward, & Janelle, 2007; Rienhoff, Tirp,
9 Strauß, Baker, & Schorer, 2016; Vickers, 2007; Wilson, Causer, & Vickers, 2015). In the case of golf
10 putting, the quiet eye period has been defined as the duration of the final ocular fixation on the ball,
11 with onset prior to the initiation of the swing movement and offset when the gaze deviates from the
12 ball, potentially even after putter-ball impact (Vickers, 2007). Longer quiet eye durations have been
13 reported for experienced versus novice golfers (Walters-Symons, Wilson, & Vine, 2017) and for
14 holed versus missed putts in experienced golfers (Wilson & Percy, 2009).

15 Despite the large body of evidence endorsing the existence of the quiet eye effect, researchers
16 still debate how it might influence performance. In order to advance our understanding and inform the
17 design of training programs aimed at improving performance, researchers have recommended
18 mechanistic and cross-disciplinary investigations to test the validity of the competing hypotheses
19 (Causer, 2016; Williams, 2016; Wilson, Wood, & Vine, 2016). A comprehensive review of the
20 putative mechanisms goes beyond the scope of the present work, and for a detailed account we refer
21 the reader to a recent review by Gonzalez et al. (2017a). In the present study, we evaluated two
22 mechanistic hypotheses: the visual hypothesis and the postural-kinematic hypothesis.

23 **Visual hypothesis**

24 Vision-action coupling constitutes a key element in the debate on quiet eye mechanisms.
25 Researchers have described the quiet eye as a perceptual-cognitive phenomenon reflecting the
26 selective processing of movement-related visual information through *overt attention* (see Posner,
27 1980). For example, in their study of the quiet eye in billiards, Williams et al. (2002, p. 197)
28 concluded that ‘To execute the shot, players must successfully integrate visual information from the

1 cue, cue ball, target ball, and pocket.’ The thesis that visual processing plays a major role in the quiet
2 eye was emphasized by Vickers (2012), who referred to the dorsal cortical stream – a visual attention
3 network (Corbetta & Shulman, 2002; Goodale & Milner, 1992) – to explain the putative mechanism
4 underlying the quiet eye effect. In short, enhanced processing of visual information has been the
5 dominant mechanism in this context, even for closed-loop aiming tasks with stationary targets, such
6 as golf putting. Indeed, in their study of the quiet eye in golf putting, Vine et al. (2015, p. 5)
7 concluded that ‘visual information is being actively extracted and processed’ during the quiet eye
8 period. In the current study we refer to this visual attention mechanism as the *visual hypothesis*.

9 Cognitive processes, including attention and perception, can be studied in an objective and
10 unobtrusive manner by recording individuals’ electroencephalogram (EEG) as they perform goal-
11 oriented actions. More specifically, the selective allocation of attentional resources to processing of
12 visual information can be assessed using the magnitude of cortical oscillations (i.e., power) within the
13 alpha frequency band (8-12 Hz) in the occipital regions of the brain. Importantly, studies have
14 established that increased occipital alpha power reflects decreased visual processing (Romei, Gross, &
15 Thut, 2010; Romei, Rihs, Brodbeck, & Thut, 2008; Vanni, Revonsuo, & Hari, 1997). EEG methods
16 have been successfully implemented in sport research (for review see Cooke, 2013; Hatfield, Haufler,
17 Hung, & Spalding, 2004). For example, EEG research has revealed that superior motor performance
18 is associated with neural efficiency by alpha gating, which describes the allocation of attentional
19 resources towards movement-related and away from movement-unrelated information processing
20 (e.g., Gallicchio, Finkenzeller, Sattlecker, Lindinger, & Hoedlmoser, 2016; Gallicchio, Cooke, &
21 Ring, 2017).

22 Given the extensive use of EEG in sport research it is surprising that, with one exception, the
23 association between quiet eye and visual processing, assessed using EEG, has been largely neglected.
24 The exception is the study by Janelle et al. (2000) that reported a positive correlation between quiet
25 eye duration and EEG occipital alpha power in experienced marksmen. Contrary to the visual
26 hypothesis, this finding suggests diminished visual processing during the quiet eye period in a
27 shooting task. Given that this critical piece of evidence appears to have been overlooked within the
28 quiet eye literature and, moreover, that this finding has never been replicated, the association between

1 occipital alpha power and quiet eye duration warrants further investigation.

2 **Postural-kinematic hypothesis**

3 An alternative *postural-kinematic hypothesis* contends that the link between quiet eye and
4 performance is accounted for by a kinematic mechanism: postural stability (involving trunk, limbs,
5 head, and eyes) before and during movement is expected to lead to better performance and longer
6 quiet eye. In the case of golf putting, a slower and more stable swing may be linked with (a) cleaner
7 putter-ball impact to optimize impact velocity and angle and thereby ensure greater putting accuracy,
8 and (b) greater likelihood of keeping the head and eyes still, resulting in delayed quiet eye offset and
9 longer quiet eye. Each of these two elements is considered next.

10 First, the association between swing biomechanics/kinematics (i.e., a slow and stable
11 movement) and superior putting performance is substantiated by research indicating that, compared to
12 less skilled counterparts, expert golfers sway less (i.e., exhibit less centre of pressure variability) (e.g.,
13 Hurrion, 2009; McLaughlin, Best, & Carlson, 2008; Richardson, Hughes, & Mitchell, 2012), generate
14 less lateral putter head acceleration (i.e., they are less likely to swing out of line) (e.g., Cooke et al.,
15 2014; Sim & Kim, 2010), and putt more slowly (e.g., Delay et al., 1997; Gallicchio, Cooke, & Ring,
16 2018).

17 Second, the association between putting biomechanics/kinematics and longer quiet eye can be
18 examined separately for stability and duration. The argument that greater movement stability is
19 associated with longer quiet eye is supported by the finding that novice golfers trained to increase
20 their quiet eye duration in a putting task also generated decreased lateral and vertical putter head
21 acceleration, compared to a control group (Moore, Vine, Cooke, Ring, & Wilson, 2012). The
22 argument that longer movement duration (i.e., slower swing) is associated with longer quiet eye is
23 supported by evidence showing that experts swung for longer than novices and that movement
24 duration was positively correlated with post-movement initiation quiet eye duration (Gallicchio et al.,
25 2018). In other words, novices, who swung the putter quicker than experts, had less reason to keep
26 their head still and dwell on the impact location, and more reason to start to track the moving ball
27 sooner (see online supplementary material, Gallicchio et al., 2018). The net result was that novices
28 exhibited an earlier quiet eye offset compared to experts. The current study aims to extend and

1 replicate the study by Gallicchio and colleagues by testing the movement duration element of the
2 postural-kinematic hypothesis, using both within- and between-participant analyses.

3 **The Present Study**

4 In the present study we had two aims¹. Our first aim was to assess whether ocular activity was
5 associated with EEG occipital alpha power and thereby test a core tenet of the visual hypothesis. Our
6 second aim was to assess whether ocular activity was associated with movement duration in order to
7 test a core tenet of the postural-kinematic hypothesis. We used EEG to examine brain activity
8 implicated with visual processing (e.g., Janelle et al., 2000), and movement sensors to examine the
9 duration of the movement (e.g., Gallicchio et al., 2018). We used electrooculography (EOG) to score
10 the quiet eye period in different phases of the movement (e.g., Gallicchio et al., 2018; Gonzalez et al.,
11 2017b; Mann, Coombes, Mousseau, & Janelle, 2011). We supplemented quiet eye information with
12 the novel ‘eye quietness’ index (Gallicchio et al., 2018), which, unlike quiet eye duration, measures
13 the extent to which the eyes are quiet (rather than dichotomizing eye movements into a state of ‘quiet’
14 or ‘non quiet’) with high temporal resolution.

15 **Method**

16 **Participants**

17 We tested 32 right-handed male relatively-inexperienced recreational golfers (age: $M = 20.09$,
18 $SD = 2.04$ years) with no formal golf handicap and occasional golf experience: they reported to have
19 played 12.06 times ($SD = 12.96$) in the 12 months preceding testing. Participants were asked to refrain
20 from alcohol, caffeine, and nicotine 3 hours prior to testing. All provided signed consent to take part
21 in the study and were compensated with £10 and research credits. This study was approved by the
22 local ethics committee.

23 **Putting task**

24 Participants putted golf balls (diameter 4.7 cm) to a 2-m distant target with a 91-cm blade-
25 style putter on a 5×1.5 m flat surface (Turftiles; Stimpmeter value: 2.27 m). The target was a 6 mm
26 diameter adhesive paper marker placed on the putting surface. Participants were instructed to execute

¹ The current report describes new analyses of a larger golf putting dataset (Gallicchio & Ring, 2018).

1 the putt at their own pace (i.e., no time pressure) with the goal to “*get the final position of the ball as*
2 *close as possible to the target*”. Prior to each putt participants were required to stand in a relaxed
3 position and maintain their gaze on a fixation cross placed at eye level on the facing wall (c. 1.5 m
4 away) for 4-5 s, until a 200-ms acoustic tone (cue stimulus) prompted them to prepare for the putt.
5 This acoustic tone was generated by a piezo buzzer controlled by an Arduino Micro board (Arduino,
6 Italy) interfaced with a computer running MATLAB (MathWorks, USA).

7 **Procedure**

8 Upon arrival in the laboratory, participants were briefed and instrumented for physiological
9 recording. Then, participants performed 10 putts to a series of targets varying in distance and extent to
10 familiarize them with the putting surface. Finally, participants putted 20 balls to a straight 2-m distant
11 target. The average time between consecutive putts was 22.82 s ($SD = 2.45$). After each putt the
12 researcher took a photo of the putting area using a ceiling-mounted camera and repositioned the ball
13 for the next putt.

14 **Physiological signals**

15 Electrophysiological signals were recorded using an ActiveTwo system (BioSemi,
16 Netherlands). The EOG was recorded using four electrodes applied on the participant’s skin near the
17 eyes: two were placed at the outer canthi of each eye and the other two at the bottom of each eye. The
18 EEG was recorded through 32 electrodes applied on scalp sites Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4,
19 F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4,
20 O1, Oz, O2 (10-20 system, Jasper, 1958). Additional electrodes were applied to the mastoids and to
21 the chest (proximal lead-II ECG montage) for offline denoising purposes (described below). The
22 signal was amplified and digitized at 2048 Hz with 24-bit resolution and no filter was set during
23 recording. All channels were recorded in monopolar. Common mode sense and driven right leg
24 electrodes were used to enhance the common mode rejection ratio of the signal.

25 Digital triggers (transistor-transistor logic inputs) were sent via parallel communication to the
26 recording system in order to detect (a) the onset of the acoustic tone (prompting the participant to
27 prepare for the putt), (b) the initiation of the backswing, and (c) the impact of the putter head with the
28 ball. Participants were instructed to align the putter head with an infrared digital switch (E18-D80NK)

1 when ready to putt: this sensor sent a digital trigger as the putter head moved away from the ball at the
2 initiation of the backswing. In addition, a piezo sensor (MiniSense 100) attached to the back of the
3 putter head was used to record putter-ball impact vibrations. This sensor was interfaced with the
4 recording system to synchronize information about the impact with the electrophysiological signals.

5 After recording, we performed the following pre-processing steps. Signals were down-
6 sampled to 512 Hz. For the analysis of the quiet eye, the electrodes positioned at the canthi of each
7 eye were re-referenced to each other to create a bipolar horizontal EOG channel. Then we applied a
8 30 Hz low-pass filter (Finite Impulse Response, filter order = 2^8) according to EOG guidelines
9 (Marmor et al., 2011). No high-pass filter was applied in order to preserve flat sections of the signal,
10 typical of ocular fixations (Acuña et al., 2014). Epochs were segmented from -9 to +3 s (0 s =
11 backswing initiation) and the voltages were linearly detrended (i.e., the best straight-line fit was
12 subtracted to each epoch signal). Finally, a 125-ms median filter was applied to attenuate ocular
13 overshoots while preserving sharp vertical edges typical of ocular saccades (Bulling et al., 2011;
14 Juhola, 1991). **Figure 1** shows the horizontal EOG channel from selected trials for illustration. All
15 single-trial waveforms can be accessed from the online supplemental material (**Supplement S1**).

16 For the analyses of EEG activity and eye quietness we applied a 0.1-40 Hz band-pass filter
17 (Finite Impulse Response, filter order = 2^{15}). Two types of epochs were segmented from -3.5 to
18 +1.5 s relative to (a) the acoustic tone (cue stimulus) and (b) the initiation of the backswing. Voltages
19 were mean-centered within each epoch. Epochs were visually inspected and were discarded from all
20 subsequent analyses if they showed movement or electrical artefacts. The mean number of
21 backswing-centered epochs that were retained was 19.84 ($SD = 0.37$, *minimum* = 19). The mean
22 number of tone-centered epochs that were retained was 19.75 ($SD = 0.51$, *minimum* = 18).
23 Independent Component Analysis (Makeig et al., 1996) was performed to attenuate any electrical
24 artefacts due to ocular, cardiac, and muscular activity in the EEG signal using the EOG and ECG
25 channels. Finally, the EEG channels were average-referenced.

26 Measures

27 **Quiet eye.** Quiet eye durations (ms) were calculated for two periods and were obtained by
28 further processing the horizontal EOG signal: QE_{pre} defined as quiet eye onset to backswing initiation,

1 and QE_{post} defined as backswing initiation to quiet eye offset. Onset and offset of the quiet eye were
2 identified through a threshold algorithm. Specifically, voltages at successive time points were
3 compared with the voltage at the instant of the initiation of backswing (i.e., time = 0 s). Quiet eye
4 onset and offset were respectively defined as the farthest time points preceding and following
5 backswing initiation that did not exceed a certain threshold (Gallicchio et al., 2018). We evaluated the
6 quiet eye durations for 30 threshold options (ranging from 5 to 150 μV in 5 μV steps). We conducted
7 exploratory analyses using all of these threshold settings (**Figure 2**), however, for our main analyses,
8 we chose a threshold of 60 μV , corresponding with eye movements of 3° of visual angle (Shackel,
9 1967). This choice was informed by visual inspection revealing that, compared to other thresholds
10 (including 20 μV corresponding with 1° of visual angle), the 60 μV threshold detected most
11 accurately the duration of the final fixation, commencing with the foot of the final square wave prior
12 to backswing initiation (**Figure 1**). Moreover, 60 μV is the same threshold deemed optimal in a
13 previous study (Gallicchio et al., 2018). The interested reader can inspect the single-trial quiet eye
14 durations identified by the different threshold options in the online supplemental material
15 (**Supplement S1**).

16 **Eye quietness.** Eye quietness (%) was computed as the standard deviation of the horizontal
17 EOG channel (HEOG-SD) in eight non-overlapping 0.5 s intervals ranging from -3 to +1 s (0 s =
18 backswing initiation) (Gallicchio et al., 2018). Each HEOG-SD value reflected how much the eyes
19 moved or were active in the horizontal plane: larger values indicated more and larger eye movements
20 (hence less eye quietness); conversely, smaller values indicated fewer and smaller eye movements
21 (hence greater eye quietness). Finally, HEOG-SD was baseline-corrected to reflect the percentage
22 change relative to average HEOG-SD in the 2 s prior to the onset of the acoustic tone. This
23 transformation was performed to minimize variability between participants and, moreover, this
24 procedure is implemented as standard in the analysis of EEG signals (Pfurtscheller & Lopes da Silva,
25 1999).

26 **Occipital alpha power.** Time-frequency decomposition was performed through short-time
27 Fast Fourier Transform (FFT), conducted on eight non-overlapping 0.5 s windows ranging from -3 to
28 +1 s (0 s = backswing initiation), to match the windows used for the analysis of eye quietness. Prior to

1 FFT, each window was mean-averaged, multiplied by a Hanning function to taper both ends, and then
2 zero-padded to reach a length of 4 s, yielding a frequency resolution of 0.25 Hz. The amplitude of the
3 signal resulting from the FFT was doubled for all positive frequencies and alpha power was computed
4 as the squared amplitude in the 8-12 Hz frequency range. Then, alpha power was baseline-corrected to
5 reflect the percentage change (Pfurtscheller & Lopes da Silva, 1999) relative to the average baseline
6 activity in the 2 s prior to the onset of the acoustic tone (cue stimulus). Finally, occipital alpha power
7 was obtained by averaging values for the O1, Oz, and O2 channels to create an occipital region of
8 interest, consistent with previous research (e.g., Gallicchio et al., 2017).

9 **Movement duration.** The duration of the swing (ms) was measured as the time between
10 backswing initiation and putter-ball impact. These two events were detected through a bespoke
11 MATLAB script that combined data from the infrared switch and the piezo sensor.

12 **Putting performance.** Radial error (cm) was computed as the distance between the target and
13 the terminal position of the ball after each putt. Scoring was performed through a bespoke MATLAB
14 script that used the photos of the target area taken after each putt (Gallicchio & Ring, 2018).

15 **Statistical Analyses**

16 We used two statistical strategies to examine the associations between ocular activity (i.e.,
17 quiet eye and eye quietness) and (a) brain activity (i.e., occipital alpha power), (b) movement
18 duration, and (c) putting performance (i.e., radial error). Correlations were computed using the
19 Spearman's rank test. Spearman's rho (ρ) was used as the effect size, with values of .10, .30, and .50
20 reflecting small, medium, and large effects, respectively (see reference values for Pearson product-
21 moment correlation in Cohen, 1992).

22 Our first strategy sought to capture the effects for each participant at the individual trial level.
23 We refer to this as trial-level analysis. This strategy involved two steps. First, we correlated the two
24 variables across all trials separately for each participant. Second, we performed a one-sample *t* test on
25 the Fisher-Z transformed correlation coefficients across all participants (cf. Klostermann et al., 2014).
26 For this analysis we report the group mean of the back-transformed Spearman's rho correlation
27 coefficient (ρ_M) along with the *t* value and the associated *p* value. Our second strategy sought to
28 compare participants using the average scores over all of their trials; this is the typical correlation

1 analysis. We refer to this as participant-level analysis. For this analysis we report the Spearman's rho
 2 coefficient (ρ) and the associated p value. The purpose of each analysis and our selection of the pairs
 3 of measures is described next.

4 **Quiet eye and eye quietness.** We correlated quiet eye and eye quietness to cross-validate
 5 these two indices of ocular activity. More specifically, we correlated QE_{pre} with pre backswing
 6 initiation HEOG-SD (i.e., in the six time intervals from -3 to 0 s) and QE_{post} with post backswing
 7 initiation HEOG-SD (i.e., in the two time intervals from 0 to +1 s).

8 **Correlates of occipital alpha power.** We correlated ocular activity (i.e., quiet eye and eye
 9 quietness) with brain activity (i.e., occipital alpha power) to test the visual hypothesis. For the
 10 analyses involving the quiet eye, we correlated QE_{pre} with pre-backswing initiation occipital alpha
 11 power (i.e., in the six time intervals from -3 to 0 s), and QE_{post} with post-backswing initiation occipital
 12 alpha power (i.e., in the two time intervals from 0 to 1 s). For the analyses involving eye quietness, we
 13 correlated HEOG-SD and occipital alpha power in each of the eight time intervals from -3 to +1 s. In
 14 addition, we evaluated the specificity of any effect to the alpha band by conducting further analyses
 15 on activity in other EEG frequencies. We examined non-alpha frequencies to evaluate the extent to
 16 which any effect for the alpha band was unequivocally attributable to visual processing rather than
 17 indicating a non-cortical phenomenon, such as elevated somatic activity.

18 **Correlates of movement duration.** We correlated ocular activity (i.e., quiet eye and eye
 19 quietness) with movement duration to test the postural-kinematic hypothesis. Because it was
 20 necessary to measure movement duration from the initiation of the backswing, we correlated only the
 21 post-backswing initiation indices of ocular activity (i.e., QE_{post} and HEOG-SD in the two intervals
 22 from 0 to +1 s).

23 **Correlates of performance.** We correlated ocular activity (i.e., QE_{pre} , QE_{post} , and HEOG-SD
 24 in each of the eight time intervals from -3 to +1 s) with radial error to explore performance effects
 25 linked with gaze behaviour.

26 Results

27 Quiet eye and eye quietness

28 We computed the quiet eye for two intervals: before backswing initiation (QE_{pre}) and after

1 backswing initiation (QE_{post}). The threshold algorithm at $60 \mu\text{V}$ identified the following mean
 2 durations: QE_{pre} 928 ms ($SD = 501$, $range = 227$ to 2623) and QE_{post} 819 ms ($SD = 219$, $range = 367$
 3 to 1213). The main analyses reported below were conducted using the $60 \mu\text{V}$ threshold (see Measures
 4 section above for the rationale underlying this choice). Nonetheless, there is a healthy debate among
 5 quiet eye researchers about the appropriate choice of this threshold (i.e., visual angle), and therefore,
 6 we have displayed the influence of threshold choice on quiet eye duration in **Figure 2A**, which shows
 7 that the higher the threshold the longer the duration.

8 We analysed eye quietness (i.e., HEOG-SD) as a function of time (**Figure 3**). Smaller values
 9 reflected less variability, hence greater quietness. Eye quietness was best (i.e., largest effect size)
 10 described by a cubic pattern, $F(1,31) = 16.84$, $p < .001$, $\eta_p^2 = .352$, whereby quietness decreased until
 11 -1 s, increased until $+0.5$ s, and finally decreased after $+0.5$ s. It is worth mentioning that the greatest
 12 quietness was evident between 0 and $+0.5$ s, that is, during the execution of the swing.

13 To evaluate the utility of eye quietness as index of ocular activity we examined its correlation
 14 with quiet eye durations. The outcomes of trial- and participant-level correlations are reported in
 15 **Table 1**. Both types of analyses confirmed that greater eye quietness (i.e., smaller HEOG-SD) was
 16 associated with longer quiet eye durations before (i.e., in the time intervals from -1.5 to 0 s) and after
 17 (i.e., in the time intervals from 0 to $+1$ s) backswing initiation, with small to large effect sizes. It is
 18 noteworthy that this association held across multiple thresholds (**Figure 2B** and **2C**).

19 **Correlates of occipital alpha power**

20 Occipital alpha power averaged $157 \mu\text{V}^2$ ($SD = 187$, $range = -59$ to 693) in the 1 s prior to
 21 backswing initiation and $125 \mu\text{V}^2$ ($SD = 158$, $range = -55$ to 535) in the 1 s following backswing
 22 initiation, indicating an overall increase from the pre-cue baseline. The topography of alpha power for
 23 the 32 EEG channels is presented in the online supplemental material (**Supplement S2**).

24 **Quiet eye.** Quiet eye durations correlated negatively with occipital alpha power, with small to
 25 large effect sizes (**Table 2**). More specifically, trial-level analyses revealed that longer QE_{pre} was
 26 associated with smaller increases in occipital alpha power from -2 to -1.5 s prior to backswing
 27 initiation. Longer QE_{post} was associated with smaller increases in occipital alpha power in the 1 s
 28 following backswing initiation (i.e., approximately during swing execution). Participant-level

1 correlations revealed that participants who showed smaller increases in occipital alpha power from -3
2 to -2.5 s and in the 1 s prior to backswing initiation were those with longer QE_{pre} .

3 **Eye quietness.** HEOG-SD was positively correlated with occipital alpha power, with small to
4 large effect sizes (**Table 2**). More specifically, trial-level correlations revealed that greater eye
5 quietness (i.e., smaller HEOG-SD) was associated with smaller increases in occipital alpha power in
6 the 2.5 s prior to backswing initiation. Participant-level correlations confirmed the same pattern for
7 the 1 s following backswing initiation: participants with greater eye quietness were those with smaller
8 increases in occipital alpha power.

9 **Alpha specificity.** The exploration of other (i.e., non-alpha) frequencies revealed that the
10 association between occipital activity and ocular activity (i.e., quiet eye and eye quietness) was part of
11 a more general phenomenon that was not specific to alpha band activity (**Figure 4**).

12 **Correlates of movement duration**

13 Movement duration averaged 719 ms ($SD = 174$, $range = 427$ to 1057). Correlations
14 examined the relation between movement duration and ocular activity (i.e., quiet eye and eye
15 quietness) to test the postural-kinematic hypothesis. Only the indices measured after backswing
16 initiation were used in these analyses (i.e., QE_{post} and HEOG-SD in the two intervals from 0 to 1 s).

17 **Quiet eye.** Quiet eye duration was positively associated with movement duration, with
18 medium to large effect sizes. The trial-level analysis revealed that movement duration was positively
19 correlated with QE_{post} , $\rho_M(18) = .32$, $t(31) = 4.19$, $p < .001$. Participant-level analysis confirmed this
20 association, revealing that participants who executed the swing more slowly were those with longer
21 QE_{post} , $\rho(30) = .53$, $p = .002$.

22 **Eye quietness.** Eye quietness was inversely associated with movement duration, with small to
23 medium effect sizes, and only for certain time intervals. More specifically, trial-level analyses yielded
24 a negative correlation between movement duration and HEOG-SD in the interval from 0.5 to 1 s,
25 $\rho_M(18) = -.18$, $t(31) = -3.40$, $p = .002$, but not from 0 to 0.5 s, $\rho_M(18) = -.01$, $t(31) = -0.18$, $p = .86$.
26 Participant-level analyses confirmed the same general pattern, albeit these were not statistically
27 significant: participants with longer movement durations tended to show greater eye quietness (i.e.,
28 smaller HEOG-SD) from +0.5 to +1 s, $\rho(30) = -.27$, $p = .15$, but not from 0 to +0.5 s, $\rho(30) = .01$, $p =$

1 .92.

2 **Correlates of performance**

3 Putting performance was assessed as radial error ($M = 22.64$ cm, $SD = 5.47$, $range = 9.93 -$
 4 35.05). Trial- and participant-level correlations examined the relation between radial error and ocular
 5 activity (i.e., quiet eye and eye quietness). These results are described below.

6 **Quiet eye.** Trial-level analyses revealed that radial error was not significantly correlated with
 7 QE_{pre} , $\rho_M(18) = -.02$, $t(31) = -0.40$, $p = .69$, and QE_{post} , $\rho_M(18) = -.03$, $t(31) = -0.84$, $p = .41$.
 8 Participant-level analyses also revealed non-significant correlations between radial error and QE_{pre} ,
 9 $\rho(30) = .12$, $p = .51$, and between radial error and QE_{post} , $\rho(30) = -.12$, $p = .53$. Additional exploratory
 10 analyses conducted with less stringent thresholds for scoring the quiet eye duration revealed a
 11 negative and statistically significant relation between radial error and QE_{post} duration (see **Figure 2B**),
 12 providing some evidence that longer QE_{post} was associated with superior putting performance.

13 **Eye quietness.** No relation emerged between radial error and eye quietness (i.e., HEOG-SD)
 14 from -3 to +1 s at the trial level, $\rho_Ms(18) = .00$ to $.06$, $ts(31) = -0.12$ to 1.37 , $ps = .18$ to $.97$, or at the
 15 participant level, $\rho_s(30) = -.07$ to $.09$, $ps = .62$ to $.89$.

16 **Discussion**

17 The goals of this study were to shed light on two putative mechanisms behind the quiet eye
 18 phenomenon². Specifically, we tested the link between ocular activity and visual processing (visual
 19 hypothesis) and the link between ocular activity and movement kinematics (postural-kinematic
 20 hypothesis). Our findings provided support for the postural-kinematic hypothesis and only limited
 21 support for the visual hypothesis. The implications of our findings are discussed below.

22 **Quiet eye and eye quietness**

23 Quiet eye was scored for separate movement phases: QE_{pre} before movement initiation and

² Our study was not designed to examine the relationship between the mechanisms and performance. Given that quiet eye duration has not been linked with performance in non-expert samples (Lebeau et al., 2016), a more difficult task and a more heterogeneous sample would be required to evaluate these relationships in a golf putting task.

1 QE_{post} after movement initiation. A threshold of $60 \mu\text{V}$ (3° of visual angle; Shackel, 1967) yielded a
2 total quiet eye duration of 1747 ms. Quiet eye durations associated with multiple thresholds and
3 different phases of movement are illustrated in **Figure 2A**. As expected, larger thresholds yielded
4 longer quiet eye durations, in line with the findings reported in a previous multiple-threshold EOG
5 study (Gallicchio et al., 2018). Moreover, these quiet eye durations are consistent with those obtained
6 using camera-based eye tracking in a similar sample (e.g., Walters-Symons, Wilson, & Vine, 2017).

7 Eye quietness was scored as the standard deviation of the horizontal EOG signal (HEOG-SD)
8 as a function of time relative to the initiation of movement. A polynomial trend analysis revealed a
9 cubic-shaped pattern consisting of three phases: first, increased ocular activity 1 to 2 s prior to
10 movement initiation; second, decreased ocular activity (i.e., increased eye quietness) during
11 movement execution; and third, increased ocular activity. It is possible that the increased ocular
12 activity in the first and third phases is attributable to saccades directed towards the target prior to
13 swing initiation and to the ball and target following swing execution, to confirm the target location
14 and monitor the rolling ball towards the target location, respectively. Importantly, the increased eye
15 quietness around movement execution should reflect the quiet eye period. This interpretation is
16 supported by the finding that eye quietness was strongly associated with quiet eye durations around
17 movement initiation. The link between quiet eye and eye quietness was robust because (a) both trial-
18 and participant-level analyses yielded medium to large effect sizes (**Table 1**), (b) the effect emerged
19 for multiple quiet eye thresholds (**Figure 2**), and (c) it replicated previous findings (Gallicchio et al.,
20 2018).

21 **Visual hypothesis**

22 Occipital alpha power was measured as percentage change from a pre-putt baseline, during
23 which participants fixated their gaze on a cross at eye level. The finding that this change score was
24 positive indicates an increase from baseline, which can be interpreted as a withdrawal of cortical
25 resources away from visual processing (Romei et al., 2008, 2010; Vanni et al., 1997). In other words,
26 the participants performed less visual processing in the moments just before, during, and just after
27 putting the ball. This evidence is in line with Janelle et al. (2000). Taken together, these key findings
28 undermine the visual hypothesis.

1 The co-examination of EEG and EOG revealed that occipital alpha power correlated
2 negatively with quiet eye durations (QE_{pre} and QE_{post}) and positively with eye quietness (HEOG-SD).
3 The size of these effects ranged from small to large (**Table 2**) and emerged for different quiet eye
4 thresholds (**Figure 2**). These results could be interpreted as suggesting that, despite the overall
5 decrease in visual processing, it decreased less for longer quiet eye durations and greater eye
6 quietness, providing some limited support for the visual hypothesis. Importantly, however, the fact
7 that these effects were not specific for time, frequency, and cortical region raises doubts about the
8 plausibility of this tentative interpretation. First, some of the significant correlations between occipital
9 alpha and both quiet eye duration and eye quietness (**Table 2**) emerged for time intervals that
10 *preceding* the onset of the quiet eye, suggesting that the alpha-gaze association is spurious rather than
11 functional. Second, the correlations between occipital activity and gaze are not specific to the alpha
12 frequency band (**Figure 4**), suggesting the association is driven by broadband general quiescence
13 rather than alpha-related visual processing. Third, these correlations are not confined to the occipital
14 region, whereas the putting-related increase in alpha power relative to baseline is localized to the
15 occipital regions (see the online supplemental material, Supplement S2). Indeed, previous analyses on
16 this dataset, reported in Gallicchio and Ring (2018), revealed that processing resources were gated
17 towards the sensorimotor regions (and away from occipital and temporal regions), presumably
18 reflecting increased attention to and processing of proprioceptive afference, expected to aid postural
19 stability. Accordingly, any interpretation of the relationship between EEG occipital alpha power and
20 ocular activity in terms of visual processing should be treated with caution: at the moment we cannot
21 rule out a more parsimonious electrophysiological interpretation whereby postural-kinematic
22 quiescence influenced EEG recordings across a broad spectrum of brain waves that includes alpha and
23 across various cortical regions including the occipital one.

24 **Postural-kinematic hypothesis**

25 Both measures of ocular activity (quiet eye and eye quietness) were robustly associated with
26 movement duration. First, longer post-movement initiation quiet eye durations (i.e., QE_{post}) were
27 associated with longer swing durations. This association emerged for both trial- and participant-level
28 analyses with large effect sizes and for multiple quiet eye thresholds (**Figure 2**). Second, greater eye

1 quietness was associated with longer swing durations. Interestingly, this association emerged only for
2 the time interval that overlapped the moment of putter-ball impact (i.e., from +0.5 to +1 s after
3 movement initiation) and, therefore, it indicates that a longer duration swing was associated with
4 greater and prolonged eye quietness. These results replicate previous findings (Gallicchio et al.,
5 2018). Taken together, they provide additional support for one key element of the postural-kinematic
6 hypothesis, namely, that ocular quiescence during movement is associated with longer movement
7 durations in closed-loop aiming tasks.

8 In line with the predictions of the postural-kinematic hypothesis, these analyses focused
9 exclusively on the post-movement initiation component of gaze behavior. It is noteworthy that the
10 handful of studies that have examined the separate contribution of pre- and post-movement initiation
11 quiet eye in golf putting have all attributed a greater importance to the latter (Causer et al., 2017;
12 Gallicchio et al., 2018; Klostermann et al., 2014; Vine, Lee, Moore, & Wilson, 2013; Vine, Lee,
13 Walters-Symons, & Wilson, 2015). These findings imply that previous quiet eye effects may be
14 attributable, at least in part, to the kinematics of the movement: a longer post-movement initiation
15 quiet eye is due to a longer (and smoother) movement execution.

16 **Performance**

17 Our study was designed to test the visual and postural-kinematic hypotheses by focusing on
18 the neurophysiological and kinematic correlates of the quiet eye and eye quietness irrespective of
19 performance. We found that gaze behavior was not consistently associated with putting performance
20 (**Figure 2**). It is not possible to compare these mostly null findings with previous findings because
21 there is a conspicuous absence of results – positive, negative, and null – within non-expert samples
22 (Lebeau et al., 2016). Crucially, the inconsistent relation between gaze and performance does not
23 undermine our findings pertinent to the visual and postural-kinematic hypotheses. Separate analyses
24 conducted on the current dataset (see Gallicchio & Ring, 2018) revealed better putting performance in
25 participants who exhibited greater EEG occipital alpha power. This effect was specific to the alpha
26 frequency and the occipital region and thereby suggests that diminished visual processing aids
27 performance. This finding is consistent with Loze, Collins, and Homes (2001) who reported that,
28 compared to worst performance, best performance in a pistol-shooting task was accompanied by

1 elevated occipital alpha, indicating reduced visual processing. Swing duration was not associated with
 2 putting performance in the current study³ whereas expert-novice differences have been reported
 3 previously (Delay et al., 1997; Gallicchio et al., 2018). It is likely that a range restriction effect
 4 (Cohen, Cohen, Aiken, & West, 2003) reduced the estimate of the swing-performance relationship in
 5 the current study because of a number of factors, including limited variability in performance scores,
 6 the homogeneity of putting ability, and short (easy) putting distance. Future studies using more
 7 difficult tasks and involving more diverse ability samples are needed to examine the extent to which
 8 the effect of gaze behaviour on performance can be attributed to visual processing and swing duration.

9 **Limitations**

10 The present findings need to be considered in light of some potential study limitations. First,
 11 our results on quiet eye duration might be biased by the fact that, unlike camera-based eye tracking,
 12 EOG does not provide spatial information on the gaze location. Despite observing that participants
 13 kept their head above the ball during the swing we cannot confirm whether their gaze was on the
 14 expected focus point (i.e., the ball) or on locations near this point (e.g., the putter head) during the
 15 quiet eye period. The uncertainty of gaze location is aggravated by the fact that the equivalence of 20
 16 μV on the horizontal EOG signal with 1° of visual angle is more of a guideline than an exact
 17 mathematical law (Shackel, 1967). With this in mind, we recommend that researchers co-record EOG
 18 with camera-based eye tracking to determine which processing parameters (e.g., EOG threshold)
 19 provide the most accurate measures of quiet eye.

20 Second, we could not integrate horizontal and vertical eye movements because the EOG was
 21 not spatially calibrated. While we concede that the horizontal signal is more meaningful than the
 22 vertical signal in a putting task (which is performed in the frontal plane) we recommend that future
 23 studies calibrate the EOG signal (e.g., Gonzalez et al., 2017b) to achieve a better voltage-to-visual
 24 angle mapping.

25 Third, our analyses could not determine whether the association between quiet eye and

³ Movement duration was not significantly associated with radial error as revealed by trial-level analyses, $\rho_M(18) = -.03$, $t(31) = -0.86$, $p = .40$ and participant-level analyses, $\rho(30) = -.05$, $p = .80$.

1 activity in the visual regions of the brain was due to fixation on the critical focus location (i.e., the
2 ball) or just a general ocular quiescence. To answer this question, future research should examine
3 occipital alpha while individuals are instructed to fixate the critical focus location or an irrelevant spot
4 nearby this location (cf. Lee, 2015; Williams, 2016). Connected to this point, future research should
5 consider recording the EEG from a larger set of electrodes to distinguish activity from primary versus
6 secondary visual regions of the brain. This point stems from an alternative interpretation of our
7 findings: the increase in occipital alpha relative to resting baseline does not dismiss the visual
8 hypothesis entirely. It is possible that this increase reflects diminished processing of task-irrelevant
9 visual information, hence a sharpened visual focus on task-relevant visual information (i.e., the ball in
10 golf putting).

11 Fourth, this study does not provide a comprehensive test of the postural-kinematic hypothesis.
12 Future studies interested in this mechanism should assess movement smoothness and postural stability
13 by recording, respectively, multi-axis movement acceleration (e.g., Cooke et al., 2014; Moore et al.,
14 2012) and body sway (e.g., Hurrion, 2009) in relation to quiet eye duration.

15 Finally, by focusing on the association between ocular activity and visual processing /
16 movement kinematics, our study tested only one path of the triadic model described by the visual and
17 postural-kinematic hypotheses: we did not examine the role of visual processing or movement
18 kinematics in the relation between quiet eye and performance. With the basic understanding accrued
19 so far, future research is now well-equipped to address causality in the proposed mechanisms by
20 employing experimental manipulations, diverse samples, difficult tasks, and process analyses.

21 **Conclusion**

22 Our study demonstrates the utility of adopting psychophysiological methods in quiet eye
23 research. We anticipate valuable developments in the mechanistic understanding of this phenomenon
24 as quiet eye researchers incorporate this methodology to study eye movements together with the
25 activity of multiple other biological systems. Furthermore, the use of EOG opens new avenues for
26 novel training programmes based on real-time eye quietness biofeedback. Our findings imply that the
27 quiet eye may be indicative of a quiet body (cf. Obrist, Webb, & Sutterer, 1969) and question the role
28 played by visual attention before and during movement execution in golf putting. It is entirely

1 plausible that attention to visual information plays an important role at an earlier stage of movement
2 planning – the so-called “green reading” in golf – where individuals make perceptual judgments on
3 spatial features of the target scene (e.g., distance, slope) to calibrate movement parameters, such as
4 force and direction (Carey, Jackson, Fairweather, Causer, & Williams, 2017). It is likely that
5 individuals internalize these parameters into an action plan and maintain it in working memory before
6 and during movement execution. Obviously, these ideas need to be addressed by future research.
7 Finally, we foresee that a multi-method approach, such as the one that we advocate, will allow
8 research teams to confirm the mechanism(s) underlying the quiet eye phenomenon as we approach the
9 end of the third decade since its discovery.

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1 **Table 1.** Trial-level analyses (i.e., average Spearman's ρ and t values) and participant-level
 2 analyses (i.e., Spearman's ρ) of the relation between quiet eye durations (QE_{pre} and QE_{post}) and eye
 3 quietness (HEOG-SD) in 8 0.5 time intervals from -3 to +1 s (0 s = backswing initiation).

4

Time	QE_{pre}			QE_{post}		
	$\rho_M(18)$	$t(31)$	$\rho(30)$	$\rho_M(18)$	$t(31)$	$\rho(30)$
-3 to -2.5 s	-.08	-1.86 [†]	-.00			
-2.5 to -2 s	.01	0.16	-.06			
-2 to -1.5 s	-.02	-0.29	-.26			
-1.5 to -1 s	-.12	-2.48*	-.25			
-1 to -0.5 s	-.30	-5.85***	-.42*			
-0.5 to 0 s	-.31	-4.34***	-.42*			
0 to +0.5 s				-.09	-2.15*	-.29
+0.5 to +1 s				-.03	-0.71	-.40*

5 Note. Only relevant comparisons are reported: QE_{pre} with pre-movement initiation HEOG-SD (i.e., 6
 6 intervals from -3 to 0 s) and QE_{post} with post-movement initiation HEOG-SD (i.e., 2 intervals from 0
 7 to +1 s).

8 [†] $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$

1 **Table 2.** Correlations between ocular activity (QE_{pre}, QE_{post}, and HEOG-SD) and occipital alpha power in 8 0.5 time intervals from -3 to
 2 +1 s (0 s = backswing initiation). Spearman's ρ is reported for the participant-level correlations. Average ρ and t values are reported for the within-
 3 participant correlations.

4

Time	QE _{pre}			QE _{post}			HEOG-SD		
	$\rho_M(18)$	$t(31)$	$\rho(30)$	$\rho_M(18)$	$t(31)$	$\rho(30)$	$\rho_M(18)$	$t(31)$	$\rho(30)$
-3 to -2.5 s	.00	0.02	-.37*				0.04	0.76	.04
-2.5 to -2 s	.04	0.84	-.27				0.11	2.61*	.09
-2 to -1.5 s	-.09	-2.24*	-.28				0.13	3.04**	.21
-1.5 to -1 s	-.03	-0.82	-.29				0.12	2.47*	.07
-1 to -0.5 s	-.08	-1.58	-.44*				0.12	2.37*	.32†
-0.5 to 0 s	-.09	-1.54	-.51**				0.09	1.67	.47**
0 to +0.5 s				-.14	-3.38**	-.10	0.05	1.04	.36*
+0.5 to +1 s				-.08	-2.21*	-.28	0.08	1.84	.42*

5 Note. Only relevant comparisons are reported: QE_{pre} with pre-movement initiation occipital alpha power (i.e., 6 intervals from -3 to 0 s) and QE_{post}
 6 with post-movement initiation occipital alpha power (i.e., 2 intervals from 0 to +1 s).

7 † $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$

1 **Figure captions.**

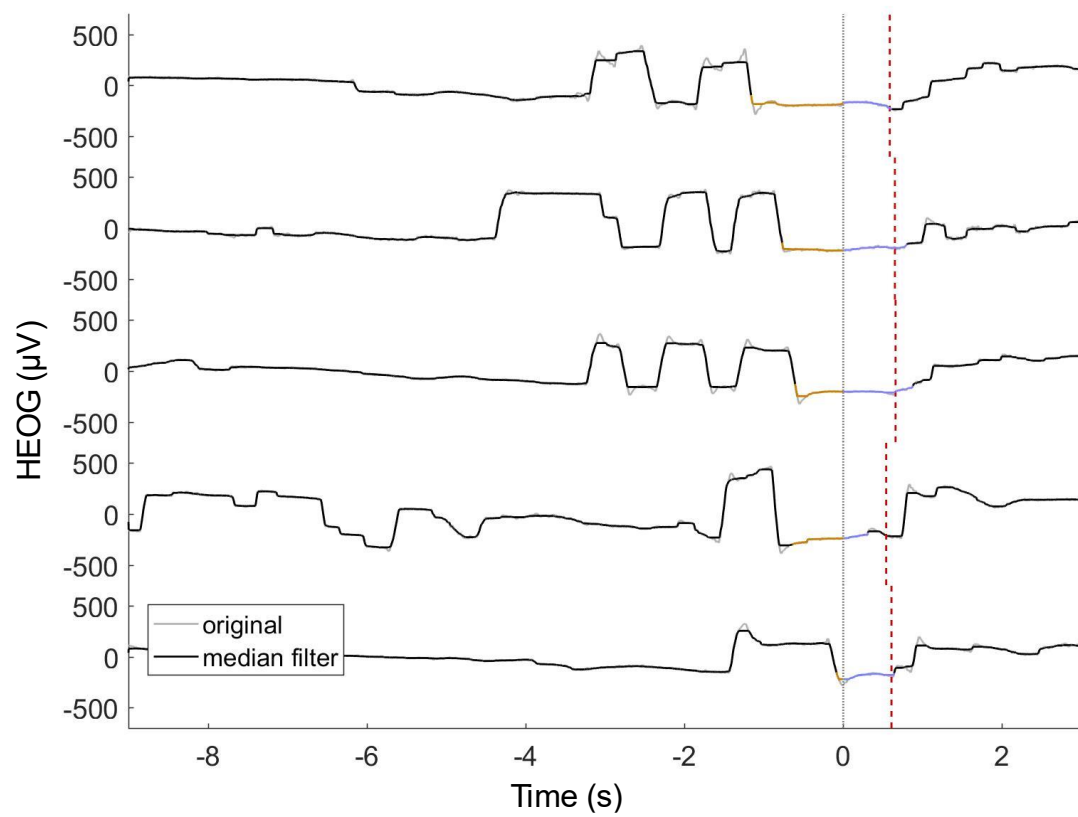
2

3 **Figure 1.** Voltage of the horizontal EOG channel as a function of time (0 s = backswing
 4 initiation) for selected putts. Increases and decreases in signal amplitude indicate saccades to the left and
 5 right, respectively, whereas a flat signal indicates absence of eye saccades (i.e., fixations). For each
 6 waveform, the grey line represents the original signal (low-pass filtered at 30 Hz); the black line
 7 represents the same signal after median filtering; orange and blue portions represent respectively QE_{pre}
 8 and QE_{post} durations identified with the 60 μV threshold; the red vertical line indicates putter-ball impact.
 9

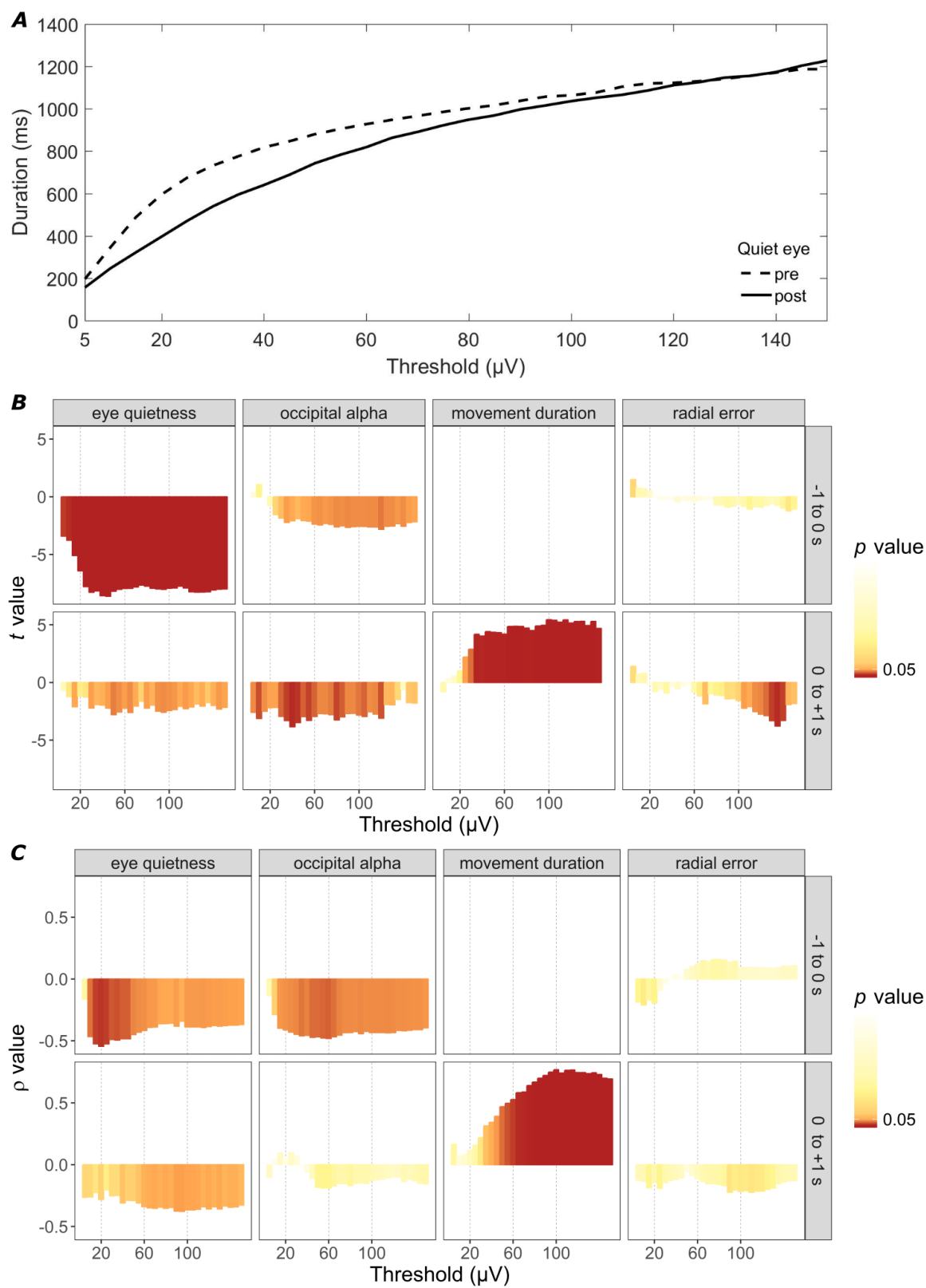
10 **Figure 2.** Effect of threshold (5-150 μV) on quiet eye durations (s) in the ‘pre’ and ‘post’ phases
 11 (panel A). Trial-level (panel B) and participant-level (panel C) analyses exploring the relation between
 12 quiet eye (s) and eye quietness (%), occipital alpha power (%), movement duration (s), and radial error
 13 (cm), as a function of thresholds (μV). Only relevant associations were tested (e.g., pre-movement
 14 initiation quiet eye duration with occipital alpha in the 1 s preceding movement initiation). The
 15 association between quiet eye and movement durations were conducted only for the post-movement
 16 initiation component of the quiet eye, in line with the predictions of the postural-kinematic hypothesis.
 17

18 **Figure 3.** Eye quietness (HEOG-SD) as percentage change from the baseline (i.e., cross-trial
 19 average activity in the 2 s prior to the onset of the acoustic tone) as a function of time (i.e., 0.5-s non-
 20 overlapping intervals from -3 to +1 s; 0 s = movement initiation). Smaller values indicate less variability
 21 on the horizontal plane hence greater eye quietness. Error bars indicate within-participant *SE* computed
 22 through normalization of the outcome factor (Cousineau, 2005)
 23

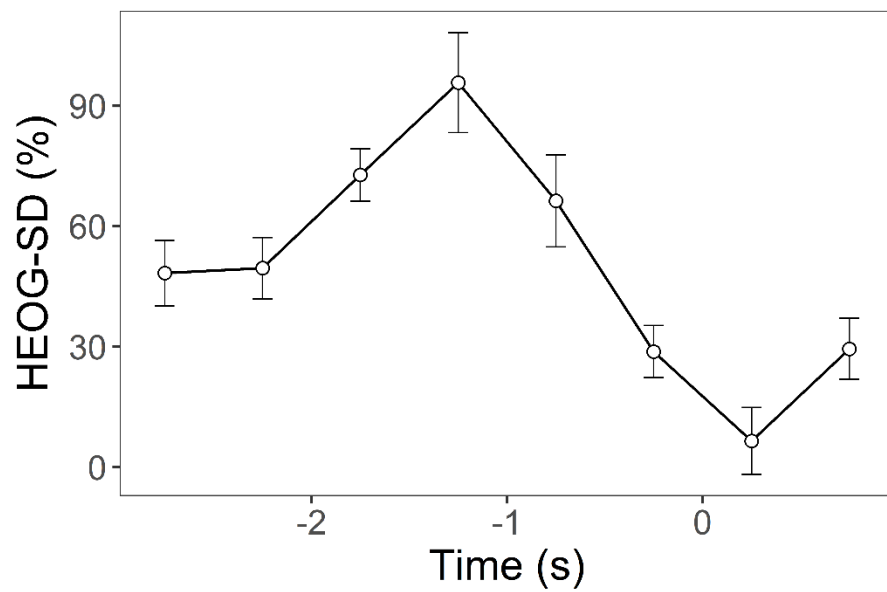
24 **Figure 4.** Trial-level (panel A) and participant-level (panel B) analyses exploring the relation
 25 between EEG power (%) in the 1 s preceding (-1 to 0 s) and following (0 to +1 s) backswing initiation
 26 and either quiet eye (s) or eye quietness (%), as a function of frequency (Hz).

1 **Figure 1**

2

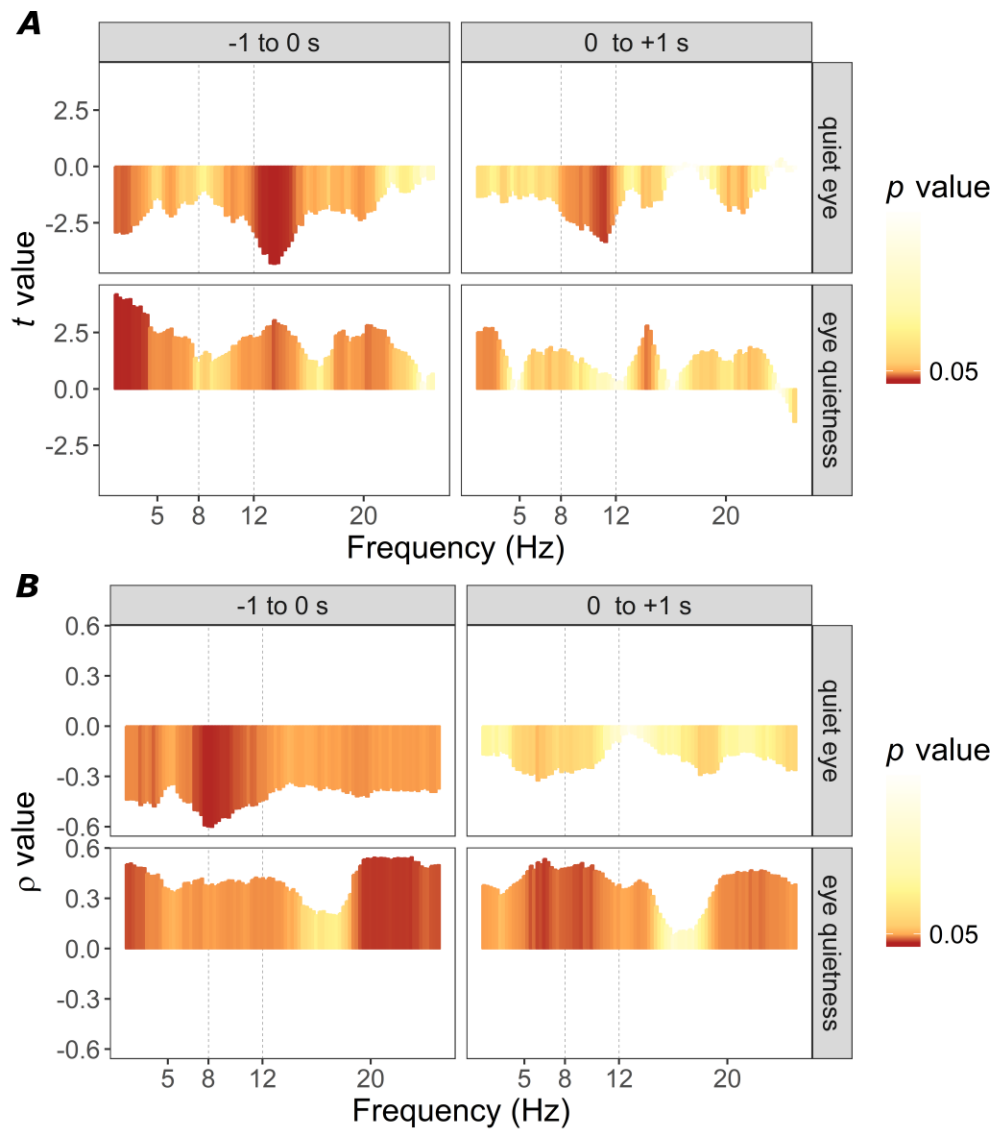
1 **Figure 2**

2

1 **Figure 3**

2

3

1 **Figure 4**

2